Grid planning for renewable energy in urban deltas

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Abstract

Climate change and the associated rise of the sea level is one of the major concerns for many urban deltas around the world, and the flooding prone region of the Netherlands is no exception. Part of the mitigation pack is decarbonizing the energy production, for example by use of renewables like wind and sun. However, renewable production takes place on a much smaller scale than traditional power plants. Large wind turbines are in the order of magnitude of several MW, whereas traditional power plants are typically measured in GW. As a result, renewable production is much more decentralized than the traditional production. This can bring benefits, if the production can be integrated into existing grids. But if the renewables are planned at remote locations, a significant cost for connecting them to the grid will result. This can be further amplified by the regulatory regime, providing financial incentives to DNO's to connect the new power plants to their existing grid instead of applying a (from the societal perspective) more efficient solution involving the TSO's. This paper quantitatively demonstrates the problems that can occur in grid planning for renewables in the current split responsibility system and advocates a more integrated approach.

Keywords: Strategic asset management, Grid planning, Renewables, Urban deltas

1. Introduction

In a recent report on climatic change (World Bank by the Potsdam Institute for Climate Impact Research and Climate Analysis, 2012) of the world bank it is argued why a 4^0 C warmer world should be avoided. Part of this argumentation revolves around a sea level rise, projected to be between 0,5 and 1 meter by 2100. But another part revolves around the increased precipitation, especially in the form of heavy precipitation events on page 53 of the synthesis report (Intergovernmental Panel on Climate Change, 2007). Both factors are a major concern for urban deltas as they increase the risk of inundation. This is especially true for the Netherlands, a country with a long history of war with the waters. Since the last major flood of 1953 the Delta works were executed, resulting in a low risk of inundation even though the country is for 30% below the average sea level. Yet, rising sea levels would increase the risk again, as every meter of sea level rise would put another 5% of the country below the sea level. The Netherlands are also at risk from the other threat, increased precipitation. The Rhine river system discharges through the Netherlands, and normative peak discharges are expected to grow from 16000 m^3/s now to 22000 m^3/s in the year 2100 (Deltacomissie, 2008).

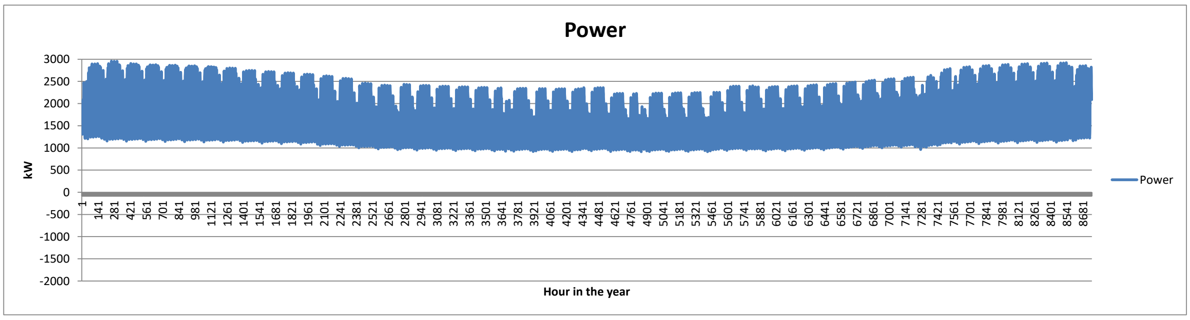
The Netherlands have the knowledge and the resources to deal with this challenges, e.g. by increasing the height of flood defences, introducing mega pumped discharge, essentially turning the Netherlands into one giant polder. Yet, the ability to deal with the change does not mean there is no debate about the potential to prevent the change happening. A major element of this preventative strategy is decarbonizing the energy production, by means of renewable sources like wind and sun. The Netherlands have committed themselves to 16% of renewable energy by 2020 and 100% by 2050. Wind is supposed to contribute by 6000 MW of land based turbines (Rijksoverheid, 2012), roughly one third of the peak consumption, though the lower load factor (2000 hours instead of 6000) means the contribution to the energy is only about 11%. As the production potential of the Netherlands is in the order of magnitude of 8 MW wind power per km^2, this requires some 750 km^2 of wind farms. Even though that is "only" 2% of a small country like the Netherlands, it is much more than what is needed for a traditional power plant, with a power density in the order of magnitude of about 1 GW per square kilometre. Renewable energy is thus much more distributed by nature than traditional power plants, putting a higher demand on the distribution grid. Furthermore, because in principle each wind turbine (i.e. each MW) can be a separate decision, the predictability of amount of wind power to be connected to the grid is much less predictable than a power plant that comes in 100s to 1000s of MW at the time. If the grid operator responds to these demands by applying good asset management practices like "wait and see", the resulting grid may well be (or most likely be) not the social optimum.

