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A spatially explicit planning approach for power systems with a high share of renewable energy sources

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HIGHLIGHTS

- A spatially explicit planning approach for high-RES power systems is proposed.
- We connect land cover assessment, VRES potential and energy system planning models.
- We reveal the role of the land-use of VRES in power system optimization models.
- Constraints on land-use were modelled in a data-driven way for the Netherlands.
- No constraints on land-use lead to infeasible capacities in regions.

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Variable Renewable Energy Sources (VRES)
Generation mix
Land-use
VRES potential
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ABSTRACT

Variable Renewable Energy Sources (VRES) are characterized by intensive land-use and variable production. In existing optimization models that minimize the total cost of the energy system, location-specific VRES production profiles are often used to estimate VRES potential, but land-use and land cover aspects have been largely ignored. In this study, we therefore connect the literature in land cover assessment, VRES potential estimation and energy system optimization modelling by proposing a spatially explicit planning approach. This approach was applied to a case of the Netherlands to showcase its applicability and strength and to give results towards various RES targets. A baseline land-use scenario, a scenario with stricter constraints on land-use that reflects social resistance and spatial policy on wind energy and, thirdly, a scenario assuming unlimited land availability were analyzed. The baseline scenario results show the optimal geographical distribution of the generation capacities over the Netherlands. Wind energy dominates the generation mix and storage is only present at the 100% RES target. Under the strict constraints on land-use, 92% of the suitable land in the country will be deployed to place wind turbines in order to reach 100% RES share compared to 37% in the baseline case. However, the cost of electricity only increases by no more than 5 €/MWh. The unlimited land scenario highlights that the regional optimized capacities are infeasible. Apart from the useful results from the case study, the proposed approach is a first-of-a-kind contribution to the literature and provides a data-driven way to operationalize the location-specific land-use of VRES such that the role of the constraints on the land-use of VRES can be revealed and that policy-relevant results can be obtained.

1. Introduction

1.1. Background

The utilization of Variable Renewable Energy Sources (VRES) is growing rapidly. Compared to traditional sources of electricity generation, several factors make them difficult to integrate into the power system. First of all, the production of wind energy and solar energy is variable and location-specific because it is driven by weather conditions. Secondly, wind turbines and solar panels are characterized by more intensive land-use compared to conventional power plants. As the share of renewable energy sources is expected to grow significantly in the coming decades, it becomes more important to consider spatial-temporal details of VRES such as land-use and location-specific production profiles, as emphasized by [1,2]. This holds especially for densely populated areas like the Netherlands or areas with abundant

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Nomenclature

$\alpha_{i,c}$	suitability factor for technology i, Corine Land over class c
f	factor that represents extra length and extra capacity considering security constraint
β_i	capacity density for technology i
$\delta_{n,m}$	length of network (n, m)
η_i^{in}	charging efficiency of storage technology i
η_i^{out}	discharging efficiency of storage technologies i
$\eta_{i,n,t}$	capacity factor for technology i at node n at time t (of wind and solar energy), 1 for other generation technologies
ω	RES target
$\tau_{n,m}$	power loss factor in line (n, m)
A_i	annuity factor of generation and storage technology i, $A_i = \frac{1-\frac{1}{(1+r)^{L_i}}}{r}$
a_i	Fixed Operation & Maintenance (FOM) costs of generation and storage technology i
$A_{n,m}$	annuity factor of line (n, m), $A_{n,m} = \frac{1-\frac{1}{(1+r)^{L_{n,m}}}}{r}$
b_i	Variable Operation & Maintenance (VOM) costs generation and storage technology i
C_i	Capital Expenditure(CapEx) of generation and storage technology i
$C_{n,m}$	Capital Expenditure(CapEx) of network (n, m)
$D_{n,t}$	power demand at node n at time t
L_i	lifetime of generation and storage technology i
$L_{n,m}$	lifetime of line (n, m)
r	discount rate
S_{unit}	area of a grid cell in Corine Land Cover data
t_{end}	last time step in T
CLC	Corine Land Cover classes
E	network connections
G	generation technologies
N	nodes
RES	Renewable Energy Sources
SC	storage conversion technologies
S	storage technologies
T	time steps
$VRES$	Variable Renewable Energy Sources
$B_{n,c}$	number of Corine Land Cover units at node n for Corine Land Cover class c
$CP_{i,n,t}$	energy charging of technology i at node n at time t
$DP_{i,n,t}$	energy discharging of technology i at node n at time t
$K_{i,n}^{max}$	maximum possible installed capacity for technology i at node n
$K_{i,n}$	capacity of generation and storage technology i at node n
$K_{n,m}$	capacity of line (n, m)
$P_{n,m,t}^{export}$	energy export from node n to node m at time t
$P_{n,m,t}^{import}$	energy import from node n to node m at time t
$P_{i,n,t}$	energy production of technology i at node n at time t
$S_{i,n,c}$	suitable area for technology i at node n for Corine Land Cover class c
$SP_{i,n,t}$	stored energy of technology i at node n at time t

nature reserves.

Although wind turbine monopiles do not occupy much land themselves, the areas between the turbines are also affected. Such indirect land-use, i.e. the land-use that does not compete with the primary use of land, causes problems for people. In particular, due to aesthetic reasons or noise pollution, social resistance is a problem for the development of VRES all across the world and indeed, the scientific community has paid attention to it. For example, the public resistance against new energy developments in Canada was investigated by [3]. [4] studied the methods to increase the social acceptance of wind energy in France. Similarly, utility-scale solar parks cause problems in direct land-use, i.e. the land-use that competes with other usages of land. These barriers hinder the development of VRES, and thus the importance of land-use is emphasized in the following literature. For example, [5] performed a study on the locations of wind farms based on land examination. [6] conducted a literature review on the optimal diversity of renewable energy alternatives, where land-use is argued as a key dimension. [7] did a land-use analysis for the German power system. Furthermore, a multi-criteria analysis with a focus on land-use to identify the high priority locations for VRES was given for the case of Bangladesh [8].

In recent years, a large body of scientific literature on modelling of power systems with high shares of Renewable Energy Sources (RES) has emerged, see e.g. the review of [9]. Optimization models with a focus on investment form a significant part of the available tools. In such models, it is usually the objective to find a minimum cost power system, given time-series of wind and solar production. These optimization models often use location-specific VRES profiles, but most of them implicitly assume unlimited land availability. As discussed, the land-use of VRES is crucial, however, this unlimited land assumption neglects it and would lead to more optimistic results than what is feasible in reality. Nevertheless, there exists literature that discusses the land-use of VRES and the location-specific VRES production profiles as a limiting factor in the optimization problem.

An optimization model for a regional energy system was proposed by [10]. As data inputs for their model, they pre-selected suitable site locations for wind and solar energy using an existing Geographic Information Systems (GIS) model that examines land cover characteristics. [11] considered land-use as surrogate for environmental impacts and minimized global land-use for future energy scenarios. [12] used an optimization model to study the power system scenarios of Great Britain. In this model, they provided a spatially explicit way to deal with the location-specific VRES data. Similarly, an Australian case study used location-specific VRES data and location-specific maximum VRES capacities as data inputs [13]. In addition, the maximum RES capacities for European countries based on land cover characteristics were used in the European power system optimization model PyPSA-Eur [14].

In the studies mentioned above, the land-use and the production profiles of VRES were considered either location-specifically or in an aggregated way. The location-specific data was either obtained from existing studies, or it was made for the specific case study, which makes it irrelevant for new cases. These are understandable choices, since these studies focused on the optimization modelling and therefore left the detailed assessments of the land-use of VRES and the necessary steps to obtain location-specific data out of scope.

Based on our literature review, we conclude that the land-use aspects of VRES in optimization models are still not fully appreciated. The comprehensive approach that considers land-use of VRES by assessing land cover data to obtain location-specific VRES potentials is often seen in other fields of research than optimization studies, and is usually country-specific. For example, some studies use GIS to assess the land-use of VRES to estimate the VRES potentials, see the case of Spain [15], Turkey [16], Germany [17], Switzerland [18], Finland [19] and India [20]. These studies focus on the detailed assessment of land-use of VRES. Similarly, another line of research concentrates on various metrics of VRES potentials such as capacity factor, maximum possible capacity, annual potential generated energy and spatial-temporal correlation. Case studies are seen for China [21], and for the globe [22].

This literature review shows that although spatial aspects of VRES are drawing attention in scientific communities, very few studies performed detailed assessments of land-use to obtain the VRES potential in optimization models for power systems with a high share of RES. Since this type of work often belongs to different fields (land cover assessment, VRES potential estimation and high-RES power system planning models), the workflow that links those fields is desired but is rarely seen [23]. In other words, we find that an integrated and spatially explicit approach is needed on how the location-specific land-use of VRES should be assessed, how that is matched to the location-specific VRES data and how those are related to the optimization model.

1.2. Contribution and audience of the paper

This paper proposes a spatially explicit planning approach in optimization models for power systems with a high share of RES. Its objective is to incorporate the location-specific land-use of VRES and the location-specific VRES production profiles in high-RES power system planning models in a systematic way. The contributions of this paper and the possible use of the approach are as follows:

1. The paper links three different scientific bodies of knowledge: data-driven land cover assessment, VRES potential estimation, and power system planning models. This approach allows to improve the traditional way of energy system planning modelling by considering actual location-specific VRES potential as a constraint. With our integrated and generally applicable method, energy system planning researchers can exploit the strength of the other two fields instead of resorting to simplistic constraints or neglecting land-use all together.
2. The approach entails all the necessary steps to systematically consider the location-specific land-use and the location-specific production profiles of VRES in the optimization model. The approach starts from the raw data including geographical boundary data, land cover data and VRES data, to the transformation of these data to the inputs of the optimization model, and then to the formulation and the results of the model.
   The approach would be valuable for optimization studies where the published location-specific data on the land-use and the production profile of VRES is not available and where case-specific data has to be compiled.
3. This data-driven approach keeps the spatial explicitness that is in line with the used database. It means that the approach gives full exposure of the land cover characteristics and control of the corresponding area to the user, i.e. the user can identify the land cover in the resolution of the database explicitly, and thus is able to include/exclude the area in various ways. Consequently, the location-specific VRES potential constraints can be changed depending on the desired level of spatial details.
4. Our approach helps to reveal the role of the land-use of VRES on the results of the power system planning optimization models. This provides a novel way to inspect the sensitivity of the optimization results to location-specific land-use constraints.
   This way of sensitivity analysis would give insights to power system modellers and policy-makers. For modellers, the impact of land-use could be quantified by the change in results such as generation mix, the spatial distribution of generation technologies and total cost of the system. For example, what is the spatial distribution of the optimized wind turbine locations if certain type of land cannot be used to build the turbines? For policy-makers, in addition to those results, this method quantifies the geographical distribution of the land-use of VRES which helps to evaluate the effect of possible spatial policies ex-ante. For instance, where will wind turbines be located and how much land will they occupy given the policy that they have to be placed at least 2 km from the residents in order to mitigate social resistance? And what are the extra system costs associated with those constraints? These kinds of analysis would not be possible without the spatially explicit planning approach, even for studies where the data has been published.
5. The case study presents the future high-RES energy system scenario for the Netherlands, which gives practical insights to policy-makers and adds to the literature in energy system planning.

