Power Expansion Optimization Model Considering Multi-Scenarios in Electricity Demand and Supply: The Netherlands

Zakaria EL KHELLOUFI [1]

[1]Delft University of Technology (TU Delft)
P.O. Box 5015, 2600 GA Delft, The Netherlands

Abstract. *The Netherlands set its strategy to reduce* CO_2 *carbon emissions by 49% by 2030. This strategy incorporates a high share of large-scale solar PV and wind onshore energy (an estimate of 35 TWh). Therefore, the country introduced an instrument to stimulate participation at the regional level, where inter-municipal decision-making take place when planning for such large renewable energy projects. The country is then divided into thirty regions, where each region need to optimally plan the incorporation of renewable energy projects into the electricity grid. On one side, the energy regions have planned only 26 TWh of electricity generation. On the other side, many uncertainties prevail the Dutch electricity supply and demand. Therefore, this study introduced a techno-economic model co-optimising generation, transmission and storage units capacity investments and operation at high spatial and temporal resolution. The co-optimization problem is solved using the linear optimal power flow considering different scenarios in electricity supply and demand. The 35 TWh electricity generation was found to be cost-optimally integrated into the electricity grid using battery and hydrogen storage, flexible gas supply and the expansion of several transmission lines at the 380kV and 150kV voltage level.*

1. Introduction

To achieve at least a reduction of 50% of European Union (EU) green gases by 2030 compared to 1990, countries within the EU need to increase both their energy efficiency and the share of variable Renewable Energy Sources (vRES) [22]. The Netherlands sets a target of at least 32% of vRES share in its energy mix by 2030 under the National Climate Agreement (KEA) [21]. Following the increase share of vRES, a goal to generate 84 TWh of electricity by vRES in 2030 is planned by the government, where 49 TWh will be generated by wind offshore energy and 35 TWh by large-scale onshore energy projects[16] (Figure 1).

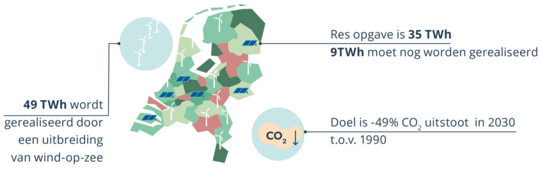


Figure 1. Renewable electricity generation targets by 2030 [16]

The 35 TWh need to be exclusively generated from large-scale wind onshore and solar Photovoltaic (PV) (> 15kW) projects. When planning large-scale renewable energy projects locally, "an inter-municipal decision-making is required regarding their cross-jurisdiction implications "[10]. According to [10], without an inter-municipal collaboration large sized municipalities with larger capacities and investment room harvest all the benefits. Therefore, inter-municipal collaboration is "essential to avoid an unfair distribution of costs and benefits within local administrations" [10]. Therefore, The Dutch government presented a package of measures and instruments in the national climate agreement to make more deliberated decisions regarding large-scale onshore technologies. The instrument is called the Regional Energy Strategy (RES), where the Netherlands is divided into different energy regions (Figure 2). The energy regions are presented by several stakeholders among others civil organization, business community, municipalities and water authorities [8].

Figure 2. Energy regions

The objective of the energy regions is to deliver their strategy of the energy transition by 2030. The strategy should incorporates the necessary amount of electricity generation by large-scale solar PV and wind onshore energy, storage units capacities, the location of the technologies and the needed infrastructure [21]. The total of the planned electricity generation by large-scale solar PV and wind onshore energy by the thirty regions so far is 26 TWh, where 9 TWh still need to be planned [20].

To ensure a successful energy transition, the renewable energy planned projects by the energy regions need to be fully integrated into the electricity grid. However, the high integration of renewable energy sources (wind and solar energy) into the electricity grid entails many challenges. The stochastic and intermittent behavior of vRES poses several problems to the electricity grid operator, among others, grid imbalance in terms of electricity demand and supply. On one side, the Dutch electricity demand growth by 2030 might have different shapes, that depend on the electrification of the transport sector and the development of power to gas/heat and heat pumps [24]. On the other side, the Dutch electricity supply is expected to have different evolution as well, that depend on the achievement of the vRES planned projects, the phasing out of coal-fired power plants and the reduction of gas installed capacity. Moreover, the peak electricity demand is expected to increase due to additional electrification that is assumed to not be flexible [26].

To optimally integrate the 26 TWh electricity generation by large-scale solar PV and wind onshore into the electricity grid, the energy regions need to define the necessary storage capacities along with their locations. However, the uncertainty prevailing the Dutch electricity system in terms of electricity supply and demand for 2030 might lead to an over-investment or under-investment problems. Moreover, the increase in peak electricity demand might causes overloading of the transmission lines, which might requires reinforcement of the transmission grid. Therefore, the goals of this article is:

- To find out the necessary installed capacity and location of storage units along with the necessary transmission expansion to adequately accommodate the 26 TWh of electricity generation from large-scale solar PV and wind onshore under uncertainty in supply and demand in a cost optimal way.
- To determine the least cost investment in large-scale solar PV and wind onshore to install the remaining 9 TWh electricity generation under uncertainty, while incorporating the 26 TWh regional plans.

The incorporation of uncertainty in optimization problems can be done using scenario construction, which energy-system modelers can use to achieve their objectives in deriving robust trends by using different scenarios [13]. Moreover, by considering different scenarios, the real world complexity can be decreased to develop power system models that can be solved within appropriate computation time. Therefore, different deterministic scenarios will be constructed to capture the different evolution the Dutch electricity supply and demand can follow for the year 2030. The following research question therefore is formulated: **Given multiple scenarios in the Dutch electricity supply and demand, what is the cost-optimal power system expansion considering energy storage systems to incorporate the regional plans by 2030?**

The paper is structured as follows: Chapter 2, provides an overview of the state of the art of methods for optimization problems in energy systems. The methodology is presented in Chapter 3. Chapter 4 introduces the scenario definitions and the key data for the scenarios. The results are presented in Chapter 5, followed by the discussion in Chapter 6 and the conclusion in Chapter 7.

2. State of Art

This section sets the basis for the further understanding of the applied research approach by presenting an overview of the methods used to optimize the power system.

In the Netherlands, the energy regions need to integrate optimally storage units into their generation expansion plans along with the necessary transmission lines reinforcement. The reinforcement of transmission lines is necessary because electricity has to be transported from remote areas where vRES are installed, to the load centers and this would poses significant challenges to the electricity grid. Therefore, generation, transmission and storage investment costs need to be optimized. The set of optimization problems in power systems is "acknowledged as optimal power flow" [14], where a cost function is optimized over different variables, such as, voltages real/reactive power outputs [7]. One of the most accepted approximation of the optimal power flow is DC Optimal Power Flow (DCOPF) [11]. In general the solution generated by DCOPF are fast but not so accurate compared to AC optimal power flow (ACOPF) [6]. ACOPF problem is the full representation of the OPF, which need to be solved via iterative algorithm due to its non-linearity nature [27]. Therefore, ACOPF problems are time consuming for large-scale projects and practically impossible to use in the body of large iterative algorithms as planning processes [2]. As a result, DCOPF problem is more favourable due to its short run time and its heuristic solution that can be used by power system operators for large network topologies. An additional challenge in OPF problems is that power systems are largely affected by uncertainties [1]. In particular, electricity demand generation and vRES installed capacity. To guarantee network stability, the treatment of uncertain parameters must be included in the optimization models.