This paper quantitatively demonstrates how such an approach results in a non-optimal solution for a substation with a large amount of wind power connected to it.

2. Integrating wind power into the grid

Renewable production therefore is by nature much more decentralized than the traditional power plants. There are two perspectives on this decentralization of energy production. One view is that it is a good thing. Energy consumption is decentralized as well, and producing energy close to the location where it is consumed reduces the losses in transporting the energy and limits the needed investments to establish the transporting infrastructure. This is especially true if the production can be integrated into existing grids. Connecting the wind turbines to the grid will cost typically € 20000 per turbine[1]. As an extra benefit, integrating wind turbines into existing load bearing circuits will reduce energy losses. The diagram below shows a typical distribution grid load profile, both without (top) and with (bottom) wind. The load factor of the losses is the sum of the squared hourly loads divided by the squared peak. The load factor of the losses of the profile without wind is 3600 hours at a peak load of 3 MW, whereas the factor is 2300 hours for the profile with wind, resulting in a reduction of the losses from 100 MWh per year to 70 MWh or a benefit of € 1650/year per cable or € 550/year per MW of wind power, resulting in a net present value of € 11000 per MW.

[1] This is only the cost of 2 joints and a connection length of 100 m (consisting of 2 cables). The cost of the switchgear is not included, that is needed in any scenario



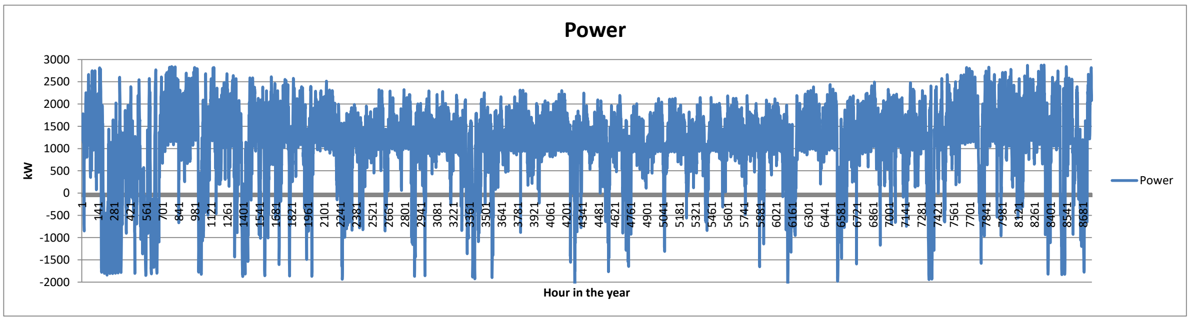


Figure 1: The diagram on top is the typical load profile of distribution load: 900 kW of small businesses (S11), 900 kW of medium businesses (s12), 1800 kW of households(S21). The numbers refer to the standard load profiles (SLP) published by the VREG[2] (VREG, 2010). The load profile below has 6 MW of wind added (generated power based on synthesized profile drawn from 10 years of KNMI (2001-2010) data for Lelystad)

However, there is another perspective to renewable production by means of wind turbines. As the Netherlands are highly planned spatially, consumption occurs in large blobs (cities and villages) with little room for wind turbines. Those are typically situated in places where not so much consumption is located. This is reinforced by the NIMBY sentiment regarding wind turbines. This means the wind power has to be transported over a significant distance.