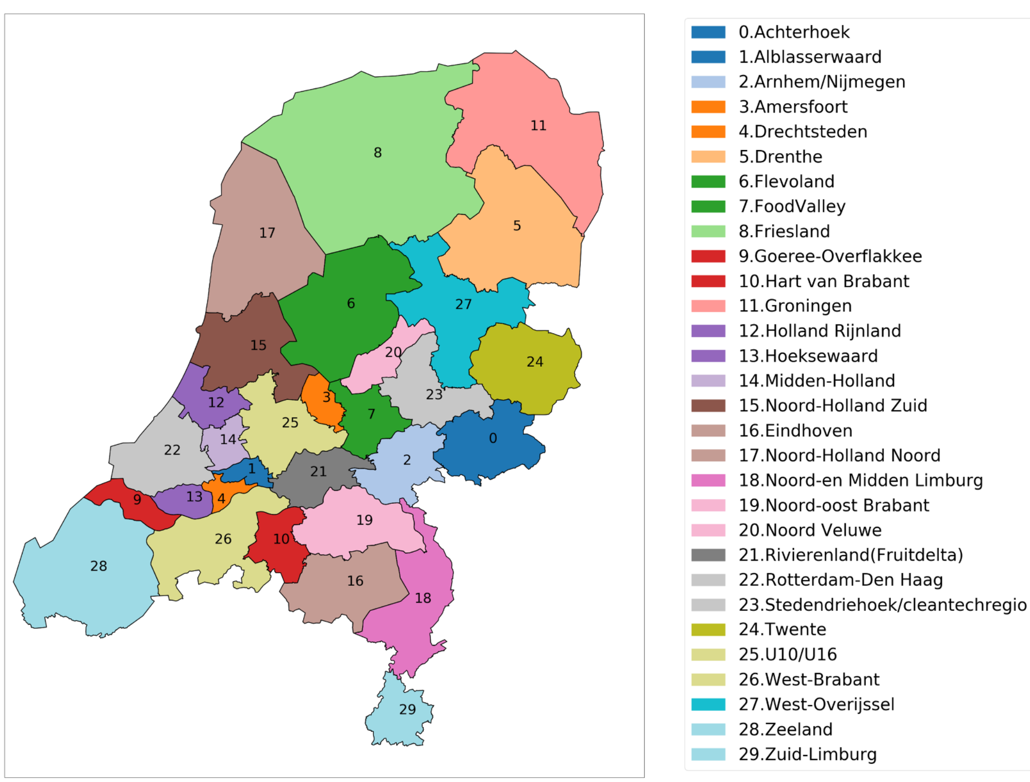

Fig. 1. 30 regions in the Netherlands.

1.3. Background of the case of the Netherlands

In the Netherlands, policy-makers put the climate agreement into practice by formulating a target amount of RES capacity that needs to be integrated into the current power system. This is done by implementing a country-wide program (Regional Energy Strategies) [24], which divides the country into 30 regions (Fig. 1) that need to coordinate where to locate the required RES capacity. However, the Netherlands is a densely populated country which makes the placement of wind turbines and solar plants difficult. Therefore, the Netherlands will be used as a case study to show the feasibility and the usefulness of our integrated, tripartite approach.

1.4. Structure of the paper

The paper is organized in the following way. Firstly, Section 2 describes the proposed approach which includes the modelling of spatially explicit data and the formulation of the optimization model. Next, Section 3 presents the scope and the input data of the case study. In Section 4, the land cover assessment is elaborated and the VRES potentials are calculated. Then, Section 5 presents and discusses the optimization results. In Section 6, conclusions are drawn.

2. Proposed Approach

Fig. 2 shows a schematic depiction of our approach. In the following sections we describe the details of the spatially explicit data modelling and how this is used in the optimization model.

2.1. Spatially explicit data modelling

The spatially explicit data includes geographical boundary data, land cover data, and VRES data.

2.1.1. Polygons and location of nodes

The starting point is a data set of coordinates that represents the geographical boundaries of the interested nodes to be modelled. The data set forms polygons that define the spatial granularity of the model, which can be, for example, an entire country or group of countries in a European power system model, or a municipality or a neighbourhood in a local power system model. The centroids of the polygons are the locations of the nodes n in the optimization model.

Starting from polygons is usually applicable to optimization studies where the results (e.g. the optimized generation capacities) at the nodes n are the focus of the study. The OpenStreetMap project [25] is a commonly-used source to find the polygons, when, for example, only the names of the municipalities are available.

2.1.2. Land cover assessment and VRES potential estimation

After obtaining the polygons, the land inside the polygon needs to be assessed in order to check how much land is available and suitable for VRES development. This is done by performing a land cover assessment.

The land cover assessment is an indispensable step in this approach since by doing the assessment, it essentially implies that each area with a certain land cover (see the definition of land cover and the database introduced in the following paragraph) is explicitly identified. Hence, any means of inclusion/exclusion of the identified areas is possible, e.g. full exclusion, partial exclusion, exclusion in radius etc. Several exemplary exclusions are explained below and will be illustrated in Section 4.1.

The land cover represents the physical material on the surface of the land, which is classified into five major categories in Corine Land Cover (CLC) database [26]. These are artificial surfaces, agricultural areas, forest and semi natural areas, wetlands and water bodies. Those categories are further divided into a total of 44 classes. The CLC database has a grid size of 100 m by 100 m. Not all the land cover is suitable for VRES development, so two steps will be taken in order to find the suitable land.

The first step is to exclude the land that is not available for VRES development physically, which is an example of fully excluding. For instance, for onshore wind turbines, the CLC classes that are considered unavailable are urban fabrics, airports, rice fields, water bodies etc. On the other hand, national parks also need to be excluded. However, the nature reserves are not a class in CLC, but they can sometimes be found in the form of polygons. These polygons, together with the area in unavailable land cover classes, are excluded. This exclusion process can be done using e.g. Python NumPy masked arrays.

Next, the remaining land is considered suitable to some degree and will thus be partially excluded based on its land cover classes. Since the resolution of the land cover data is not fine enough to assess the land cover on the scale of individual wind turbines and solar panels, it is common in the literature to assign suitability factors $\alpha_{i,c}$ to each land cover class [17]. The value of the suitability factor depends on technology i and Corine Land Cover class c. After the assignment of suitability factors, the suitable areas for technology i at location n for CLC class c are obtained (see Eq. (1)).

$$S_{i,n,c} = S_{unit} B_{n,c} \alpha_{i,c}, \forall\ i \in VRES, \forall\ n \in N, \forall\ c \in CLC \quad (1)$$

where i is either wind or solar energy, $B_{n,c}$ is the number of grid cells

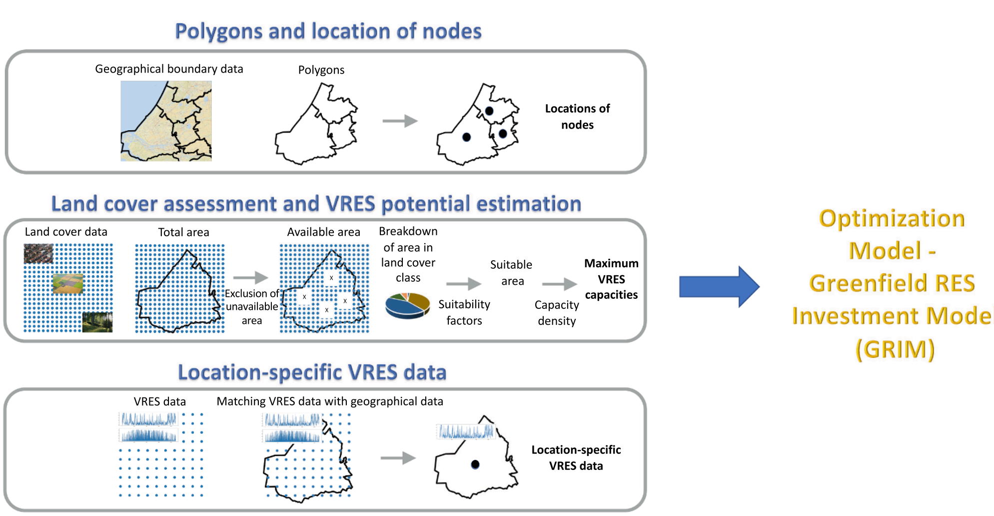

Fig. 2. Schematic of the approach.

(100 m ∗ 100 m) at node n for CLC class c, S_{unit} is the area of a grid cell, $S_{unit} = 0.01\text{km}^2$.

Since some of the unavailable land is selected based on the CLC classes, in principle, in the first step, a suitability factor of zero could be assigned. However, the separation of the two selection steps will explicitly give two different ways to adapt the approach to specific cases. In the first step, the exclusion of unavailable land can be based on any land cover, e.g. residential areas with social resistance for VRES technologies can be excluded, or even a settlement area in the radius of certain CLC classes can be excluded as well (see an example in Section 4.1). In the second step, suitability factors can be changed depending on the local surface conditions, e.g. if the trees in forest area are high, or the slope of the ground is large, these conditions would make the suitability factors even lower. In this way, by changing the exclusion criteria and the suitability factors, the approach provides a flexible way to use VRES potential constraint based on location-specific conditions, such as local surface conditions, social acceptance and local spatial policies.