The modelling and the optimization of the Dutch power system will be performed using a linear optimal power flow following different scenarios in electricity supply and demand. Both electricity supply and demand will be developed using a spatio-temporal approach. In the next section, the methodology used will be presented.

3. Methods: Model

The methodology used in this article provides a comprehensive approach to co-optimize the expansion of electricity generation, storage units and transmission lines.

3.1. Model description

The modelling and the optimization of the Dutch electrical power grid is done using Python for Power System Analysis (PyPSA) model [3], which is a free software toolbox. In the model, each energy region is presented by a single bus with different electricity demand and generation portfolios. The power generation portfolio is represented by the combination of different generation technologies: gas, coal, wind onshore, wind offshore and solar. To consider adequately the fluctuations in electricity generation from vRES, a whole year is simulated with an hourly resolution. Two assumptions are considered concerning the modelling of renewable energy sources: (1) The availability of renewable energy resources power is derived from the installed capacity and weather condition of the year 2017, (2) curtailment is allowed.

3.2. Model Objectives

The first objective of the model is finding the necessary energy storage systems and transmission lines capacities to incorporate the planned 26 TWh of electricity generation from large-scale solar PV and wind onshore. Therefore, the model is intended to find the optimal investment costs in storage units and transmission lines, and the dispatch in generation and storage units by performing the LOPF.

The second objective consists of finding the necessary installed capacity to meet the planned 35 TWh of large-scale solar PV and wind onshore based on the outcome of the first optimization problem. Therefore, the LOPF will be used to find the optimal investment in large-scale solar PV and wind onshore to generate the remaining 9 TWh along with the necessary storage units and transmission lines capacities.

3.3. Objective function

The optimization problem is a linear optimal power flow model that minimizes the annual system costs. The linear problem computing the LOPF is implemented using PyPSA.

The objective function of the linear optimal power flow problem performed is shown in Equation 5.1, where s refers to storage units, m to buses, l to branches, r to generators and t to time. The optimization variables are the annualized lines fixed costs (F_l), storage investments ($H_{m,s}$), and the generation dispatch of both storage units ($h_{m,s,t}$) and generators ($p_{m,r,t}$), where the marginal costs of storage units and generators are respectively ($o_{m,s}$) and ($o_{m,r}$) which are important for the dispatch optimization and can be expressed in (EUR/MWh). The fixed capital costs for storage units s are defined by $c_{m,s}$ in (EUR/MW). The time steps (called snapshots) are weighted by the parameter w_t that can take values from 0 to 8760. The optimisation is run over all hours t for a specific year with fluctuated supply and load conditions. The variable and parameters are defined in the table below ([12]).

Variables, coefficients and indices	
M	total number of buses
L	total number of transmission lines
S	total number of storage units
R	total number of generators
T	total hours of the time interval
m $\in \{1, .., M\}$	bus label
l $\in \{1, .., L\}$	line label
s $\in \{1, .., S\}$	storage unit label
r $\in \{1, .., R\}$	generator label
t $\in \{1, .., T\}$	time step
w_t	weight of the snapshot
$g_{m,r,t}$	generator dispatch (MW)
$G_{m,r}$	generator power capacity (MW)
$\tilde{G}_{m,r}$, $\bar{G}_{m,r}$	minimum and maximum install-able generator potential (MW)
$\tilde{g}_{m,r}$, $\bar{g}_{m,r}$	minimum and maximum power availablility $\in \{0, 1\}$
$o_{m,r}$	marginal cost of a generator (EUR/MWh)
K	M x L incidence matrix
pn,t	total active power injection at a bus m (MW)
$f_{l,t}$	power flow at a line l at time interval t (MW)
F_l	power rating at a line (MW)
B	diagonal L x L matrix of line susceptances
$\theta_{m,t}$	voltage angle at a bus m at time interval t (rad)
$y_{m,t}$	inleastic load (MW)
$h_{m,s,t}$	dispatch of a storage unit (MW)
$H_{m,s}$	power capacity of a storage unit (MW)
$\tilde{h}_{m,s,t}$, $\bar{h}_{m,s,t}$	power availability per unit of storage capacity
$\tilde{H}_{m,s}$, $\bar{h}_{m,s}$	installable potential of a storage unit (MW)
$u_{m,s,t}$	state of charge of a storage unit (MWh)
$q_{m,s}$	hours at nominal power to fill up a storage unit
$\eta_{m,s,-}$, $\eta_{m,s,+}$	charging and discharging efficiency
$o_{m,s}$	marginal cost of storage units (EUR/MWh)
$c_{m,s}$	capital cost of storage units (EUR/MW)
c_l	fixed cost of a transmission line l (EUR/MW$_{km}$)

$$\min_{H_{m,s},g_{m,r,t},o_{m,s},F_l}[\sum_t(w_t(\sum_{m,r,t} o_{m,r}g_{m,r,t}+\sum_{m,r,t} o_{m,s}h_{m,s,t}))+\sum_{m,s} c_{m,s}H_{m,s}+\sum_l c_lF_l] \quad (1)$$

where, w_t is equal to 1 and $\sum_t w_t$ is equal to 8760.

3.4. Model constraints

This objective function is subject to [3]:

- The Power balance and transmission constraints

$$\sum_l K_{m,l}f_{l,t} = \sum_r p_{m,r,t} + \sum_s h_{m,s,t} - y_{m,t} \qquad \forall m,t \qquad (2)$$

where, $y_{n,t}$ is the inelastic load that needs to be met either by generator, the capacity flow $f_{l,t}$ of a transmission line l or storage units each time t.

The Kirchhoff current laws; Current Law and Voltage Law; take the following form:

$$p_{m,t} = \sum_l K_{m,l}f_{l,t} \qquad \forall m,t \qquad (3)$$

$$f_{l,t} = \sum_n (BK^T)_{lm}\theta_{m,t} \qquad \forall m,t \qquad (4)$$

$$\theta_{0,t} = 0 \qquad \forall t \qquad (5)$$

The power flow constraint is:

$$|f_{l,t}| \leq F_l \qquad \forall t,l \qquad (6)$$

where, all branches $f_{l,t}$ are constrained by their capacities F_l.

- Generator constraints

For conventional generators, their dispatch $(p_{m,r,t})$ is constrained by their capacity $P_{m,r}$

$$\tilde{P}_{m,r} \leq p_{m,r,t} \leq \bar{P}_{m,r} \qquad \forall m,r,t \qquad (7)$$

The dispatch of renewable energy generators on the other hand depends on weather condition. As a consequence, this dispatch is translated to an availability $\bar{p}_{m,r,t}$ per units of its capacity:

$$\tilde{p}_{m,r,t}P_{n,r} \leq p_{m,r,t} \leq \bar{p}_{m,r,t}P_{m,r} \qquad \forall m,r,t \qquad (8)$$

Generators power capacity is also constrained by the maximum install-able potential capacity.

$$\tilde{P}_{m,r} \leq P_{m,r} \leq \bar{P}_{m,r} \qquad \forall m,r \qquad (9)$$

- Storage operation

The storage dispatch and power generation are constrained by their maximum capacity [12],

$$\tilde{h}_{m,s,t} H_{m,s} \leq h_{m,s,t} \leq \bar{h}_{m,s,t} H_{m,s} \qquad \forall m, s, t \tag{10}$$

$$\tilde{H}_{m,s} \leq H_{m,s} \leq \bar{H}_{m,s} \qquad \forall n, s \tag{11}$$

The state of charge of a storage units is subject to two constraints [12]:

$$0 \leq e_{m,s,t} \leq q_{m,s} Hm, s \qquad \forall m, s, t \tag{12}$$

and time linking constraint [12],

$$u_{m,s,t} = \eta_{m,s,0} u_{m,s,t-1} + \eta_{m,s,+} [g_{m,s,t}]^{+} - \eta_{m,s,-}^{-} 1 [g_{m,s,t}]^{-} \qquad \forall m, r, t \tag{13}$$

"The Positive and negative components of the equation are expressed by $[.]^{+} = max(;0)$, $[.]^{-} = min(.;0)$" [12]. The storage units have a charging and discharging efficiency denoted respectively by $\eta_{m,s,+}$ and $\eta_{m,s,-}$.

