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OFFSHORE ENERGY HUBS IN THE DECARBONISATION OF THE NORWEGIAN CONTINENTAL SHELF

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ABSTRACT

This paper studies the investment planning of a decarbonised Norwegian continental shelf energy system considering the connection and interfaces with the European energy system. A multi-horizon stochastic mixed-integer linear programming model is developed for such a problem. We consider short-term uncertainties, including wind and solar capacity factors, energy load, platform production profiles, and hydro power production limits. Hydrogen based energy hubs are considered both onshore and offshore for potential renewable power generation, distribution and storage. Future hydrogen market or demand is not included in the model. The results of multi-period planning towards 2050 show that: (a) offshore energy hubs are essentially wind power generation, conversion and distribution hubs, (b) a combination of offshore wind and power from shore may be a cost-efficient pathway for cutting emissions from the Norwegian continental shelf, (c) a total of 1.6 GW offshore wind may be needed to achieve a near zero emission Norwegian continental shelf energy system, 80% of which may be added in the first investment period and (d) offshore grid design is important for decarbonisation by distributing wind power efficiently; all five offshore platform clusters are connected to at least three other clusters by 2040, and they are fully connected by 2050.

Keyword: multi-horizon stochastic programming, mixed-integer linear programming, offshore oil and gas decarbonisation, investment planning under uncertainty

NOMENCLATURE

Sets

$\mathcal{I}$	set of operational nodes
$\mathcal{I}_0$	set of investment nodes
$\mathcal{I}_i$	set of investment nodes i ($i \in \mathcal{I}_0$) ancestor to operational node i ($i \in \mathcal{I}$)
$\mathcal{P}$	set of all technologies
$\mathcal{L}$	set of transmission lines
$\mathcal{Z}$	set of regions
Ω	set of operational scenarios
$\mathcal{S}^T$	set of time intervals
$\mathcal{T}$	set of operational time periods in all time intervals
$\mathcal{G}$	set of thermal generators
$\mathcal{F}$	set of fuel cells
$\mathcal{R}$	set of renewable generations
$\mathcal{E}$	set of electrolysers
$\mathcal{S}$	set of electricity storage
$\mathcal{S}^{Hy}$	set of hydrogen storage

Variables

x_{pzi}^{PInst}	newly installed capacity of technology p in region z in investment node i ($p \in \mathcal{P}, z \in \mathcal{Z}, i \in \mathcal{I}_0$) [MW, MWh, kg]
x_{pzi}^{PAcc}	accumulated capacity of technology p in region z in operational node i ($p \in \mathcal{P}, z \in \mathcal{Z}, i \in \mathcal{I}$) [MW, MWh, kg]
x_{li}^{LInst}	newly installed capacity of line l in investment node i ($l \in \mathcal{L}, i \in \mathcal{I}_0$) [MW]
x_{li}^{LAcc}	accumulated capacity of line l in operational node i ($l \in \mathcal{L}, i \in \mathcal{I}$) [MW]
γ_{pzi}^{P}	binary variable, 1 technology p is built in region z in investment node i, 0 otherwise ($p \in \mathcal{P}, z \in \mathcal{Z}, i \in \mathcal{I}_0$)
γ_{li}^{L}	binary variable, 1 line l is built in investment node i, 0 otherwise ($l \in \mathcal{L}, i \in \mathcal{I}_0$)
$y_{pz\omega ti}^{P}$	power output of technology p in region z in scenario ω in operational period t in operational node i ($p \in \mathcal{P}$, $z \in \mathcal{Z}$, $\omega \in \Omega$, $t \in \mathcal{T}$, $i \in \mathcal{I}$) [MW]
$y_{l\omega ti}^{P}$	power flow in line l in scenario ω in operational period t in operational node i ($p \in \mathcal{P}$, $z \in \mathcal{Z}$, $\omega \in \Omega$, $t \in \mathcal{T}$, $i \in \mathcal{I}$) [MW]
$y_{gz\omega ti}^{G}$	power output of thermal generator g in region z in scenario ω in operational period t in operational node i ($g \in \mathcal{G}$, $z \in \mathcal{Z}$, $\omega \in \Omega$, $t \in \mathcal{T}$, $i \in \mathcal{I}$) [MW]
$y_{fz\omega ti}^{F}$	power output of fuel cell f in region z in scenario ω in operational period t in operational node i ($f \in \mathcal{F}$, $z \in \mathcal{Z}$,