To quantify the land requirement of VRES technologies, capacity density, defined as the maximum potential installed capacity per unit area, needs to be incorporated into the calculation. The maximum VRES capacity is calculated according to Eq. (2):

$$K_{i,n}^{max} = \sum_{c \in CLC} S_{i,n,c}\beta_i, \forall\, i \in VRES, \forall\, n \in N \tag{2}$$

where β_i is capacity density, which is 5 MW/km^2 for wind [27], and 30 MW/km^2 for solar [28] in this study.

2.1.3. Location-specific VRES data

After specifying the location of nodes (polygons), the VRES data that determines the wind and solar energy production at the same spatial resolution needs to be obtained. This location-specific VRES data is defined as the normalized VRES energy output for VRES technology i at node n at time step t, which lies in the range of 0 to 1, and will be referred to as capacity factors $\eta_{i,n,t}$ in Eq. (5) of the optimization model.

The available VRES data is usually wind speed at hub height and solar irradiation data from meteorological measurements or reanalysis data sets, then the data will be transformed into VRES capacity factors $\eta_{i,n,t}$ [29].

The location of the VRES data either corresponds to the location of the meteorological stations or at the grid points of the reanalysis data that is being used. In the next steps of the proposed approach, we resolve the geographical inconsistency between the VRES data and the polygons n.

The first step is to find all the VRES data points inside the polygon. If there is at least one data point inside the polygon, we then take the mean of the data at those points to be the VRES data for the node n. However, if there are no data points inside the polygon, the VRES data at node n will be the linear interpolation of the data at the surrounding points.

In theory, it is possible to obtain the VRES data sets at each node n, e.g. in the work of [29]. However, it is important to understand that the VRES generation can be anywhere in the polygon other than at the node n. For wind and solar energy, the data at the node n is most of the time different from the averaged data in the polygon. Therefore, we estimate the VRES data in the whole polygon instead of only at the centroid.

2.2. Optimization modelling

In the next section, we present our optimization model, that we labeled the Greenfield Renewables Investment Model (GRIM). This model is a linear programming model that minimizes the total annualized cost of investment and operation. This optimization model has a set of hypothesis and hence it is important to clarify the scope and the usage of this model before presenting the detailed formulations.

2.2.1. Scope and usage of the model

The main contribution of the approach is to systematically find the location-specific maximum potential VRES capacities and then to consider them in the power system planning optimization model. In this way, the effects of the location-specific land-use limit of VRES on the power system planning can be revealed. In order to focus the reader on this main contribution, the formulation of the maximum VRES potential constraints will be discussed in detail. Instrumentally, the rest of the power system planning model will be simplified.

The presented model aims to include only the essential components of the state-of-the-art power system investment optimization models (e.g. spatial-temporal RES production profiles, energy storage, network flows), and it is meant to showcase how the maximum VRES potential constraints can be linked to this family of optimization models.

For instance, GRIM assumes there is no existing power generation, no storage and no networks. This assumption is referred to in the word greenfield in the acronym. In addition, real network topology, AC network flow formulation, comprehensive inclusion of different generation and storage technologies, ancillary services, power system stabilities, etc. are not taken into account. These aspects have been extensively discussed in power system models and thus not the focus of this work. Nevertheless, it is straightforward to apply the proposed method and fine-tune the optimization model to other detailed models of readers' interest. Furthermore, the model disregards carbon pricing and does not take into account opportunity cost or loss of revenues when certain land areas are re-purposed, e.g. when agricultural land is changed into solar parks or wind farms.

2.2.2. Objective function

The objective function is to minimize total annualized cost consisting of Capital Expenditure (CapEx) cost of generation and storage technologies C_i, CapEx cost of networks $C_{n,m}$, Fixed Operation & Maintenance (FOM) costs a_i and Variable Operation & Maintenance (VOM) costs b_i. All costs are annualized by an annuity factor A_i (for generation and storage technologies) or $A_{n,m}$ (for networks). The network cost depends on the length $\delta_{n,m}$, the capacity $K_{n,m}$ of the line and the factor f which will be explained in Section 2.2.6.

$$\begin{aligned}\text{Min.} \sum_{i\in(G+SC+S)} \sum_{n\in N} \frac{C_i K_{i,n}}{A_i} + \sum_{(n,m)\in E} \frac{f\delta_{n,m}C_{n,m}K_{n,m}}{A_{n,m}} + \sum_{i\in(G+SC)} \sum_{n\in N} a_i K_{i,n} \\ + \sum_{t\in T} \sum_{i\in G} \sum_{n\in N} b_i P_{i,n,t}\end{aligned} \tag{3}$$

The decision variables are the capacity of generation and storage units $K_{i,n}$ of technology i at node n, the network capacity $K_{n,m}$ of line (n, m), the energy production $P_{i,n,t}$ of generation technology i at node n at time t, the energy charging of storage $CP_{i,n,t}$ and the energy discharging of storage $DP_{i,n,t}$ of storage technology i at node n at time t, the energy export $P_{n,m}^{export}$ and the energy import $P_{n,m}^{import}$ from node n to node m at time t.

The optimization model has a set of constraints, as described below.

2.2.3. Energy balance constraints

The energy supply has to match the demand at every time step. This means the energy that comes into the node, is equal to the energy that flows out of the node at all time steps. Therefore, at every time step, the sum of the demand, the energy export and the energy charging of storage are equal to the sum of the energy production, the energy import and the energy discharging of storage. $\tau_{n,m}$ is used to account for the power loss in the lines. More discussions of network modelling are given in Section 2.2.6.

$$D_{n,t} + \sum_{(n,m)\in E} P^{export}_{n,m,t} + \sum_{i\in SC} CP_{i,n,t} = \sum_{i\in G} P_{i,n,t} + \sum_{(n,m)\in E} (1-\tau_{n,m}) P^{import}_{n,m,t} + \sum_{i\in SC} DP_{i,n,t}, \forall n \in N, \forall t \in T \quad (4)$$

2.2.4. Energy production constraints

For conventional generation and biomass plants, the energy production per time step cannot exceed the installed capacity, thus $\eta_{i,n,t} = 1$. For wind and solar energy, the energy output per time step depends on the installed capacity and the capacity factor $\eta_{i,n,t}$ that reflects the meteorological conditions (see Section 2.1.3 for modelling of the capacity factor).

$$P_{i,n,t} \leqslant \eta_{i,n,t} K_{i,n}, \forall i \in G, \forall n \in N, \forall t \in T \quad (5)$$

2.2.5. VRES potential constraints

The upper bound of the installed capacities $K^{max}_{i,n}$ for wind turbines and solar panels are given.

$$K_{i,n} \leqslant K^{max}_{i,n}, \forall n \in N, \forall i \in VRES \quad (6)$$

$K^{max}_{i,n}$ is derived using Eq. (2) and the process of obtaining $K^{max}_{i,n}$ is described in Section 2.1.2.

For conventional generation technologies and biomass, the maximum potential installed capacity is not considered as they are not as land-intensive as wind and solar energy.

2.2.6. Network constraints

The network is modelled as a fully-controllable direct current network [30], and thus only active power is modelled. The energy import and export cannot exceed the thermal limits of the line.

$$0 \leqslant P^{import}_{n,m,t}, P^{export}_{n,m,t} \leqslant K_{n,m}, \forall (n, m) \in E, \forall t \in T \quad (7)$$

In this way, energy conservation is preserved, however, interested modellers could add other constraints by ensuring e.g. voltage conservation.

This study follows the modelling approach of [30] by firstly increasing the line capacity to 1.5 times to fulfil the $n-1$ security requirements. This increase of line capacity will influence the network cost in the objective function and the optimized network capacity. Secondly, in reality, the network length $\delta_{n,m}$ may not be the shortest length between nodes, due to physical barriers such as buildings, protected areas. The land cover assessment does not take into account the possible detour of the network, hence a factor of 25% is added to the line length between two nodes. These effects are modelled by adding a factor f ($f = 1.5 * 1.25$) to the objective function.

2.2.7. Storage constraints

The stored energy at time t is equal to the sum of the stored energy at time $t-1$ and the net charging energy. While charging/discharging, losses are included by incorporating the efficiency coefficients.

$$SP_{i,n,t} = SP_{i,n,t-1} + \eta^{in}_i CP_{i,n,t} - \frac{1}{\eta^{out}_i} DP_{i,n,t}, \forall i \in S, \forall n \in N, \forall t \in T \quad (8)$$

The energy charging/discharging per time step cannot exceed the capacity of the storage conversion, and the stored energy per time step cannot exceed the energy content of the storage unit.

$$SP_{i,n,t} \leqslant K_{i,n}, \forall i \in S, \forall n \in N, \forall t \in T \quad (9)$$

$$DP_{i,n,t}, CP_{i,n,t} \leqslant K_{i,n}, \forall i \in SC, \forall n \in N, \forall t \in T \quad (10)$$

Besides, since only one year is modelled, the storage is considered to be cyclic. This means, when t is the first step of the year, $t-1$ becomes the last time step of the year, i.e. Eq. (8)becomes

$$SP_{i,n,0} = SP_{i,n,t_{end}} + \eta^{in}_i CP_{i,n,0} - \frac{1}{\eta^{out}_i} DP_{i,n,0}, \forall i \in S, \forall n \in N \quad (11)$$

2.2.8. RES target constraint

A RES target constraint is added to indicate the minimum percentage of RES in total energy production. This RES target is specified by ω, ranging between 0 and 1.

$$\omega \sum_{i\in G} \sum_{n\in N} \sum_{t\in T} P_{i,n,t} \leqslant \sum_{i\in RES} \sum_{n\in N} \sum_{t\in T} P_{i,n,t} \quad (12)$$

2.2.9. Non-negativity constraints

At last, all the decision variables must be equal to or larger than zero.

$$0 \leqslant K_{i,n}, K_{n,m}, \forall i \in (G + SC), \forall n \in N, \forall (n, m) \in E \quad (13)$$

$$0 \leqslant K_{i,n}, SP_{i,n,t}, CP_{i,n,t}, DP_{i,n,t}, \forall i \in S, \forall n \in N, \forall t \in T \quad (14)$$

$$0 \leqslant P_{i,n,t}, \forall i \in G, \forall n \in N, \forall t \in T \quad (15)$$

3. Scope and Data Inputs of the Case Study

The background of the case study was explained in Section 1. This section presents the scope of the case study, the corresponding input data and how they were modelled as inputs to the optimization model.