4. Scenario definitions and data collection

4.1. Scenario definitions

The scenarios were developed to capture the uncertainty in the Dutch electricity supply and demand by 2030. The uncertainty in electricity supply is present in the actual plans of the energy regions regarding the electricity generation from large-scale solar PV. However, the uncertainty in electricity demand is regarding the expected electricity demand in the different sectors. Therefore, a two-phase scenario planning was developed, where generation type and capacity uncertainty (achievement of 50% and 100% of large-scale planned solar PV projects by the energy regions) are presented in the first-phase and the allocation of the installed capacity to segments of two different electricity demand shapes (medium growth and high growth) as a second phase decision. The electricity demand in Scenario1 (high growth) and Scenario2 (medium growth) are respectively retrieved from [4] and [18].

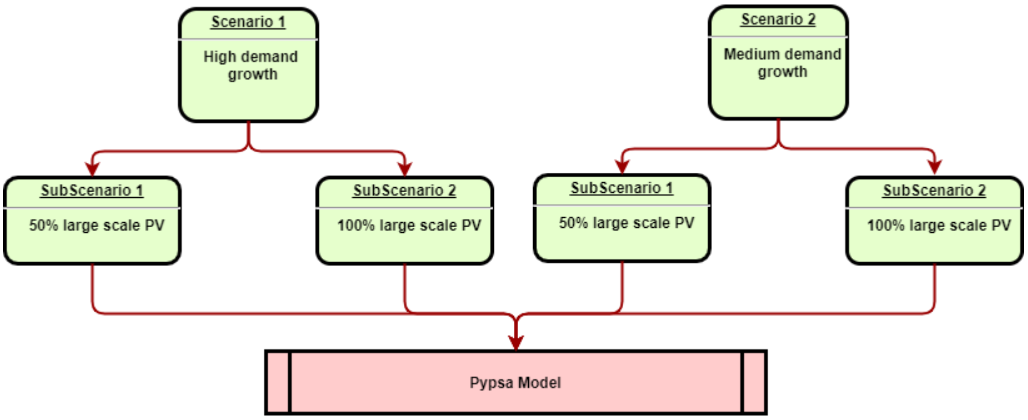


Figure 3. Network topology

4.2. Data

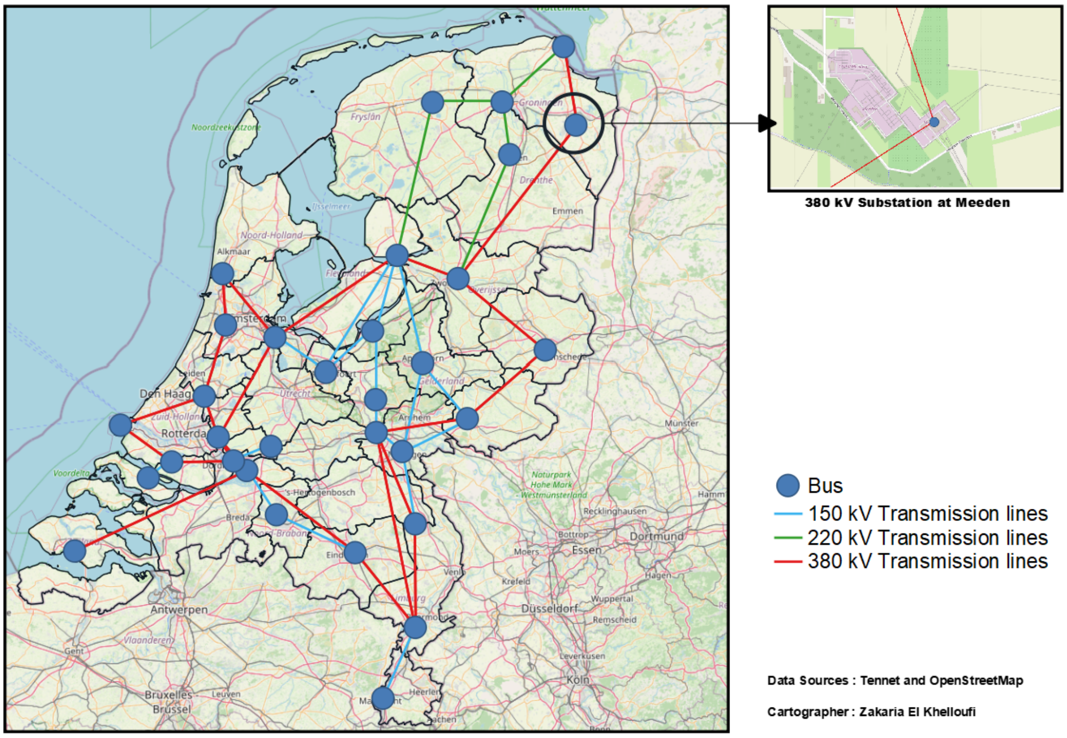
The data underlying the model is presented in this section.

4.2.1. Network topology

To integrate the regional plans into the modelling of the Dutch power system, each energy region need to be linked to a grid substation (bus), where electricity supply and demand are affiliated to. The following process was used for the selection of the buses used in the model:

1. Filtering the grid buses of the HV network (380kV/ 220kV).
2. Validating and adjusting manually the location of the HV buses using real grid map.
3. Incorporating the 150kV infrastructure, in case the 380kV/220kV buses are missing from a region.

The transmission lines connecting two energy regions in the model were modelled by adding the transmission lines in series and in parallel connecting the buses linked to the energy regions in the electricity grid. The transformers were added respectively to the buses that are connected to the transmission lines with different voltage levels. Figure 4 gives an overview of the network topology chosen, where all the energy regions are represented by one bus except for Groningen region (three buses). The sources used to model the different components are described in Table 1. This topology is used for all the scenarios for the year 2030.



Data Sources : Tennet and OpenStreetMap

Cartographer : Zakaria El Khelloufi

Figure 4. Network topology

Components	Data	Voltage level	Sources
Transmission lines	Coordinate	380 kV/220 kV/150 kV	OSM [17]
	length	380 kV/220 kV	Static grid model [23]
		150 kV	HoogspanningsNet[1]
	Capacity	380 kV/220 kV/150 kV	HoogspanningsNet
	Electrical Properties	380 kV/220 kV	Static grid model
		150 kV	PyPSA model
Buses	Coordinate	380 kV/220 kV/150 kV	OSM
Transformers	Coordinate	380 kV/220 kV/150 kV	OSM
	Capacity	380 kV/220 kV/150 kV	HoogspanningsNet

Table 1. Open grid data sources used to extract the Dutch grid data

4.2.2. Electricity demand

The approach adopted to model the Dutch demand profiles addresses both the spatial and temporal demand variations in the different energy regions. The spatial demand variations are developed by dividing the electricity demand into different sectors (households, industry, buildings, transport and agriculture) within the energy regions. The temporal variations are developed by scaling down the hourly sectoral electricity demand data of the Netherlands according to the accumulative yearly sectoral regional electricity demand. Therefore, hourly sectoral regional electricity demand profiles are conceived.