A cable capable of transporting the power produced by wind turbines is typically cost some € 100.000 per km for a 10 MW capacity[3]. Losses in such a cable at full load are about 50 kW per km. Given a load factor of the losses for a wind profile of 1200 hours per year, this results in 60 MWh of loss per km per MW per year. At a cost of € 55 per MWh, the cost of the energy losses are about € 3300 per year. Expressed in a net present value at 5% real interest this accumulates to roughly € 66000 per km, almost as much as the cost of the cable. The total cost is € 166000 per km. Given that remote wind

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[2] The Flemish regulatory body. Load profiles available at http://www.vreg.be/verbruiksprofielen-0. The profile used is that of 2011 (http://www.vreg.be/sites/default/files/uploads/documenten/technische%20reglementen/100898.XLS)

[3] Based upon connection tariff list LIANDER, 200 € /m for a 10 MW connection that is redundant. For wind farms a non-redundant connection is good enough. ENERGIEKAMER 2012. Tarievenbesluiten RNB Elektriciteit 2013

farms consist of several turbines placed some 500 m apart, typically some 5-15 kilometres[4] from the nearest connection point to the grid, it is clear that producing at remote locations comes at a cost.

3. The case study situation

The situation of the case study is substation Zeewolde, located in the Flevopolder, a part of the Netherlands claimed over the sea in the period 1950-1968. The area is several meters below sea level. The map below shows the Zeewolde area with wind turbines, power station and power lines marked on the map. The map is a screen shot of the ENIPEDIA powerplant database of the Delft University of Technology.

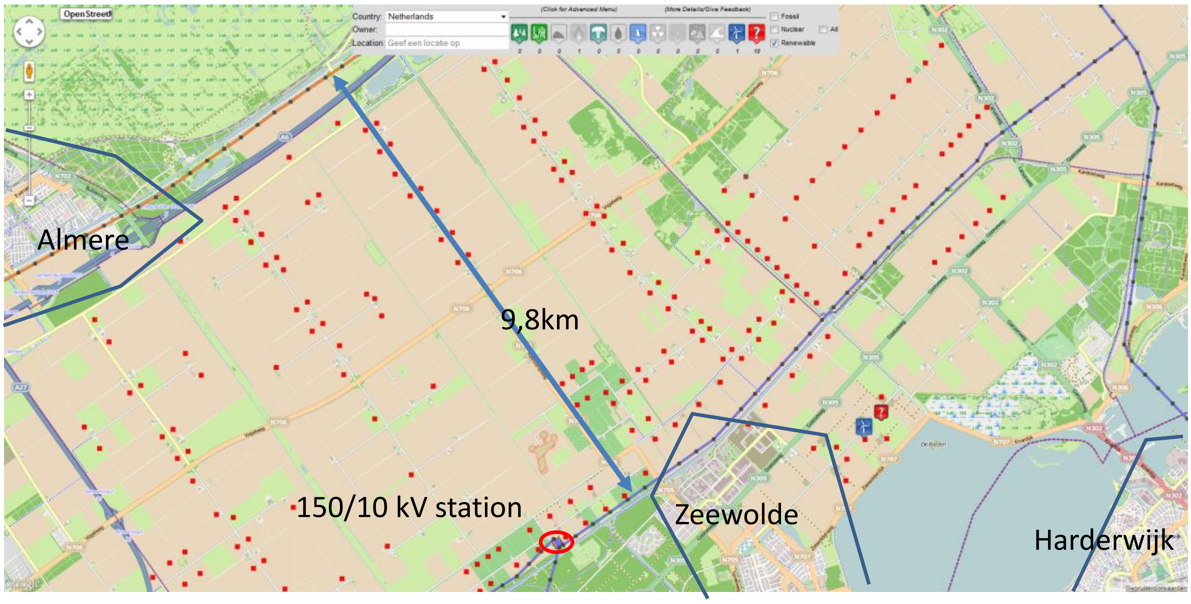

Figure 2: Map of the Flevoland area showing the locations of wind turbines (ENEPEDIA, 2012)

The land use is mostly agricultural, with a few population centres. The dotted line on the top left is a 380 kV line, the dotted line on bottom right is a 150 kV line. To indicate the scale of the map, the distance between those lines is 9,8 kilometre. The circle is Zeewolde 150 kV substation. The dots are wind turbines. Detailed information on the wind farms can be found in an online database[5] (The Windpower, 2012). The table below lists the windfarms in this area.