3.1. Scope of the case study

As explained in Section 2.2.1, the presented model intends to only include the essential components that are typically considered in this family of optimization models. Therefore, the results of this example are meant to illustrate the usage of the approach and to reveal the role of land-use constraints in the power system planning models, given the context of the Netherlands.

3.2. Data inputs

The data modelling and the optimization modelling were done using Python. The most used packages in this study are NumPy, Pandas, netCDF4, shapely, NetworkX and Pyomo.

3.2.1. Polygon data

The geographical granularity is the 30 regions in the Netherlands. In this case, the regions are not administrative units (e.g. provinces), hence their polygons are not directly available in databases. Therefore, all the municipality polygons were first downloaded from the OpenStreetMap project and were then merged into the desired regions. The result is a Python dictionary with region names as the keys and polygons as the values including longitude and latitude coordinates.

3.2.2. Land cover data

The land cover data was obtained from the Corine Land Cover database [26] which has coverage for all the European countries. The suitable areas and the maximum potential installed capacities in each polygon were obtained. This land cover assessment and the calculation of maximum potential installed capacity will be elaborated in Section 4.

3.2.3. VRES data

The hourly wind speed was taken from the KNW data set, downloaded from KNMI (Royal Netherlands Meteorological Institute)[31]. The wind data of CLC classes belonging to water bodies are excluded, as only onshore wind turbines are considered in this study (see Section 3.2.6). The wind speed data set contains data for different heights covers the whole of the Netherlands with 2.5 km horizontal resolution. The power curve of Vestas V90 3 MW wind turbine was used to convert the wind speed to hourly wind capacity factor, and the wind speed at 80 m was used to match the hub height. Ideally, wind and solar data from the same data source are used. Unfortunately, the KNMI data set only has wind speed, so solar data was taken from another data set [29]. The solar data was extracted for each node *n* (i.e. the centroid of the polygon). The weather data in 2015 was used. In Fig. 3, the time-series for the region Rotterdam-Den Haag are illustrated.

3.2.4. Network topology

As mentioned in Section 2.1, the detailed modelling of the power network is out of the scope of this work. For the purpose of the case study, we assume a meshed network where adjacent polygons are connected.

3.2.5. Demand data

The data of hourly power demand for the Netherlands in 2015 (113 TWh) was derived from ENTSO-E(European Network of Transmission System Operators for Electricity) [32]. The hourly power demands for the 30 regions were scaled according to the population in each region (see Fig. 6) obtained from the OpenStreetMap project that includes population information. The time-series of power demand in the region Rotterdam-Den Haag is illustrated in Fig. 3.

3.2.6. Cost parameters

The chosen generation technologies are onshore wind turbines, solar PV, biomass plants, coal plants and CCGT plants. The land and feedstock requirements for biomass are not included. Offshore wind is not included (see discussions in Section 5.5). The storage technologies are hydrogen storage and flow battery storage. Pumped hydro storage is not considered due to non-availability in the Netherlands. The discount rate is 5%. The cost parameters are summarized in Table 1.

Wind and solar curtailment costs are essentially taken into account because by curtailing, the same investment cost would lead to lower production and hence a higher cost of electricity.

The network cost in our study is relatively high compared to other studies (see e.g. [33,35,36,30]) due to two reasons. Firstly, according to the 2019 data [37] from network operators in the Netherlands, the network cable cost is 3000 €/ MW/km - 50000 €/MW/km. Secondly, the costs related to substations and the distribution network cost are often not included in existing studies. Therefore, the chosen network cost is considered reasonable and even conservative for the Netherlands.

According to [38], for the Netherlands, the transmission and distribution loss factor is 4.77% in 2014. In addition, considering the fact that the lengths of all the network connections in this paper are less than 100 km, 5%/100 km is used as a typical number representative for the Dutch power networks.

4. Modelling of VRES Potentials

In this section, the land cover characteristics in the Netherlands will be assessed and the maximum potential installed capacities and the annual capacity factors of wind and solar energy will be calculated.

4.1. Land cover assessment

Table 2 gives the detailed land cover assessment for the Netherlands: CLC classes available for VRES development, available areas for each available CLC class, percentages of them in terms of the total area of the country, suitability factor for each available CLC class, suitable areas and percentages of them in terms of the total area of the country. Each column is further elaborated below.

First of all, unavailable land cover and nature reserves are excluded from the total area. In the Netherlands, existing wind turbines are to a large extent built along the roads or highways and at the construction sites such as the Rotterdam Port area. Therefore, the transport area is not excluded. Some of the urban areas are considered available as well (see Table 2 for the CLC classes that are considered available). Next, since most of the nature reserves in the Netherlands are small monuments, we excluded only the two largest reservations, Veluwe and Waddenzee. After those exclusions, the rest is considered available for VRES development. These criteria are based on physical conditions and this is considered as a moderate exclusion.

In addition, a stricter exclusion on land-use for wind energy is given. The rationale behind this is that if social resistance against wind energy is taken into account, the land will be even more limited. In this case,

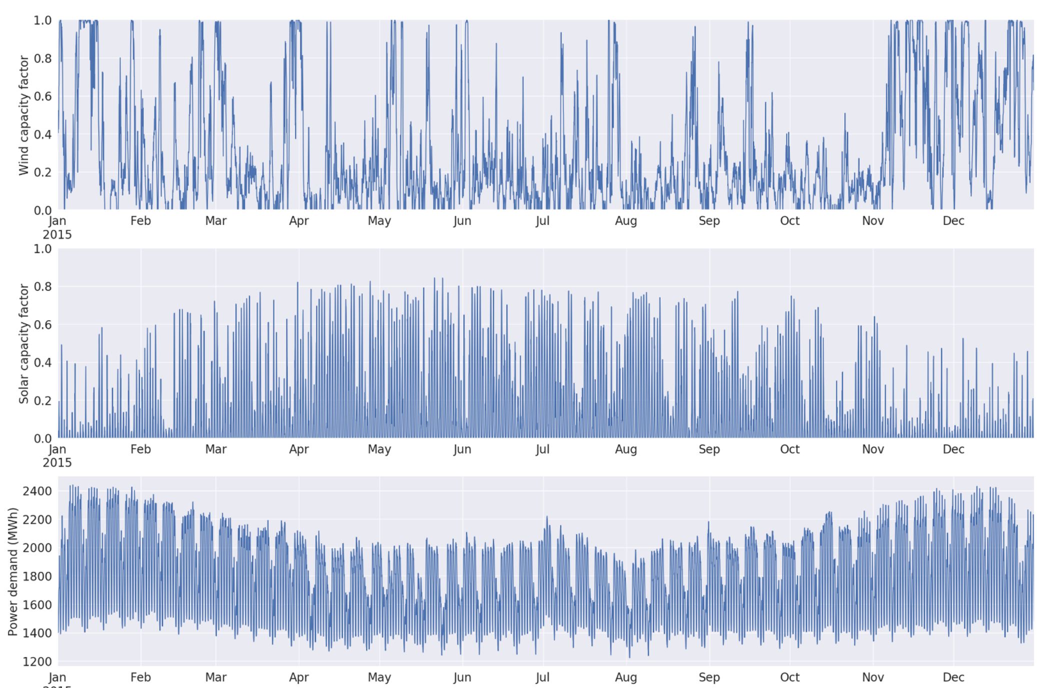

Fig. 3. Time-series of wind capacity factor, solar capacity factor and power demand for the region Rotterdam-Den Haag.

Table 1
2050 estimation of cost parameters (based on [30,33–36], except for the network cost and power loss factor).

Technology	CapEx (€/kW)	FOM (€/kW)	VOM (€/kW/yr)	Lifetime(yr)
Onshore wind	1205	45	0.002	25
Solar PV	925	21	0.001	25
Biomass	2640	90	0.0845	33
Coal	1600	28	0.03	42.5
CCGT	800	20	0.046	30
Hydrogen conversion	2400	0.04		
Hydrogen Storage	0.06 €/kWh	62% (in/out efficiency)		
Flow battery conversion	650	0.9		
Flow battery Storage	450 €/kWh	90% (in/out efficiency)		
Network	10000 €/MW/km	5%/100 km (power loss factor)		

Table 2
The land cover characteristics of the available and the suitable land for VRES development in the Netherlands. Suitability factors are based on own compilation and the work of [17].

CLC class	Available area (km^2)	Percentage	Suitability factor	Suitable area (km^2)	Percentage
2 Discontinuous urban fabric	3288.10	7.91%	0.3	986.43	2.37%
3 Industrial or commercial units	807.18	1.94%	0.8	645.74	1.55%
7 Mineral extraction sites	46.25	0.11%	0.5	23.13	0.06%
8 Dump sites	21.49	0.05%	0.5	10.75	0.03%
9 Construction sites	153.67	0.37%	0.3	46.10	0.11%
12 Non-irrigated arable land	7366.88	17.72%	0.4	2946.75	7.09%
15 Vineyards	0	0	0.1	0	0
16 Fruit trees and berry plantations	71.63	0.17%	0.1	7.16	0.02%
18 Pastures	10089.93	24.28%	0.6	6053.96	14.57%
20 Complex cultivation patterns	5304.71	12.76%	0.1	530.47	1.28%
21 Land principally occupied by agriculture, with significant areas of natural vegetation	1136.94	2.74%	0.1	113.69	0.27%
23 Broad-leaved forest	568.16	1.37%	0.3	170.45	0.41%
24 Coniferous forest	1146.76	2.76%	0.3	344.03	0.83%
25 Mixed forest	725.17	1.74%	0.3	217.55	0.52%
26 Natural grasslands	475.29	1.14%	0.6	285.17	0.69%
27 Moors and heathland	246.85	0.59%	0.6	148.11	0.36%
29 Transitional woodland-shrub	13.62	0.03%	0.5	6.81	0.02%
30 Beaches, dunes, sands	143.04	0.34%	0.3	42.91	0.10%
32 Sparsely vegetated areas	0	0	0.8	0	0
35 Inland marshes	364.74	0.88%	0.1	36.47	0.08%
36 Peat bogs	80.21	0.19%	0.1	8.02	0.02%
37 Salt marshes	96.69	0.23%	0.1	9.67	0.02%
Sum	32147.31	77.35%	n.a.	12633.38	30.40%

the land is constrained in addition to the moderate exclusion. This stricter exclusion assumes that all the land in the built environment, i.e. all the CLC classes of Artificial Surface, is excluded. Furthermore, the area in their 2 km radius is excluded as well. In this way, the social resistance and spatial policies of wind energy are operationalized and thus the feasible wind energy potential is quantified.