National demand profiles

The hourly electricity demand for the year 2030 are generated for each sector using the Energy Transition Model (ETM) [5] based on the forecast electricity demand by 2030 in each scenario (Table 2).

Sector	Scenario1	Scenario2
Households	86.12	71
Building	113.88	118
Transport	25.33	14
Industry	184.55	155
Agriculture	35.27	48

Table 2. Electricity demand by sector in 2030 (PJ)

Regional demand profiles

The accumulative yearly sectoral regional electricity demand are retrieved from Klimaatmonitor[2] for the year 2017. A linear growth of electricity demand of the energy

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[2] https://klimaatmonitor.databank.nl

regions between 2017 and 2030 is assumed. Regional demand profiles for the year 2030 are conceived by scaling down the hourly sectoral electricity demand created by ETM for each sector.

4.2.3. Electricity generation

The modelling of electricity generation addresses as well the spatio-temporal variations of electricity generation in each region. The spatial supply variations are developed by clustering generation resources by fuel type (e.g. solar, wind, gas). Then, the installed capacity within each fuel type is summed and assigned to the appropriate energy region (regional level). The assignment is done based on the location of the generation resources. Since temporal supply profiles are weather dependent, an accurate parametrization is needed using both wind speed and solar irradiation.

Wind onshore and solar PV generation

The installed capacity of solar and wind onshore energy for the year 2030 are computed by translating the energy regions plans (TWh) to installed capacity (MW). To achieve this translation different assumptions regarding the specifications of wind turbines and solar PV are made. Regarding wind energy, the specifications of the wind turbines are set to 80 m for the turbine height and VestasV90 3000 for the turbine mode. Regarding solar energy, the specification of the solar photovoltaics are 37 degrees for the tilt and 180 degrees for the Azimuth. Both wind speed and solar irradiation are retrived from Renewables.ninja[3] for each region.

Two sub-scenarios are considered while computing the installed capacity of large-scale solar PV projects: 50% of projects achieved (Sub-secnario1) and 100% of projects achieved (Sub-scenario2). Figure 5 and Figure 6 give an overview of the installed capacity of wind onshore and solar PV per region for the year 2030.

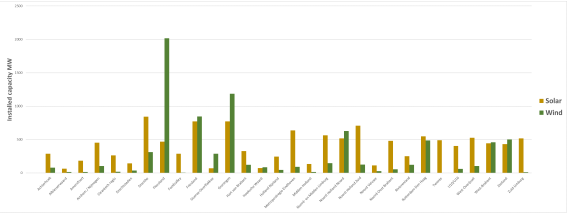

Figure 5. solar PV and wind onshore installed capacity by region in 2030 in Sub-scenario1 (MW)

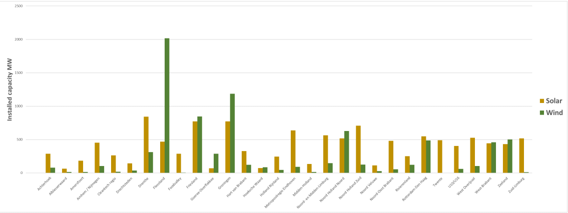

Figure 6. solar PV and wind onshore installed capacity by region in 2030 in Sub-scenario2 (MW)

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[3] https://www.renewables.ninja/

Wind offshore generation

The installed capacity of wind offshore energy for the year 2030, is retrieved from the 2030 Road-map developed by TenneT [25]. Wind offshore projects are assigned to the appropriate energy region based on the location of the bus they are connected to in the HV grid. The installed capacity of wind offshore for the year 2030 is displayed in Figure7.

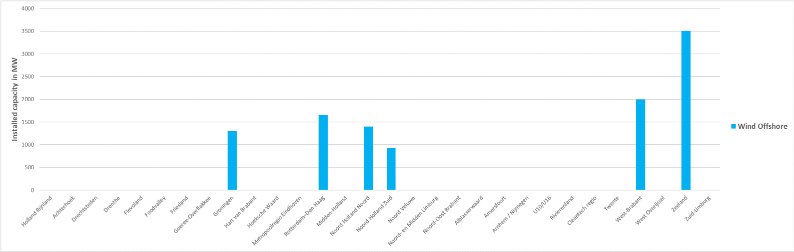

Figure 7. wind offshore installed capacity by region in 2030 in Sub-scenario1 and Sub-scenario2 (MW)

Fossil fuel-based generation technologies

In both sub-scenarios, the capacity of coal by 2030 is expected to be 0. Regarding gas power plants, the installed capacity and the location of the power plants is retrieved from the tool-set Powerplantsmatching [9]. The Netherlands set a plan to phase out gas by 2030 in Groningen. To ensure that the electricity demand is met in the model for both scenarios the installed capacity in Groningen is reduced to the half only. Therefore by 2030 gas installed capacity is expected to be 15986 MW. Figure 8 gives an overview of gas installed capacity within th energy regions by 2030.

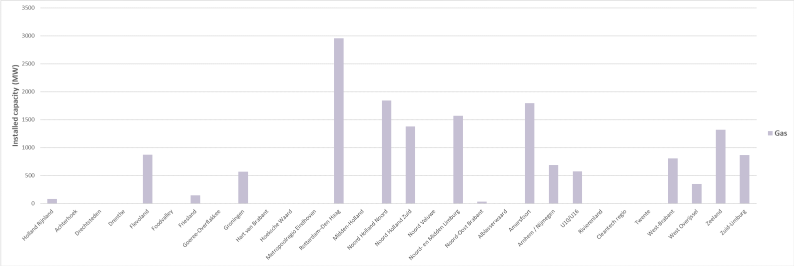

Figure 8. Gas installed capacity by region in 2030 in Sub-scenario1 and Sub-scenario2 (MW)

Storage units

So far there is no installed capacity of energy system storage in the Netherlands. Then, the installation of unlimited storage capacities at all buses at a certain variable and capital cost is allowed in the optimization model. Therefore, the model can build storage units while computing the LOPF. However, to better analyse the energy storage systems, a specification of the type of storage is needed. In this article short-term and long-term storage units are used following the specifications described in [12].

- Short-term storage can be represented by large-scale battery storage facilities that operate on an hourly scale with an energy to power ration of q = 6, meaning that the batteries can provide and store energy for 6h. Moreover, the round-trip efficiency chosen is 93,27%.
- Long-term storage units can be presented by compressed hydrogen stored in underground salt caverns operating as seasonal storage units. Hydrogen storage can provide and store energy for 168h with a charging efficiency of 0.725 and a discharging efficiency of 0.425.

Cost assumptions

The different capital cost assumptions are presented in Table3, Table4 and Table5.

Storage units	Capital Costs	Efficiency of charging	Efficiency of discharging	Energy to power ration
Battery	65822 EUR/MW	0.9327	0.9327	6 h
Hydrogen	65402 EUR/MW	0.725	0.425	168 h

Table 3. Battery storage assumption for 2030 [19]

Line Type	**Capital Cost in** $EUR/MVAkm$
380 KV	85
220 kV	290
150 kV	230

Table 4. cost of transmission lines by 2030 [15]

vRES	**Capital Cost in** EUR/kW_{el}
Wind onshore	1182
Solar PV	600

Table 5. Overnight costs by 2030 [12]

5. Results

In this chapter, both the regional and national results will be discussed for the different sub-scenarios.