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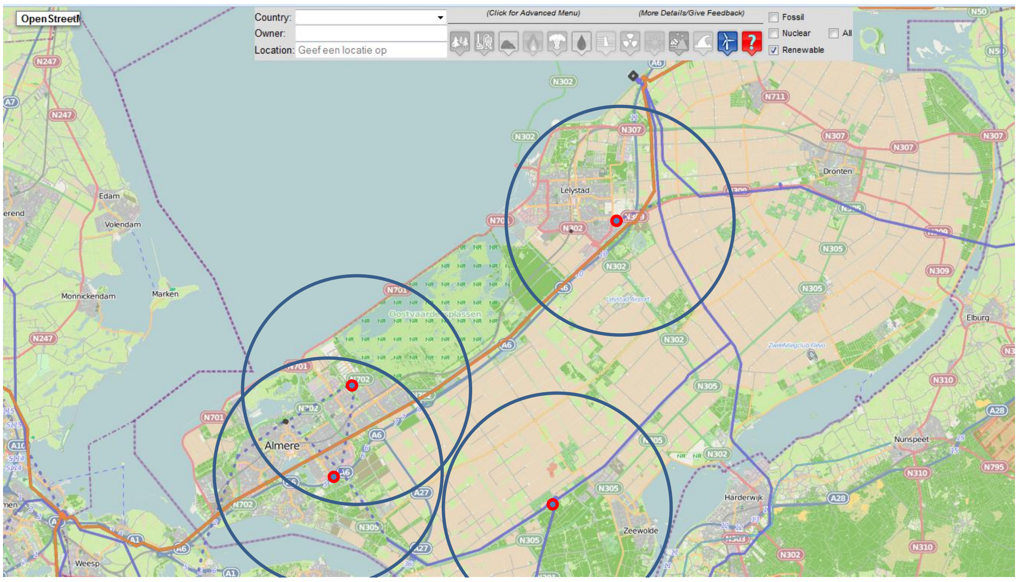
[4] This is the Dutch situation. In the densely populated country it is hard to be more than 15 km from the nearest high voltage substation.

[5] http://www.thewindpower.net/country_windfarms_en_10_netherlands.php.

Table 1 list of windfarms in the Zeewolde Area (source www.thewindpower.net). The voltage guess is based upon the power. Up to 13 MW can be supplied by a single 10 kV at 800 mm^2 cable.

ID	**Name**	**kW**	**Turbines**	**Avg kW/Turbine**	**kV (guess)**
24	Bloesemlaan	18150	20	907,5	20
58	Dodaarsweg	18780	23	816,5217391	20
67	Eemmeerdijk	18000	18	1000	20
74	Eolienne	10000	10	1000	10
82	Futenweg	10500	6	1750	10
92	Gruttoweg	19710	23	856,9565217	20
151	Lepelaarweg	11400	12	950	10
187	Ooievaarsweg	15280	16	955	20
204	Pijlstaartweg	36000	24	1500	20
207	RachelCarson	18000	18	1000	20
208	Reigerweg	12570	16	785,625	10
221	Schollevaarweg	20400	22	927,2727273	20
239	Sterappellaan	10950	12	912,5	10
289	Wulpweg	14600	17	858,8235294	20
295	Zeewolde	125560	126	996,5079365	20
	Total	**359900**	**363**	**991,4600551**	
	Total 10 kV	**55420**			
	Total 20kV	**304480**			

These wind turbines are connected to the Zeewolde substation. Apparently it was easier to connect them to Zeewolde, even though there are other 15 kV stations in the neighbourhood as shown on the map below.