Fig. 4 shows all the land, the available land after moderate exclusion and after strict exclusion in the Netherlands.

The moderate exclusion will be the baseline case to be elaborated in this section, but the optimization results of both cases will be discussed in Section 5.

The land that is available for VRES development in the Netherlands is 77.35% of the total land. This means that, in the baseline case, around 80% of the land can be used for the installation of wind turbines and solar panels. However, different local conditions such as spatial policies could be implemented, which will change the exclusion criteria and the suitability factors. This would reduce the amount of suitable land in the end.

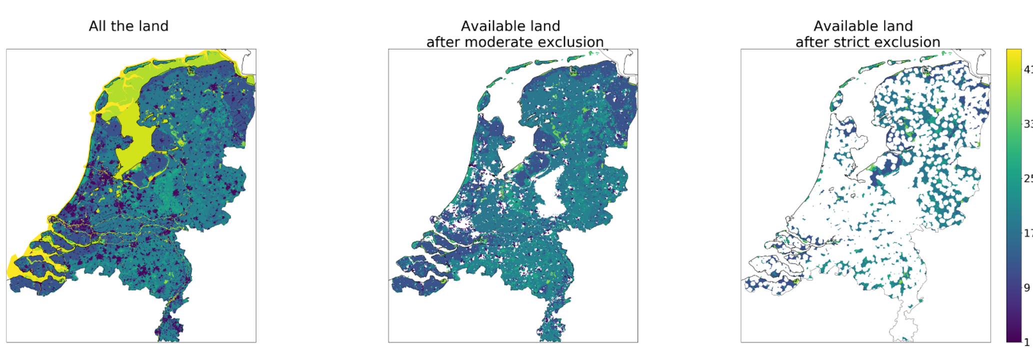

Fig. 4. Land in the Netherlands (the colored area represent different CLC classes, the white area is either not in the Netherlands or is excluded). Left to right: all the land, the available land after moderate exclusion and the available land after strict exclusion.

Then, the suitability factors are applied on the available area resulting in the suitable areas. The suitability factors for wind turbines and for solar panels are similar for most of the land use classes. The only difference is that solar panels are allowed to be put on building rooftops, hence, a suitability factor of 0.3 is given to discontinuous urban fabric for solar panels. This land cover assessment aims to give a general understanding of the available land and suitable land for VRES development in the Netherlands.

The total suitable area is 12633.38 km^2, which is 30.40% of the land in the Netherlands. The regional distribution of the suitable areas of the available CLC classes was calculated as well. The four CLC classes with the largest areas in Table 2 are illustrated in Fig. 5.

In summary, the CLC class of pastures is the most suitable land cover class for VRES development in the Netherlands, occupying 14.57% of the total area. Non-irrigated arable land also plays an important role with a percentage of 7.09%. Other CLC classes are not prominent, but among all, discontinuous urban fabric and industrial or commercial units are the most significant for solar panels and for wind turbines, respectively.

4.2. Maximum VRES capacities and annual capacity factors

Maximum VRES capacities at all regions are calculated based on Eq. (2). The suitable areas for wind and solar energy in the Netherlands are 11646 km^2 and 12633 km^2, respectively, occupying 28.02% and 30.40% of the total land of the Netherlands. This leads to 58.23 GW of potential wind capacity and 379 GW of potential solar capacity. Fig. 6 illustrates the geographical distribution of the maximum potential capacities.

Furthermore, the annual capacity factors are shown in this figure as well. For wind energy, the western and northern coastal regions have more favourable wind conditions than those of other regions. The annual capacity factors range between 0.20 and 0.36. With regard to solar energy, this range is smaller, which is 0.11 to 0.14. Moreover, unlike wind, solar annual capacity factors do not show a strong geographical pattern and are distributed rather evenly across the country.

5. Optimization Results and Discussions

This section presents the results from the optimization model in terms of the generation mix, the spatial distribution of the generation capacity and the total cost of the system. It starts with the scenario with the baseline VRES potential constraints obtained from Section 4.2. Afterwards, the scenario concerning strict VRES constraints based on the strict exclusion criteria on land-use (described in Section 4.1) will be used to check the sensitivity of the model outcomes to this constraint. Lastly, the scenario without the constraints on the land-use of VRES is briefly presented, which imitates the existing studies.

5.1. Baseline scenario with moderate VRES potential constraints

5.1.1. Generation mix

Fig. 7 shows the generation mix for five RES targets for different scenarios.

At the 0% RES target, coal plants comprise most of the capacity to supply base demand, whereas the capacity of CCGT is 25% of that of coal and it supplies the peak demand. At the 20% RES target, wind comes into the generation mix by bringing in an extra capacity compared to the first target. Then, starting from the 50% target, solar PV appears. Regarding the fossil fuels, the capacity of CCGT is equal to coal at this target and it surpasses coal when RES share is above 50%. In other words, when the RES share is below 50%, coal represents the majority of the fossil fuel capacity. Moreover, going from 20% to 50% RES, the total capacity doubles, which is mainly due to the investment in solar and wind energy. At the 80% RES target, biomass for the first time appears in the generation mix to replace some of the coal capacity. However, coal and CCGT are still in the generation mix to provide controllable power production.

The fossil fuels are gone at the 100% RES target, in which they are replaced by more biomass. Hydrogen storage is being deployed to cover periods of little VRES production. Storage only appears at the 100% RES target, while for other targets, fossil fuels plants can cover those periods. In addition, out of the two storage options in the model, hydrogen storage seems to be more cost-effective than flow battery storage under existing cost parameters of both technologies.

With respect to the RES capacities for all the targets, wind capacity stays almost the same at the 50%, 80%, and 100% RES target, solar capacity has reached its peak deployment at the 80% target. Nevertheless, the total wind capacity is higher than the total solar capacity for all the targets. Apparently, wind is more cost-effective than solar power. Hence, wind energy plays a dominant role with solar energy and biomass complementing its variable production.

5.1.2. Spatial distribution of the generation capacities

Fig. 8 shows the generation capacities in the 30 regions in the Netherlands and the land-use for onshore wind and solar PV represented by the fraction between the used land and the suitable land.

At the 0% RES target, coal and CCGT plants are located mainly in Noord-Holland Zuid and in Rotterdam-Den Haag regions (these are the regions in the densely populated west of the country). This result is plausible since these regions are also demand centres in the Netherlands (see Fig. 6). Besides, there is 22 MW of onshore wind, which is

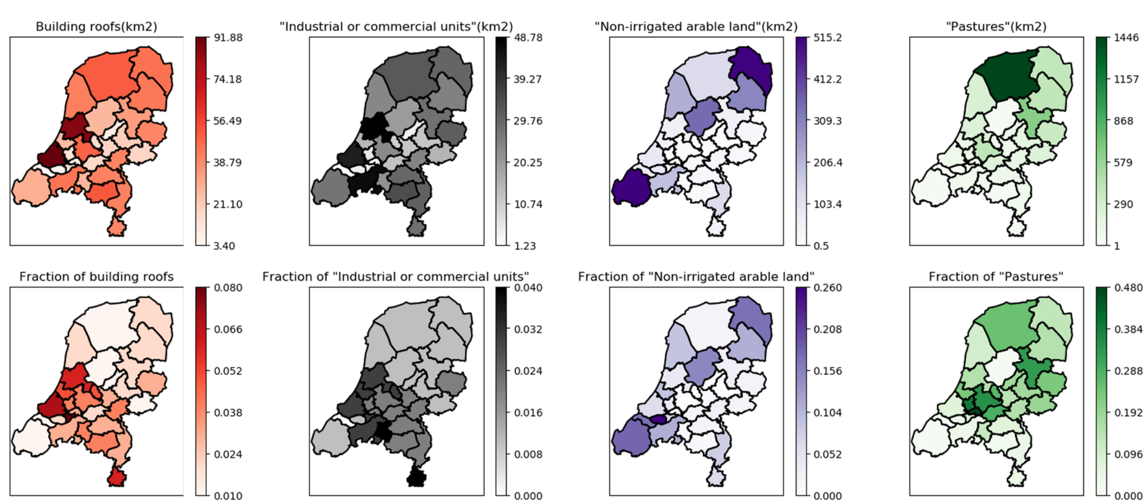

Fig. 5. Selected land cover characteristics for the 30 regions in the Netherlands.

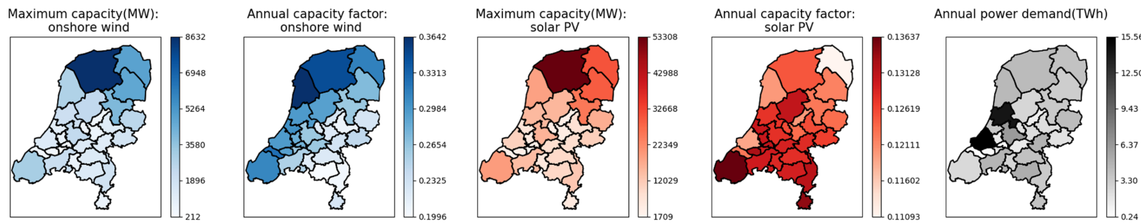

Fig. 6. The geographical distribution of five figures in the Netherlands. Left to right: the maximum potential installed capacity (MW) and the annual capacity factor for onshore wind turbines, the maximum potential installed capacity (MW) and the annual capacity factor for solar PV, and the annual power demand (TWh).