5.1. Regional Results

PyPSA model is used to optimize the dispatch in generation and storage units and the investment in storage units and transmission lines under a medium growth and high growth of electricity demand by 2030. Therefore, the main results are the sitting and the sizing of the energy storage units as well as the required transmission lines expansion. Two sub-scenarios are considered: Sub-scenario1 (where 50% of solar PV installed capacity is achieved) and Sub-scenario2 (where 100% of solar PV installed capacity is achieved).

5.1.1. Scenario1

In this section, the results regarding the transmission lines, the storage units and the electricity generation will be presented for both sub-scenarios.

Transmission lines

The optimization results show that a transmission expansion is needed to incorporate the vRES electricity supply into the electricity grid in Sub-scenario1. The extended transmission lines are the connections between: Zeeland- West Brabant, West Brabant - Hart van Brabant, FoodValley - Noord Veluwe, U10/U16 - Amersfoort, Amersfoort -Noord Veluwe. The capacities of the transmission lines and the average loading are shown in Figure 9.

Regrading Sub-scenario2, the model extended the following connections: Zeeland - West Brabant, West Brabant - Hart van Brabant, FoodValley - Noord Veluwe, Amersfoort - U10/16, Noord Veluwe - Amersfoort and Hoekse Waard - Rotterdam Den Haag (Figure 10). The overloaded transmission lines are the 380 kV transmission line between Zeeland and West-Brabant region and the 150 kV transmission lines between Zuid-Limubrg- Noord en Midden Limburg and West-Brabant - Hart van Brabant. The 380 kV transmission line connecting West-brabant and Noord en MiddenLimburg is overloaded as well.

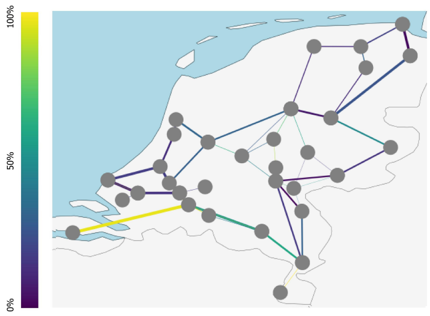

Figure 9. Transmission lines capacity and average loading in Sub-scenario1

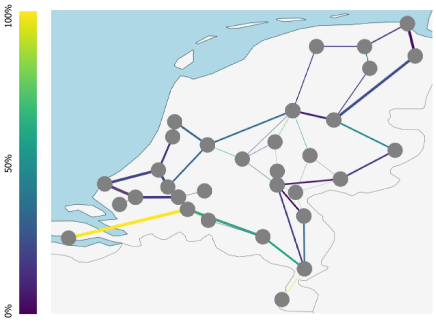

Figure 10. Transmission lines capacity and average loading in Sub-scenario2

Storage units

Based on the investment costs in storage units and transmission lines, the model found the optimal storage units expansion. Under this scenario, a high share of vRES is expected. Therefore, a high capacity of storage units is needed to handle the vRES fluctuations. In Sub-scenario1, 1509 MW of battery storage and 225 MW of hydrogen storage are required (Figure 11). The model built hydrogen capacity only in Zeeland region.

Regarding Sub-scenario2, the required storage installed capacity is 792.42 MW from hydrogen storage and 2372.35 MW installed capacity from battery storage (Figure 12). The model built hydrogen storage in two regions: Zeeland and West Brabant.

Regarding battery storage, U10/16, Achterhoek, Arnhem/Nijmegen and Zeeland are the regions that needed the most of battery storage capacities.

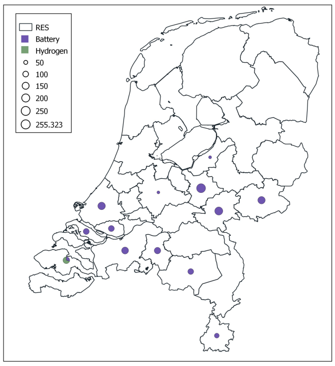

Figure 11. Storage units distribution within the energy regions in Sub-scenario1 (MW)

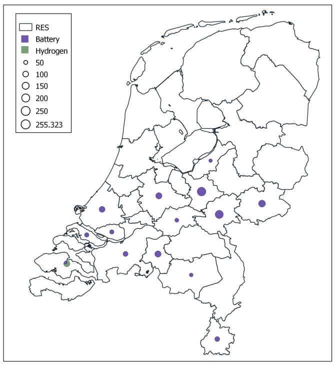

Figure 12. Storage units distribution within the energy regions in Sub-scenario2 (MW)

The transmission and storage expansion costs in Sub-scenario1 and Sub-scenario2 are respectively 1.86 billion euro and 1.67 billion euro.

Electricity generation

The electricity supply in Sub-scenario1 is displayed in Figure 13. The implementation of hydrogen storage in the power system increases the electricity supply from wind offshore energy to 173.048. The supply of electricity from solar, wind onshore and gas is respectively 45.05 PJ, 58.48 PJ and 109 PJ.

In Sub-scenario2, the electricity supply from solar energy increased to 57.6 PJ. However, the electricity supply from wind onshore and gas decreased respectively to 56.6 PJ and 102.4 PJ (Figure 14). However, the electricity supply from wind offshore remained the same.

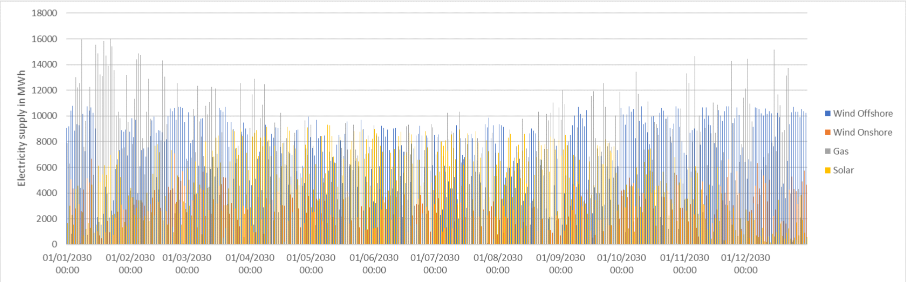

Figure 13. Electricity supply in Sub-scenario1 in MWh

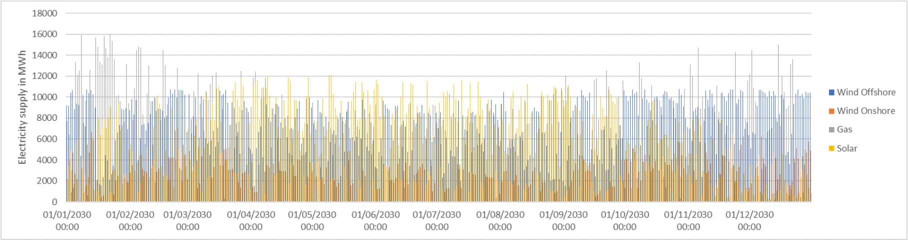

Figure 14. Electricity supply in in Sub-scenario2 in MWh

5.1.2. Scenario2

In this section, the results regarding the transmission lines, the storage units and the electricity generation will be presented for both sub-scenarios.

Transmission lines

The capacities of the transmission lines and the average loading in Sub-scenario1 are shown in Figure 15. The optimization results show that a transmission expansion is needed to incorporate the vRES electricity supply into the grid, especially at the 150 kV electricity grid. The extended transmission lines are the connections between: Zeeland-West Brabant, West Brabant - Hart van Brabant, Rivierenland - Arnhem/Nijmegen, FoodValley - Noord Veluwe, Regio Amersfoort - Rivierenland, U10/U16 - Amersfoort, Flevoland - Noord Veluwe and Amersfoort - Noord Veluwe.
Similarly to Sub-scenario1, the connections that needed more capacities in Sub-scenario2 are: Zeeland - West-Brabant, West-Brabant - Hart van Brabant, Rivierenland - Arnhem/Nijmegen, FoodValley - Noord Veluwe, Regio Amersfoort - Rivierenland, U10/U16 - Amersfoort, Flevoland - Noord Veluwe and Amersfoort - Noord Veluwe (Figure 16).