The full list of wind power connected to these stations is in the table below (source: Quality and Capacity document 2011-2016 (LIANDER, 2011)

Table 2: The connected load and production to the stations in the map

Substation	**Voltage [kV]**	**Capacity 2011 [MVA]**	**Peak load basis 2012 [MW]**	**Wind 10 kV [MW]**	**Wind 20 kV [MW]**	**Total**
Almere	150	132	57,6	0	0	0
De Vaart	150	132	56,8	0	0	0
Zeewolde	150	380	28,2	54,9	301	355,9
Zuiderveld	150	132	59,4	56,2	0	56,2

Furthermore, most of the wind power is connected by means of 20 kV, whereas consumption at this station is at 10 kV. The wind turbine locations are not near to the distribution grid, therefore not allowing for integration into the existing grid. This list reasonably complies with the estimate bases on the wind farms. That these numbers match should not be surprising. The wind farm operators would have to pay for the cable connecting their farm to the substation. As long as the only voltage was 10 kV, it makes sense to match the wind farm power with the cable capacity. Most 10 kV farms are therefore in the 10 MW range, whereas 20 kV farms are in the 20 MW range.

4. Evaluating alternatives

However, in hindsight this may not have been the best solution. Implementing the 20 kV solution earlier might have been more cost effective from a total societal perspective. And what if the voltage would have been even higher, up to 30 kV? Given the large amount of wind power that might have been a better solution right from the start.

To answer this question, a simple model has been developed to evaluate the options economically. The average length of the cables to connect a wind farm to substation Zeewolde has been set at 10 km. At the average power of 1 MW per turbine the distance between the turbines is about 500 m. It is assumed wind parks could be reshuffled to reach the cable capacity.

Table 3: base data

	10 kV	**20 kV**	**30 kV**
Cable capacity	10 MW	20 MW	30 MW
Maximum number of turbines	10	20	30
Base cable length	10 km	10 km	10 km
Additional length	500 m	500 m	500 m
Total length at full capacity	15 km	20 km	25 km
Cable cost	100 k€	110 k€	120 k€
Energy loss	3300 €/km/yr 66000 €/km NPV	3300 €/km/yr 66000 €/km NPV	3300 €/km/yr 66000 €/km NPV

	10 kV	20 kV	30 kV
	(5%)	(5%)	(5%)
Connection cost per turbine (compact substation)	60 k€	65 k€	70 k€
Connection cost 150kV substation	100 k€	120 k€	140 k€
Transformer cost 150 kV (150MW)	2400 k€	2400 k€	2400 k€
Transformer cost per MW	16 k€	16 k€	16 k€

These costs are high level estimates, based upon the tariff list of LIANDER[6]. These may not reflect true costs, but can be assumed to be about right, given their acceptance by the regulator. The tariff list applies to 10 kV connections. 20 kV and 30 kV costs are higher, but not exceptionally. TKF supplies their Twenpower cable for all voltages in the table above, with the only difference between cables in isolation thickness[7]. The cost difference therefore is estimated at +10% for 20 kV and +20% for 30 kV. The same reasoning holds for the compact substation. Largest part of the costs are the building and its installation, the switchgear inside is about 10-20 k€. Switchgear at higher voltages is more expensive, but again not exceptionally. ABB supplies their base model SaferRing /SafePlus up to 36 kV[8]. Extra costs of 5 k€ and 10 k€ are used.

Table 4: Cost calculation

CAPEX	10 kV	20 kV	30 kV
Feeder (base length plus sub connection)	1600 k€	2320 k€	3140 k€
Transformer cost per cable	160 k€	320 k€	480 k€
Connections	600 k€	1300 k€	2100 k€
Total	2360 k€	3940 k€	5720 k€
CAPEX Per turbine	236 k€	197 k€	191 k€
OPEX			
Energy loss connection	660 k€	660 k€	660 k€
Energy loss intra farm (full load at 1/3 of length)	88 k€	220 k€	330 k€
Total OPEX	748 k€	880 k€	990 k€
OPEX per Turbine	75 k€	44 k€	33 k€
Total costs per turbine	311 k€	241 k€	224 k€
Total cost excluding transformer	295 k€		

[6] https://www.acm.nl/download/documenten/nma/104092_6%20Liander%20N.V.%20tariefvoorstellen22-202118.xls
[7] http://www.tkf.nl/CATALOGUS/tabid/236/language/en-US/language/nl-NL/Default.aspx?en-US=Default.aspx&nl-NL=Default.aspx. The specs used are 50420 (10 kV), 54218 (20 kV), 56195 (30 kV)
[8] http://www.abb.com/product/db0003db004279/c125739900636470c125683f0036fd39.aspx , Catalogue SafeRing_SafePlus 36kV 1VDD006114 GB May 2012.