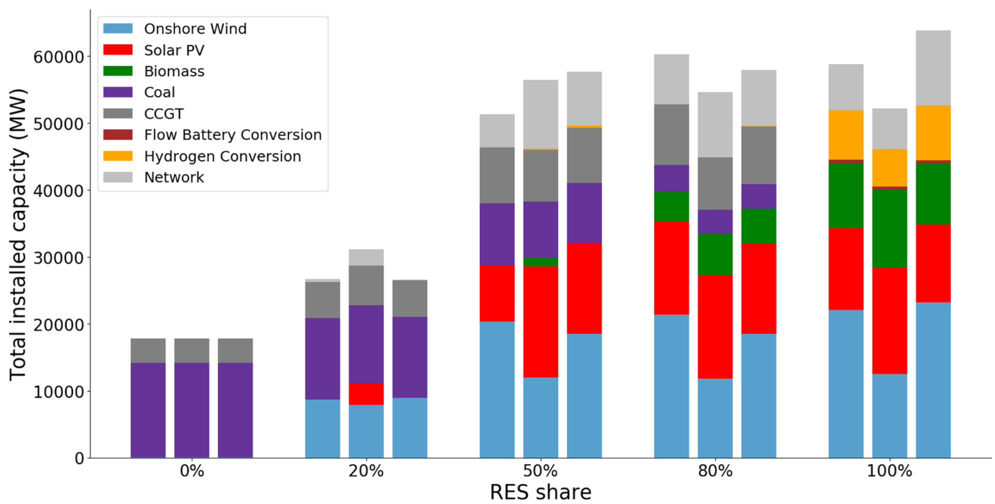

Fig. 7. Total installed capacity (MW) for different RES targets for the three scenarios. At each RES target, left to right: baseline scenario, new policy scenario and unlimited land scenario.

negligible compared to the capacities of coal and CCGT.

At the 20% RES target, wind energy is installed mainly in these two demand centres. However, due to their limited size, wind energy also has to be installed in the neighbouring regions to supply the two demand centres. Results show that the Rotterdam-Den Haag region is fully occupied by wind turbines, and two of its neighbouring regions Goeree-

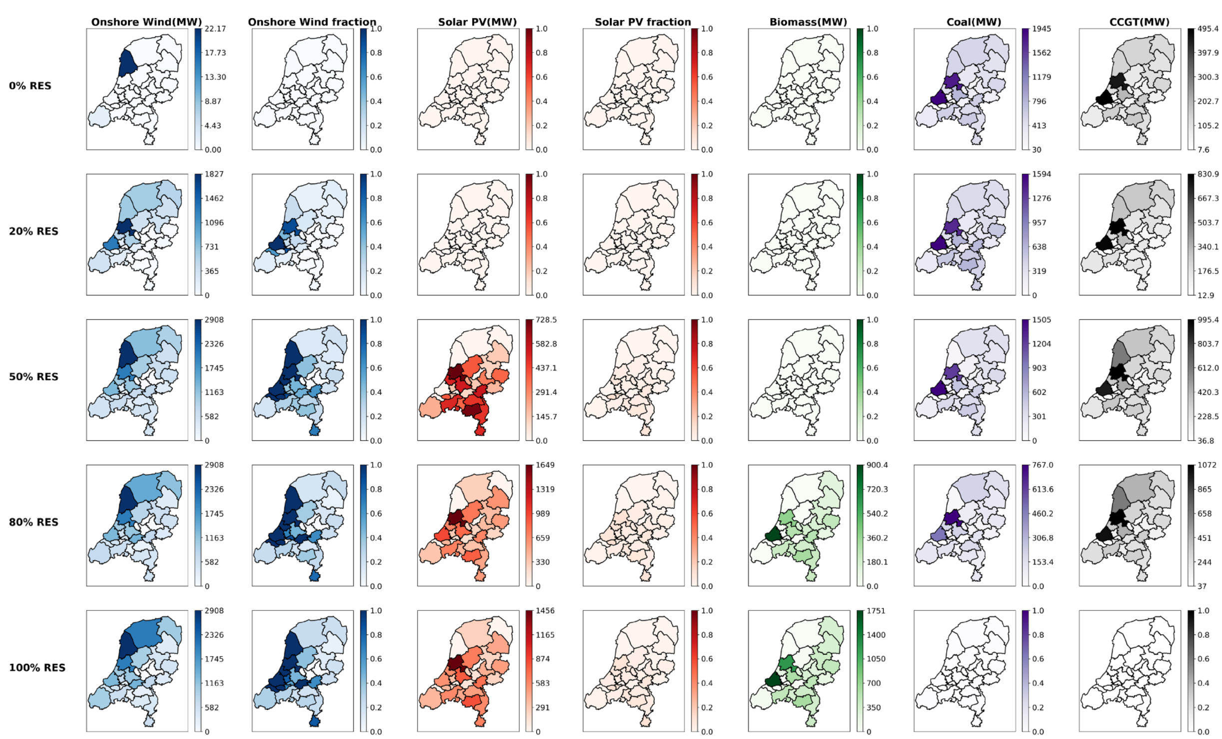

Fig. 8. Generation distribution for the 30 regions for different RES targets. Left to right: onshore wind (MW), onshore wind fraction, solar PV (MW), solar PV fraction, biomass (MW), coal (MW), CCGT (MW).

Overflakkee and Holland-Rijnland provide additional wind energy capacity. The other demand center, Noord-Holland Zuid, nevertheless, still has land for wind turbines.

From the 50% to the 100% RES target, wind capacities continue to expand from the two demand centres to their neighbouring regions as well as to the northern regions where the wind conditions are good, e.g. Noord-Holland Noord and Friesland. However, due to their large maximum potential capacity and relatively long distance to the demand centres, they are not heavily occupied by wind turbines. By contrast, most of the neighbouring regions of the demand centres are fully occupied. At the 100% RES target, 7 out of the 30 regions are fully used for wind turbines which corresponds to 38% of the total suitable land and 11% of the total land of the Netherlands.

5.1.3. Total cost

The total cost of the system is divided by the total power demand (113 TWh) to represent the cost of electricity (Fig. 9). Most of the cost is proportional to the installed capacity in Fig. 7 except for the operation cost. This operation cost, however, accounts for a significant part of the total cost. It includes the Fixed Operation & Maintenance (FOM) cost, and the Variable Operation & Maintenance (VOM) cost. Here the VOM cost, i.e. the fuel cost is the main differentiator of the total costs for the different RES targets. From the 0% to the 50% RES target, although the cost of electricity increases, the operation cost actually decreases because of the lower capacity for coal and CCGT. However, instead of decreasing, the operation cost increases for the 80% RES target, which is due to the introduction of biomass in the generation mix. The incremental increases in cost for the five RES targets are 4 €/ MWh, 12 €/ kWh, 24 €/ MWh and 23 €/ MWh. Another important finding is that the cost of network is at maximum 1.5% of the cost of electricity which is at the 100% RES target. This small contribution implies that the assumptions we made for the cost and topology of the network do not have a significant influence on the key performance indicators of the overall system, i.e. the generation mix and the system's total cost.

5.2. New policy scenario with strict constraints on the land-use of VRES

The merit of our approach is that it assesses the land cover in a spatially explicit way such that the VRES potential constraint can be adapted based on any selection of the allowed land cover as described in Section 2.1.2. To give an example of the usage and the relevance, apart from the baseline scenario, a 2 km exclusion scenario that reflects social resistance and spatial policy was proposed in Section 4.1. The results of this scenario are discussed in this section.

5.2.1. Spatial distribution of wind capacity

In Fig. 10, the geographical distribution of the land-use of wind turbines represented by the fraction between the used land and the suitable land is shown.

Under the 2 km policy, only 7% of the total area in the Netherlands are suitable for wind turbines, instead of the 30% in the baseline case. Compared to the baseline case, this strict VRES constraint on land-use has a larger impact on the occupied land. At the 20% RES target, 70% of the regions are fully occupied by wind turbines, whereas only one region is entirely used in the baseline case. At the 100% RES target, 93% of the regions are wholly possessed, which corresponds to 92% of the total suitable land and 6% of the total land of the Netherlands.

5.2.2. Generation mix

Fig. 7 shows the total installed capacity for the new policy scenario. First of all, due to the strict wind energy constraints on land-use, there is a decrease in wind capacity for all the RES targets and the wind capacity is almost reaching its maximum potential. Secondly, there is a capacity increase in solar energy and in biomass. Moreover, compared to the baseline case, these two technologies both come earlier into the generation mix as the RES share increases. Solar energy first appears at the 20% RES target, and biomass appears at the 50% RES target at the earliest. This indicates that solar energy and biomass compensate for the decrease of wind capacity compared to the baseline scenario. Thirdly, there is an indispensable rise in the network capacity at the 20%, 50% and 80% RES target, because wind power is now produced in larger quantities at larger distances from the demand centres. Storage, again, is only present at the 100% RES target.

5.2.3. Total cost

Next, the costs of electricity are compared as well. There is not a significant cost rise for all the RES targets, which varies between 2 €/MWh to 5 €/MWh. This implies that the extra cost of extra solar and biomass energy is almost equal to the cost reduction in wind energy.

5.3. Unlimited land scenario with no constraints on the land-use of VRES

As mentioned in Section 1, most of the existing optimization studies do not include the constraints on the land-use of VRES. Therefore, the effects of this simplification on the optimization results are unknown. In this scenario, we assess the model results without the VRES potential constraints (Eq. (6)). In this way, the drawbacks of the existing models will be unveiled, and hence the advantage of our approach will be further elaborated.