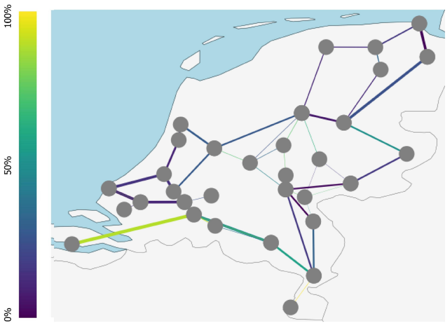

Figure 15. Transmission lines capacity and average loading in Sub-scenario1

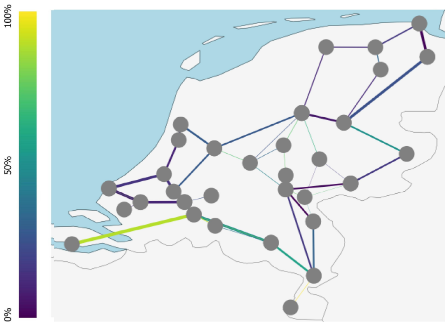

Figure 16. Transmission lines capacity and average loading in Sub-scenario2

Storage units

In Sub-scenario1, the required storage installed capacity is 792.42 MW from hydrogen storage and 2372.35 MW installed capacity from battery storage (Figure 17). The model built hydrogen storage in two regions: Zeeland and West-Brabant. Regarding battery storage, U10/16, Achterhoek, Arnhem/Nijmegen and Zeeland are the regions that needed the most of battery storage capacities.

The optimization results show that 2495 MW of battery storage and 588 MW of hydrogen storage are needed to incorporate vRES planned projects in Sub-scenario2 (Figure 18). The model built hydrogen capacity in two regions: Zeeland and West-Brabant. Regarding battery storage, the model built 445 MW in Achterhoek, 395 MW in Zeeland and 306 MW in Arnhem/Nijmegen.

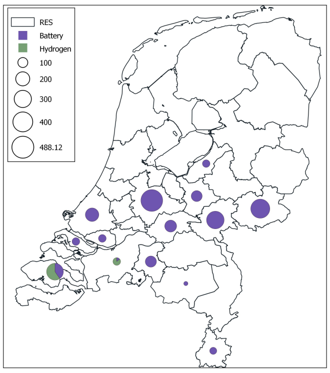

Figure 17. Storage units distribution within the energy regions in Sub-scenario1 (MW)

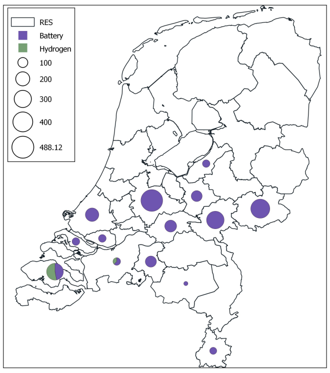

Figure 18. Storage units distribution within the energy regions in Sub-scenario2 (MW)

The transmission and storage expansion costs in Sub-scenario1 and Sub-scenario2 are respectively 2.34 billions euro and 2.08 billions euro.

Electricity generation

In Sub-scenario1, 137.48 PJ electricity supply from gas is needed, where the electricity peak supply is 16000 MW. The electricity supply from wind onshore/offshore and solar is respectively 62.06 PJ/171.86 PJ and 46.61 PJ (Figure 19).

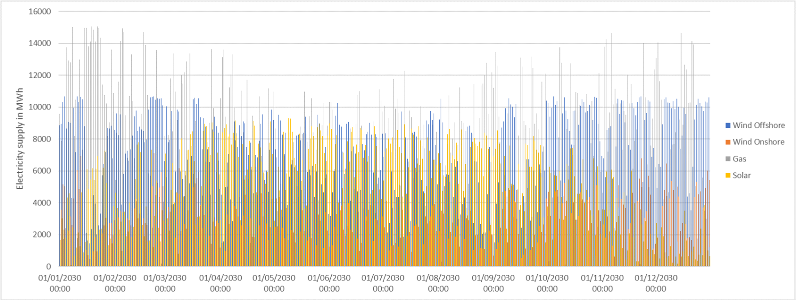

Figure 19. Electricity supply in Sub-scenario1 by 2030

The electricity supply from gas is 129.37 PJ, where the peak gas supply is 15985 MW in Sub-scenario2. The electricity supply from solar energy is 60.4 PJ and from wind offshore/onshore is respectively 171.6 PJ and 60.85 PJ (Figure 20).

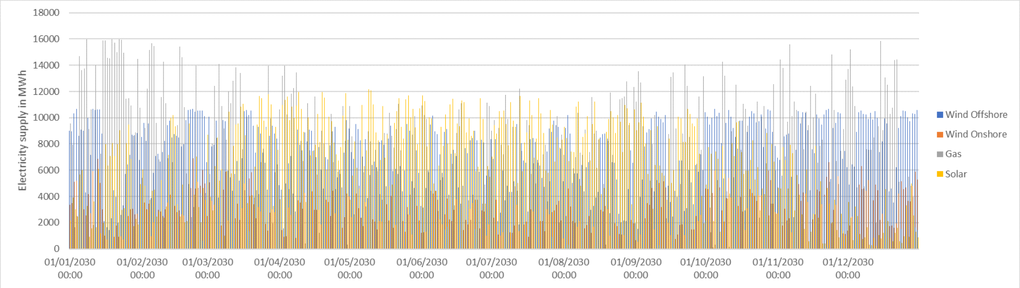

Figure 20. Electricity supply in Sub-scenario2 by 2030

5.2. National Results

The national target consists of generating 35 TWh of large-scale solar PV and wind onshore. Since only 26 TWh was planned by the energy regions, 9 TWh remain unplanned. To find the best location of the remaining 9 TWh within the energy regions along with the necessary storage and transmission lines capacity, the LOPF was performed to optimize the expansion costs of large-scale solar PV and wind onshore, storage units and transmission lines. This expansion is based on the results of the first optimization problem. Therefore, the necessary storage and transmission lines capacities of Scenario1 and Scenario2 are implemented as inputs in the second optimization problem. Only Sub-scenario1 (100% of solar PV installed capacity is achieved) in each scenario will be considered to perform the expansion.

5.2.1. Scenario1: Sub-scenario2

The optimization results show that the remaining 9 TWh of electricity generation is needed from wind onshore energy. Moreover, the best location to install the generation capacities from wind onshore is Rotterdam-Den Haag region. The model expended the installed capacity of wind onshore energy in Rotterdam-Den Haag region from 487.7 MW to 2807 MW. The electricity supply from wind offshore is 154.83 PJ, wind onshore 91 PJ, gas 89.32 PJ, solar 61.92 PJ (Figure 21).