It is clear that from the perspective of the needed distribution grid the higher voltages are preferred. The 20 kV solution performs about 20% better than the 10 kV solution and about 10% worse than the 30 kV solution. This holds even if the cost of the transformer is excluded for the 10 kV solution, given that the first amount can be connected without installing a transformer. The difference is also large enough to hold if the estimates for cable and equipment costs at higher voltages are off.

However, from the perspective of the grid operator the advantage of higher voltages is not that clear. This is because the wind farm pays for the connection, and absorbs the costs of the losses. Furthermore, connecting the wind farms by means of the existing transformers, lowers the fee the DNO has to pay to the system operator. According to the tariff decision for 2012[9], the fee is 12,80 per kWmax per year, plus 1,29€ per kWmax per month (Energiekamer, 2011). Due to the intermittent characteristics of wind power, the effect is not large (like the losses), but it is there. Using the same load profiles as in figure 1, scaled up to 29,5 MW total, the addition of 55 MW of wind power reduces the peak to 28,5 MW, resulting in a reduction of the fee of about 35k€ per year, resulting in a net present value of about 700 k€ This is summarized in the table below.

NR	Alternative	Cost from social perspective	Cost from grid operator perspective (assuming cost of connection to be paid by wind farm)
1	10 kV, first 55 MW on existing installation	55*295 k€ (existing) +308*311 k€(new) = 112 M€	-700 k€ (existing)
2	10 kV, all new	363*311 k€ = 113 M€	0
3	20 kV, first 55 MW on existing 10 kV installation (this is the actual situation)	55*295 k€ (existing) +308*241 k€(new) = 90 M€	-700 k€
4	20 kV all new	363* 241 k€ = 87 M€	0
5	30 kV, first 55 MW on existing 10 kV installation	55*295 k€ (existing) +308*224 k€(new) = 85 M€	0
6	30 kV all new	363*224 k€ = 81 M€	0

Even though this table suggests the grid operator took a benefit at the cost of society, it has to be remembered that this tariff system was not in place when the first 55 MW of wind turbines was installed. Furthermore, when the first wind farm requested a connection, it was not clear the number would grow that high. And you simply do not build a 150 MW 150/20 kV substation for 10 MW of wind turbines. But because of the first decision, the same reasoning would hold for the second wind farm, the third and so on, until the capacity limit of the station was reached and a new transformer would have to be installed anyway. Only at that point, changing to 20kV became the reasonable option. The reason 20 kV was adopted instead of 10 kV most likely was simply that 20kV is a reasonably common voltage for distribution whereas 30 kV is not. Furthermore, the difference between the alternatives 3 and 4 is not that big, though it would be larger than the benefit of postponing the new transformer. Yet, as the actor determining what technology to use is not

[9] https://www.acm.nl/nl/publicaties/publicatie/4543/Vaststelling-maximum-tarieven-en-rekenvolumina-TenneT-2012/ , document https://www.acm.nl/nl/download/bijlage/?id=7474

necessarily the actor paying for the use of the technology there is a risk of not selecting the optimal solution.

5. Conclusion

Wind power can produce a significant part of the electricity needs, however, connecting them to the grid is no triviality. Preferably they would be connected into existing grids, to minimize connection costs and even have a net benefit for the grid. However, in densely populated urban deltas the population centres hardly have space for wind turbines, condemning them to the rural areas where no grids exist to connect to. In those rural areas, uncoordinated planning can result in unneeded cost because grid operators will use a wait and see approach. The tariff system may even advance non-optimal solutions. If a more integrated approach would be used, including long term planning and evaluation on total societal costs, a better, less expensive solution could be found. It may be difficult to implement integrated planning in a liberalized energy market, but given the benefits it can bring it should be given a try.

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