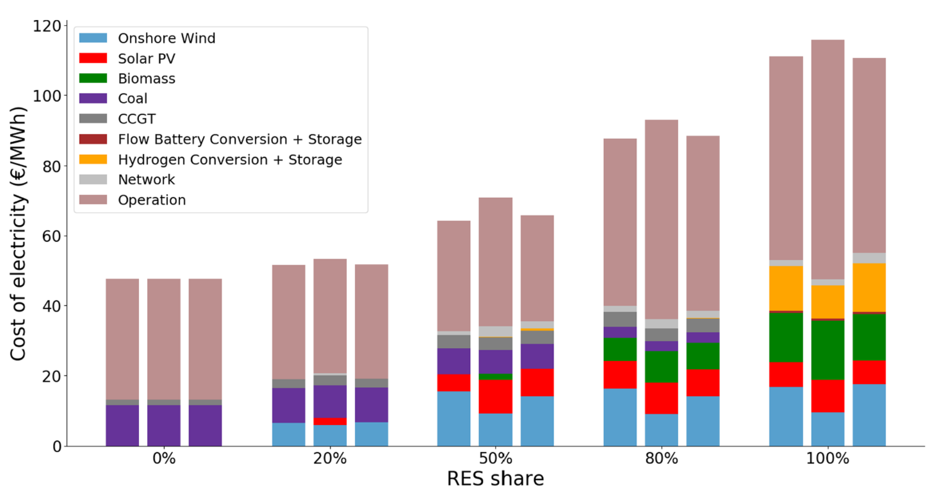

Fig. 9. Cost of electricity (€/MWh) for different RES targets for the three scenarios. At each RES target, left to right: baseline scenario, new policy scenario and unlimited land scenario.

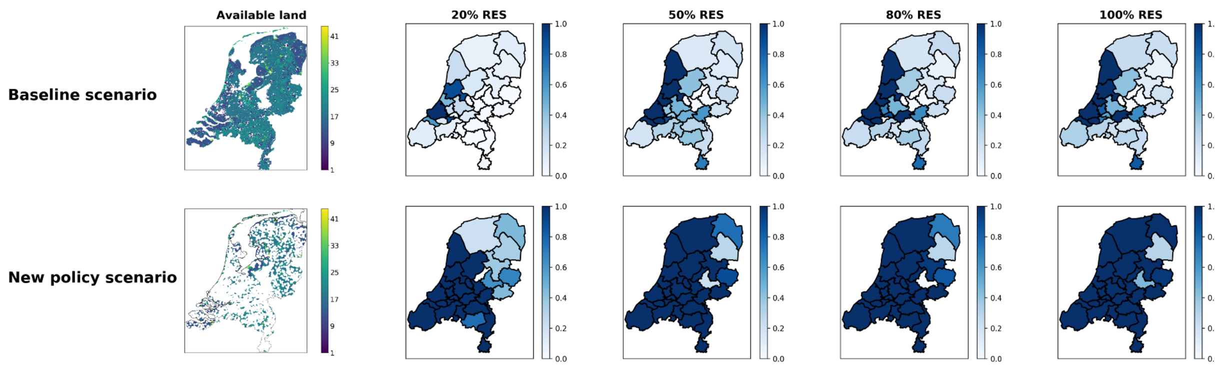

Fig. 10. The fraction of the used land over the suitable land of wind turbines under the two scenarios: baseline scenario and new policy scenario.

5.3.1. Spatial distribution of wind capacity

In Fig. 11, the geographical distribution of the wind capacity and the fraction between the used land and the suitable land are shown. The left two columns present results from the baseline scenario, the right two columns show results from this scenario.

At the 20% RES target, due to the land-use constraints, the baseline scenario results in capacities mostly in the two demand centres and its surroundings. In the unlimited land scenario, the results are similar but the capacities are more concentrated. This trend becomes clearer at the 50%, 80% and 100% RES target. At the 50% and 80% target, in the baseline scenario, the coastal regions around the demand centres are fully occupied by wind turbines. However, in this scenario, only three regions are wholly packed with wind turbines. These three regions have the best wind conditions in the neighbourhood, and thus wind turbines are preferred to be placed there. This tendency to place the wind turbines in the model without land-use limits of VRES results in unrealistic land occupation. Goeree-Overflakkee region has to install 4.64–4.91 times its maximum allowable capacity, and Rotterdam-Den Haag region has to install 1.31–1.35 times its maximum allowable capacity. At the 100% RES target, the numbers are even higher. In the baseline scenario, the coastal regions are already fully occupied and the capacities have to be built in the north or in the south. And the maximum installed capacity is 2908 MW in Noord-Holland Noord region. In the current scenario, this pattern of capacity expanding to the neighbouring regions does not appear. Instead, the model prefers to install capacities in the three regions with the favourable wind conditions, of which the maximum capacity is 6032 MW. Consequently, the capacities in these three regions are beyond the physical limits of land. Compared to their maximum allowed capacities, Goeree-Overflakkee region has to install 7.63 times, Noord-Holland Noord region has to install 2.07 times and Rotterdam-Den Haag region has to install 1.42 times.

5.3.2. Generation mix

Compared to the results in the baseline scenario, in this scenario,

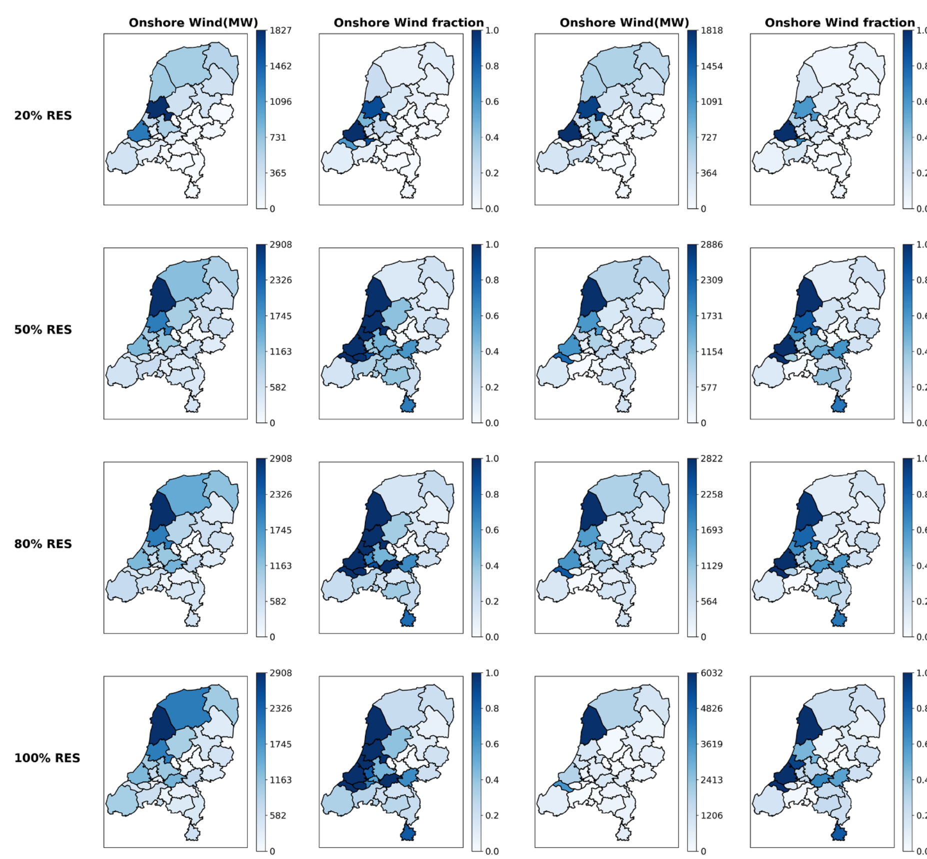

Fig. 11. Wind capacity and the fraction between the used land and the suitable land. Left two column: baseline scenario. Right two column: unlimited land scenario.

there are two main differences. Firstly, the total capacity is higher at 50%, 80% and 100% RES target. This is due to the increase in network capacity in all three targets. And there is a major difference in solar capacity at 50% RES target. Secondly, storage comes into the generation mix much earlier in this scenario, although its capacity is not high.

5.3.3. Total cost

Due to the difference in the generation mix, the cost breakdown is also different which corresponds to the generation mix. However, the difference in total cost is not significant. Since in this scenario, the total wind capacity does not change much, whereas the spatial distribution shows a different pattern.

5.4. Discussions of the results

In this case study, three scenarios are analyzed to show how the proposed approach can be used. It must be emphasized that the role of the land-use constraints deduced from the results (e.g. in cost, capacity) are case-specific, given the situation in the Netherlands. For other cases with either unique land suitability (e.g. prohibited zones), or different distribution of demand or meteorological profiles, the results might not be comparable to the Dutch case. Nevertheless, the obtained results from the three scenarios will be further compared. This is in order to give an example on what key results can be analyzed and what conclusions can be drawn.

In Section 5.1, the baseline scenario is based on the realistic assessment of the land cover, and thus this scenario takes the actual location-specific land-use limit of placing VRES technologies into account. Next, in Section 5.2, a stricter constraint on the land-use of VRES is applied. If a spatial policy to mitigate the social resistance of VRES is designed (e.g. the 2 km policy in this case), this scenario shows the effects on the optimization results and the land-use coverage of such a policy. At 100% RES target, 92% of the suitable land in the Netherlands will be fully occupied. At 50%, 80%, 100% RES target, the wind capacity is reduced by 9182 MW or 43% on average, compared to the baseline scenario.

Then, Section 5.3 shows the optimization results without any constraints on the land-use of VRES. The total capacity and the cost of the system are similar to those of the baseline scenario. This is because for this specific Dutch case, on the one hand, the favourable VRES locations are not excluded much (by e.g. nature reserves). This means that the VRES capacity constraints play a less significant role compared to the case where the favourable VRES locations are excluded more. On the other hand, the VRES land-use constraints will essentially change the optimal spatial distribution of the VRES capacity, and thus more network is needed. However, in this model, since the cost of network is not a significant component of the total cost of the system, the total cost is similar to that of the baseline scenario.

Nevertheless, Section 5.3.1 indicates that without the constraints on land-use, the optimal capacities in some regions would be infeasible in reality. Our approach gives the unique kind of realistic result that would be needed for planning purposes and that would be not obtained using existing approaches. In addition, for other cases, other insights, such as the changes in total capacity and total cost between the baseline scenario and the unlimited land scenario might be seen.