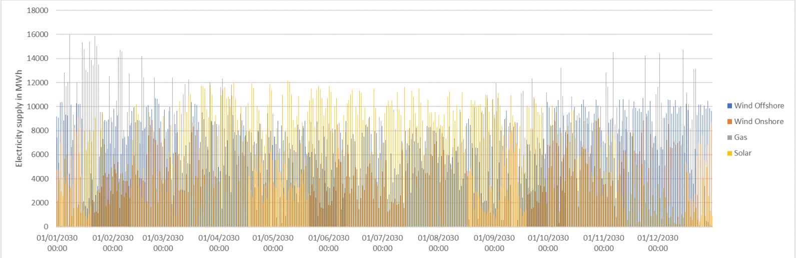

Figure 21. Electricity supply in Scenario1 by 2030 (MWh)

Transmission lines

No transmission lines expansion was needed to incorporate the 9 TWh electricity generation from wind onshore energy. The transmission lines capacities and average loading are displayed in Figure 22.

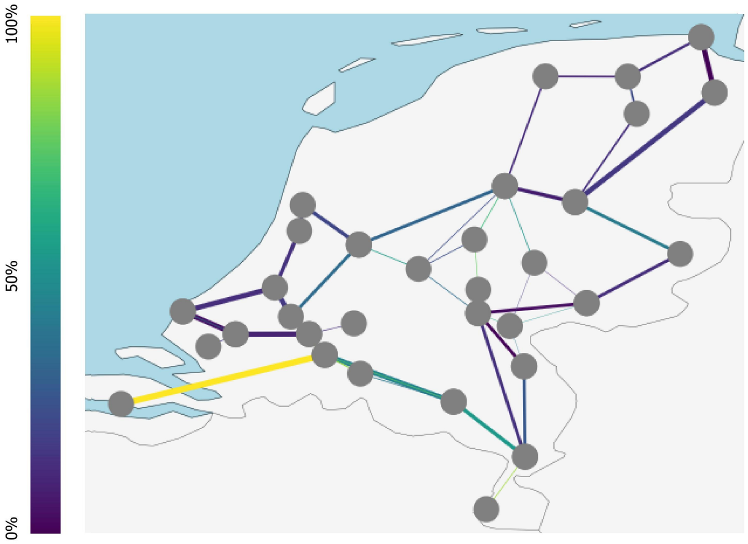

Figure 22. Transmission lines capacity and average loading in Scenario1 2030

As shown in Table 6, the transmission lines with the high loading are mainly located at the 150 kV voltage level. Only two 380 kV transmission lines have high loading.

Voltage level	Connections	Loading
380 kV	Zeeland - West Brabant	72.5%
150 kV	West Brabant - Hart van Brabant	71.2%
150 kV	Hoekse Waard - Rotterdam-Den Haag	64.1%
150 kV	Noord en Midden Limburg - Zuid Limburg	74.1%
150 kV	FoodValley - Noord Veluwe	63.7%
380 kV	West Brabant - Midden Holland	61.8%

Table 6. Transmission lines loading at different voltage levels (%)

Storage units

The necessary storage capacities to incorporate the 35 TWh are 509 MW of hydrogen storage and 1509 MW of battery storage (Figure 23). The model built new hydrogen storage capacities in West-Brabant (12 MW), Flevoland (219 MW) regions and expended the capacity in Zeeland region from 225 MW to 278 MW. Regarding battery storage, no new capacity was built.

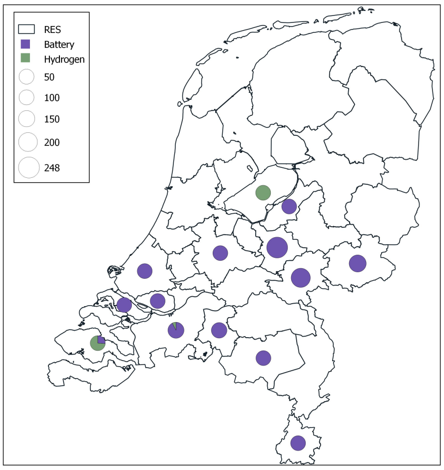

Figure 23. Storage units distribution within the energy regions in Scenario1 (MW)

5.2.2. Scenario2: Sub-scenario2

Similarly to Scenario1, The optimization results show that the remaining 9TWh of electricity generation is needed from wind onshore energy in Rotterdam-Den Haag region (Figure 24). The model expended the installed capacity of wind onshore energy in Rotterdam-Den Haag region from 487.7 MW to 2785.8 MW.

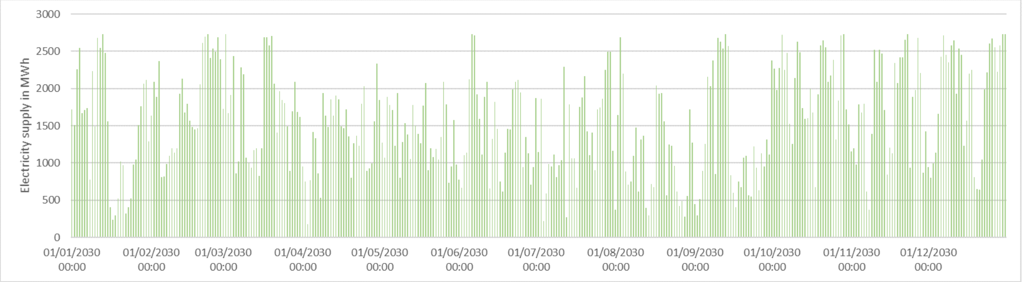

Figure 24. Electricity supply of wind onshore energy after the expansion in Rotterdam-Den Haag region in MWh

The electricity supply from wind offshore is 154.83 PJ, wind onshore 91 PJ, gas 89.32 PJ, solar 61.92 PJ (Figure 25).

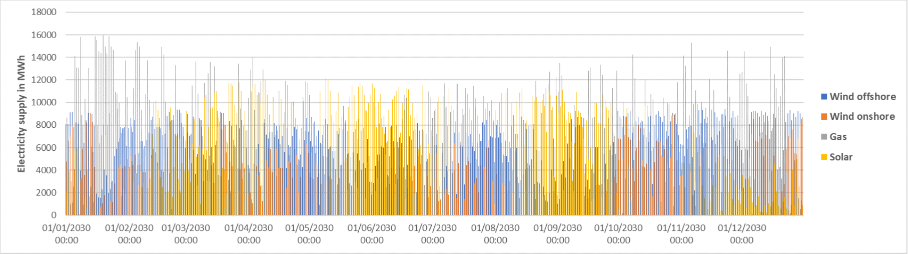

Figure 25. Electricity supply in Scenario2 by 2030 (MWh)

Transmission lines

No transmission lines expansion was needed to incorporate the 9 TWh electricity generation from wind onshore energy. The transmission lines capacities and average loading are displayed in Figure 26.

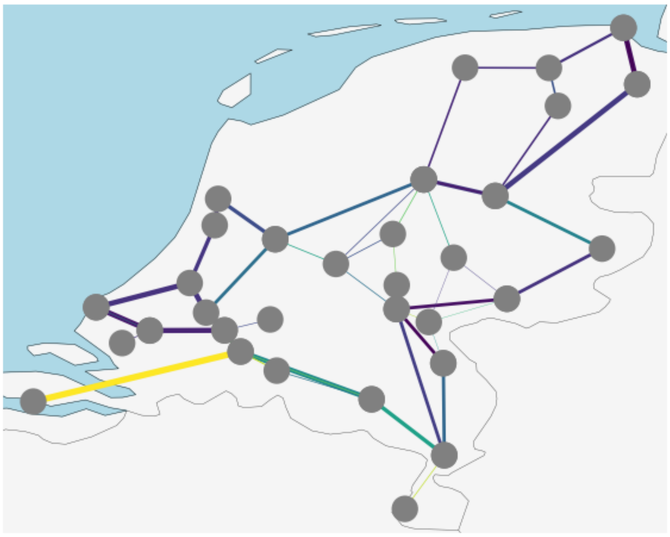

Figure 26. Transmission lines capacity and average loading in Scenario2 by 2030

As shown in Table 7, the transmission lines with the high loading are mainly located at the 150 kV level. Only one 380 kV transmission line have a high loading.

Voltage level	Connections	Loading
380 kV	Zeeland - West Brabant	83.6%
150 kV	West Brabant - Hart van Brabant	76.4%
150 kV	WestBrabant - Metropoolregio Eindhoven	64.4%
150 kV	Noord en Midden Limburg - Zuid Limburg	75.9%
150 kV	Rivierenland - Arnhem / Nijmegen	74.1%
150 kV	FoodValley - Noord Veluwe	66.7%
150 kV	Flevoland - Noord Veluwe	64%
150 kV	West-Brabant - Midden-Holland	63.6%

Table 7. Transmission lines loading at different voltage levels (%)

Storage units

The necessary storage capacity to incorporate the 35 TWh in Scenario2 is 2779.7 MW of battery storage and 587.7 of hydrogen storage (Figure 27). Regarding battery storage, the optimization model expended the capacity in different regions: Hart van Brabant region from 132 MW to 269 MW, FoodValley region from 51.31 MW to 55 MW and Arnhem/Nijmegen region from 305.8 MW to 450.7 MW. No extra capacity was needed in hydrogen storage.

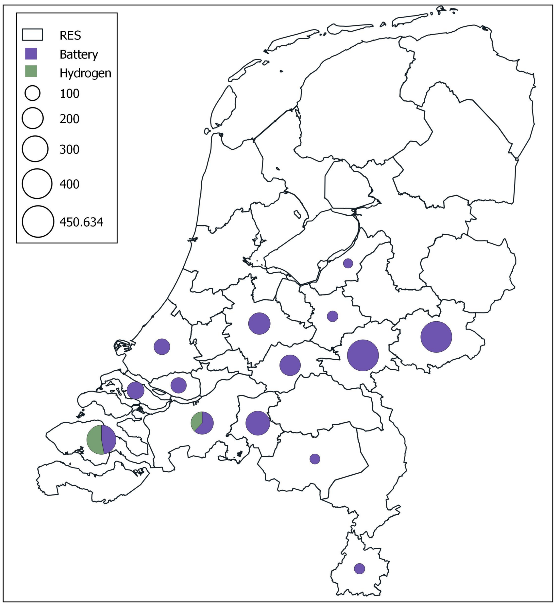

Figure 27. Storage units distribution within the energy regions in Scenario2 in MW

6. Discussion

In this chapter the regional and national results will be analyzed for both scenarios along with a critical appraisal.

6.1. Regional results

6.1.1. Scenario1

Under this scenario, the assessment of the vRES plans of the energy regions was performed for a medium growth of electricity supply. In both sub-scenarios, where 100% and 50% of large-scale solar PV projects were achieved, the electricity supply from gas does not exceed 109 PJ. According to [18], to achieve a reduction of 49% of CO_2 by 2030 compared to 1990, a generation of approximately 120 PJ is needed from gas and 0 PJ from hard coal. Therefore, the national goal can be achieved with the regional plans. However, 15994 MWh of gas peak electricity supply is required.

In both sub-scenarios transmission lines capacity is required. At the 380kV voltage level, only the line connecting Zeeland to West-Brabant needed more capacity. However, at the 150kV voltage level different lines needed to be expended: West Brabant - Hart van Brabant, FoodValley - Noord Veluwe, U10/U16 - Amersfoort, Amersfoort -NoordVeluwe in Sub-scenario1. In Sub-scenario2 an additional capacity between Hoekse Waard - Rotterdam Den Haag regions was built.

The storage capacity needed in Sub-scenario1 is 1509 MW of battery storage and 225 MW of hydrogen storage. In contrast to 792.42 MW from hydrogen storage and 2372.35 MW from battery storage in Sub-scenario2. In Both sub-scenarios the distribution of battery storage is almost similar within the energy regions, except for Rivierenland region, where more capacity was needed in Sub-scenario2. The model built hydrogen capacity only in Zeeland region in both sub-scenarios.

6.1.2. Scenario2

Under this scenario, the assessment of the vRES plans of the energy regions was performed for a high growth of electricity supply. In both sub-scenarios, where 100% and 50% of large-scale solar PV projects were achieved, the electricity supply from gas exceed 130 PJ. As discussed in Sub-section 6.1, to achieve a reduction of 49% of CO_2 by 2030 compared to 1990 according to [18], a generation of approximately 120 PJ is needed from gas and 0 PJ from hard coal. Therefore, under the actual vRES planned projects by the energy regions, the target in reducing CO_2 can not be achieved.

Regarding hydrogen storage, the model built additional capacities in two different locations: Zeeland and West-Brabant, where 792 MW and 587.78 MW were needed respectively in Sub-scenario1 and Sub-scenario2. Battery storage in both sub-scenarios is almost similar 2400 MW, where the regions with the highest battery installed capacity are: Zeeland, U10/U16, Achterhoek, Arnhem/Nijmegen and Flevoland.

The transmission lines that needed more transmission capacities are similar to the transmission lines defined in Sub-section 6.1.1.

6.2. National results

The expansion of the electricity generation from large-scale solar PV and wind onshore to 35 TWh shows that more investment costs are needed at the level of storage units. However, no capacity was needed in the transmission lines. In both scenarios, the model expended the installed capacity from wind onshore energy in Rotterdam-Den Haag region from 487 MW to approximately 2800 MW. In Scenario1, the model built new hydrogen capacities in West-Brabant and Flevoeland regions. However, in Scenario2 no hydrogen storage new capacities were built. Regarding battery storage, capacities were expended in Hart van Brabant, Foodvalley and Arnhem/Nijmegen regions in Scenario2. The electricity generation from gas does not exceed 112.29 PJ in both scenarios. Therefore, the national target in reducing CO_2 is achieved.

6.3. Critical appraisal

The modelling of the vRES depends on weather data. In this article 2017 weather data were used. Therefore, the results regarding the installed capacity within the energy regions in the different scenarios may change. Moreover, the sizing of the storage units might change as well since it is directly related to the electricity generation from the vRES. However, it won't have a high effect on the spatial allocation of the storage units.

The optimal power flow used to optimize the investment costs is the LOPF. The LOPF does not take into considerations the non-linear effects of the power transmission in AC networks (e.g. reactive power flows or voltage stability). Additional aspects, such as the transmission lines between other countries, reserve power, transmission losses, demand side management and sector-coupling were not considered.

7. Conclusion

In this article a techno-economic model was presented that optimises investment and operation costs of the power system of the Netherlands with 32 buses in hourly resolution at regional level. The main focus of the article lies on the assessment of the energy region's vRES planned projects in achieving the national targets set for 2030.

By performing the linear optimal power flow, cost-optimal solutions were found for all conceived scenarios in electricity supply and demand. Solution integrating the 35 TWh of electricity generation from large-scale solar PV and wind onshore were found to be cost-optimal with battery and hydrogen storage units, flexible gas supply and new transmission capacities between different energy regions. A 49% of CO_2 reduction by 2030 compared to 1990 is achievable within the model assumptions in all scenarios.

The model is built by combining different open sources data that are freely available. Therefore, the model is suitable for a collaborative improvement by different stakeholders. Moreover, this work can be extended to explore other directions such as the variations of both CO_2 cap and price, coupling to other sectors such as gas network and the interconnection between surrounding countries.

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