To give an indication of how the results could be used directly for real-life purposes, they are first validated by comparing the cost of electricity to the Dutch electricity price, and then the generation mix is compared to the literature. In 2015, the electricity consumption from RES in the Netherlands is 2%. According to TenneT [39], the 2015 average Dutch wholesale price is 40 €/MWh. In Fig. 9, for 2% RES, the cost of electricity is between 47 €/MWh and 52 €/MWh. However, the wholesale price does not include capital costs. The operational part of the cost of electricity is between 32 €/MWh and 35 €/MWh. This cost is comparable but lower than the real-world electricity price, which is reasonable since other costs such as taxes are not calculated. Despite different production profiles of VRES were used, the generation mix of 100% RES scenario for other case studies, such as Australia [40], Portugal [41], islands across the globe [42], Europe [30], shows that wind dominates in the generation mix of RES. This trend is consistent with

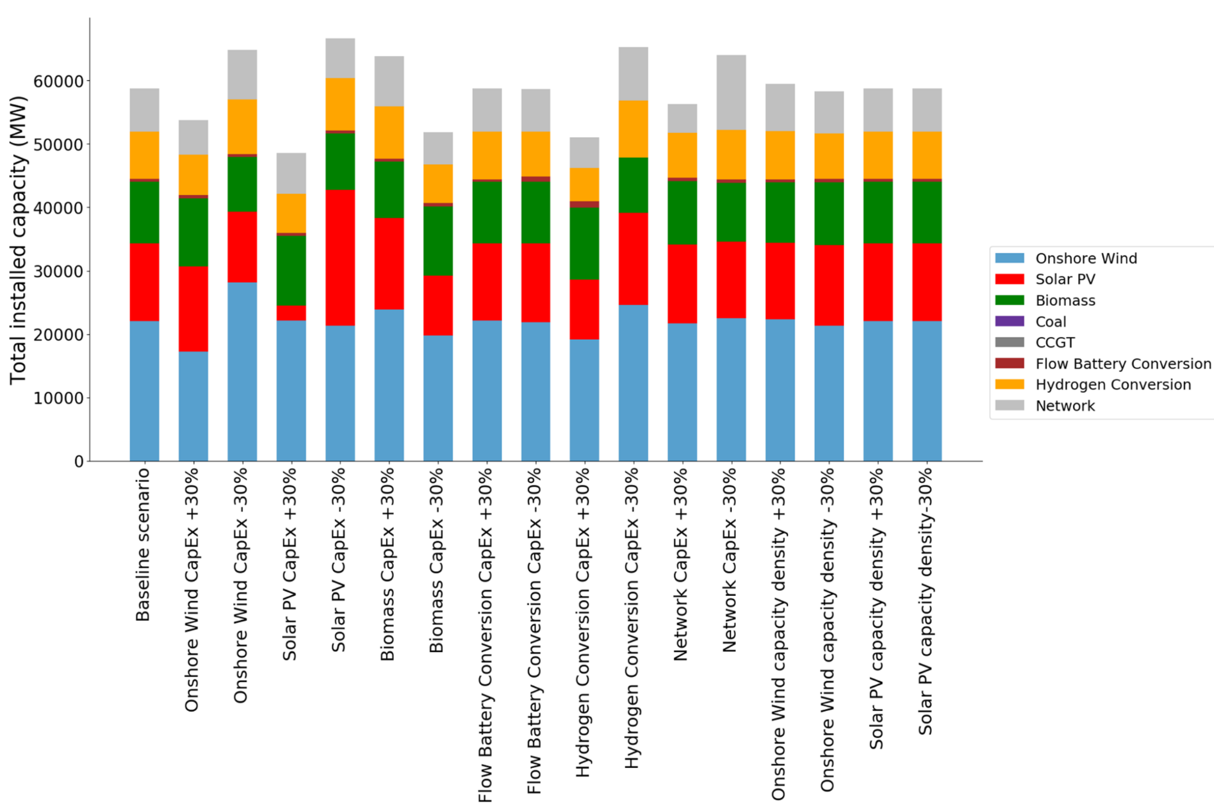

Fig. 12. Sensitivity study for the total installed capacity at 100% RES target of the baseline scenario.

our results.

Because the 100% RES scenarios have not materialized in the real world yet, it is impossible to validate those results using real world data. Furthermore, uncertainties in the input data are also unavoidable. In such cases, a sensitivity study adds additional insights on the robustness of the results. We therefore performed sensitivity experiments by varying the CapEx of the technologies and the capacity densities to + 30% and −30% compared to their original values and evaluate the effects on total installed capacity (Fig. 12) and and the cost of electricity (Fig. 13) at 100% RES target of the baseline scenario. The results show that the CapEx has a stronger influence on the installed capacities than the capacity densities. A change in solar PV CapEx has the highest effect on the installed capacities. Overall effects on the costs are more limited, ranging from roughly 105 €/MWh to 115 €/MWh. In summary, the trend still holds that wind plays the most important role, biomass serves as controllable generation and hydrogen is the main storage source, given our assumptions.

5.5. Discussions of the approach and future work

Our approach shows useful and promising results, but every work, ours also, has some possible extensions that warrant further research. Firstly, we provided the detailed VRES potential constraints based on the land-use of VRES, but the planning of networks will also be influenced by land cover characteristics (e.g. no-go zones), which were ignored in our approach. The next step is to investigate the sensitivity of the outcomes when there are constraints on land-use for networks. Secondly, different technologies (e.g. offshore wind) will be considered in the future. These two possibilities are not included in the current approach, as they feature different methodologies. For instance, in order to apply this approach to offshore wind, data sets other than the CLC database that show the suitability of installing offshore wind turbines would be required.

6. Conclusions

We provided a spatially explicit planning approach for power systems that integrates the location-specific land-use of VRES into the optimization model. Instead of relying on land-use data from other studies, this data-driven approach is a first-of-a-kind study in the literature on power system optimization modelling that bridges three fields of studies: land cover assessment, VRES potential estimation and energy system planning models. It considers location-specific VRES potential constraints which can be adapted to local conditions (e.g. social resistance, spatial policy and physical conditions) regarding land-use and reveals the role of the land-use of VRES on the results of such planning models.

A case study for a densely populated area, in our case the Netherlands, has been done to show the strength of the approach and to give policy-relevant results. We found that under moderate VRES potential constraints (the baseline scenario), wind energy will be the primary energy source in the generation mix for scenarios for high-RES targets. Storage only plays a role at the 100% RES target. At this target, wind turbines would cover 38% of the suitable land in the Netherlands.

In addition, we applied a stricter spatial policy (the 2 km policy as described in Section 4.1) on wind energy. The results showed that 92% of the suitable land in the country then has to be used for wind turbine installations to achieve 100% RES target with minimum cost. However, the total cost of the system under this policy has not increased much compared to the baseline scenario, since solar energy and biomass can compensate for wind energy at just a slightly higher system cost. Besides, due to the reduction in wind capacity, solar energy and biomass both come into the generation mix earlier compared to the baseline scenario, whereas storage still only appears at the 100% RES target.

At last, the results on the scenario with no land-use constraints on VRES were analyzed. The optimal capacities are infeasible considering the land limits, making the results not instructive for planning purposes in reality.

We conclude that, for new spatial policies that address the social resistance of VRES, the VRES potential constraints considering land-use

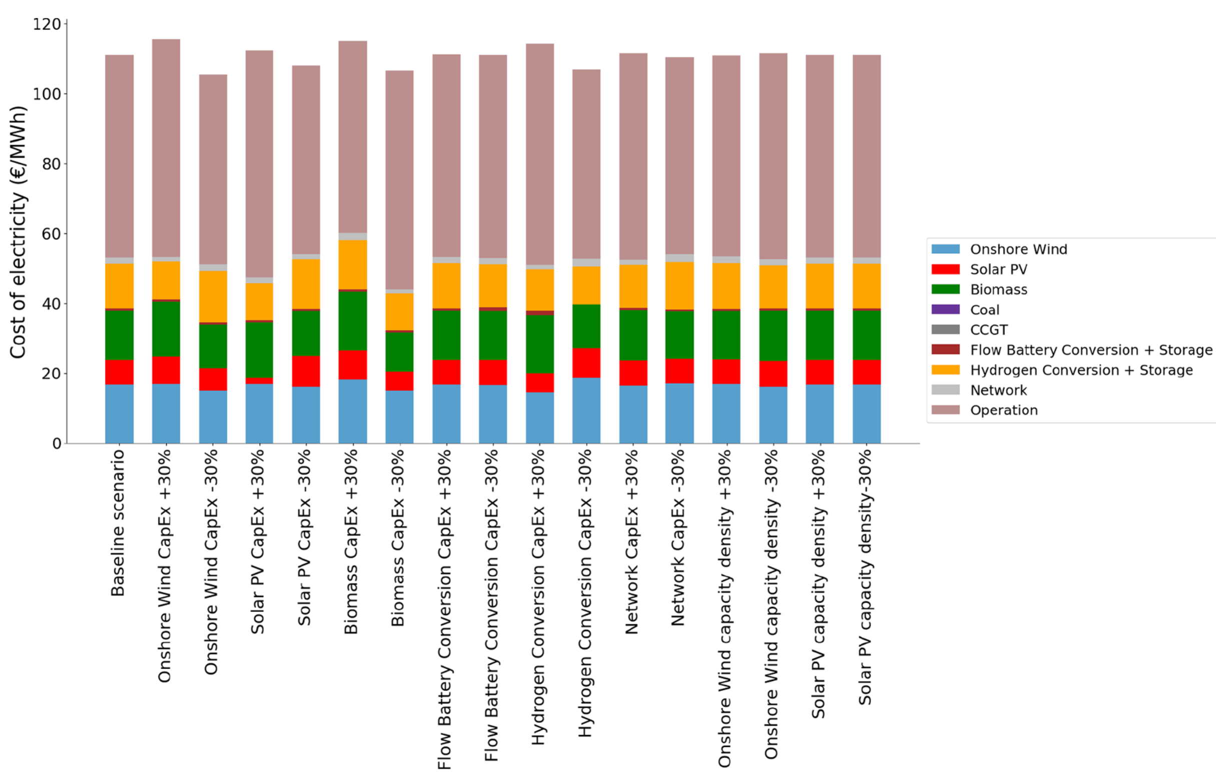

Fig. 13. Sensitivity study for the cost of electricity at 100% RES target of the baseline scenario.

have a significant influence on the optimization results and would thus require drastically different policy measures. Therefore, our integrated approach is a necessary next step in creating more policy-relevant models for large-scale deployment of RES in densely populated areas or areas with abundant nature reserves. The proposed approach elaborates the essential steps to operationalize land-use in the constraints after which its impacts on the optimization results will be revealed.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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