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	$\omega \in \Omega, t \in \mathcal{T}, i \in \mathcal{I})$ [MW]
$y^{R}_{rz\omega ti}$	power output of renewable generator r in region z in scenario ω in operational period t in operational node i ($r \in \mathcal{R}, z \in \mathcal{Z}, \omega \in \Omega, t \in \mathcal{T}, i \in \mathcal{I}$) [MW]
$y^{E}_{ez\omega ti}$	power input of electrolyser e in region z in scenario ω in operational period t in operational node i ($e \in \mathcal{E}, z \in \mathcal{Z}, \omega \in \Omega, t \in \mathcal{T}, i \in \mathcal{I}$) [MW]
$y^{LShed}_{z\omega ti}$	load shedding in region z in scenario ω in operational period t in operational node i ($z \in \mathcal{Z}, \omega \in \Omega, t \in \mathcal{T}, i \in \mathcal{I}$) [MW]
$y^{S+(-)}_{sz\omega ti}$	power input (output) of storage s in region z in scenario ω in operational period t in operational node i ($s \in \mathcal{S}, z \in \mathcal{Z}, \omega \in \Omega, t \in \mathcal{T}, i \in \mathcal{I}$) [MW]
$l^{S}_{sz\omega ti}$	storage level of s in region z in scenario ω in operational period t in operational node i ($s \in \mathcal{S}, z \in \mathcal{Z}, \omega \in \Omega, t \in \mathcal{T}, i \in \mathcal{I}$) [MWh]
$l^{SHy}_{sz\omega ti}$	storage level of hydrogen storage s in region z in scenario ω in operational period t in operational node i ($s \in \mathcal{S}^{Hy}, z \in \mathcal{Z}, \omega \in \Omega, t \in \mathcal{T}, i \in \mathcal{I}$) [kg]
$v^{SHy+(-)}_{sz\omega ti}$	hydrogen input (output) of hydrogen storage s in region z in scenario ω in operational period t in operational node i ($s \in \mathcal{S}^{Hy}, z \in \mathcal{Z}, \omega \in \Omega, t \in \mathcal{T}, i \in \mathcal{I}$) [kg]

Parameters

$\pi^{I_0}_{i}$	probability of investment node i ($i \in \mathcal{I}_0$)
π^{I}_{i}	probability of operational node i ($i \in \mathcal{I}$)
$\delta^{I_0}_{i}$	discount factor of investment node i ($i \in \mathcal{I}_0$)
δ^{I}_{i}	discount factor of operational node i ($i \in \mathcal{I}$)
π^{Ω}_{ω}	probability of scenario ω ($\omega \in \Omega$)
κ	discounted scaling effect depending on investment time step
C^{PInv}_{pi}	variable term for investment cost of technology p in investment node i ($p \in \mathcal{P}, i \in \mathcal{I}_0$) [€/MW,€/MWh, €/kg]
C^{PFInv}_{pi}	fixed term for investment cost of technology p in investment node i ($p \in \mathcal{P}, i \in \mathcal{I}_0$)
C^{LInv}_{li}	variable term for investment cost of line l in investment node i ($l \in \mathcal{L}, i \in \mathcal{I}_0$) [€/MW]
C^{PFInv}_{li}	fixed term for investment cost of line l in investment node i ($l \in \mathcal{L}, i \in \mathcal{I}_0$)
X^{PHist}_{pzi}	historical capacity of technology p in region z in operational node i ($p \in \mathcal{P}, z \in \mathcal{Z}, i \in \mathcal{I}$) [MW, MWh, kg]
X^{LHist}_{li}	historical capacity of line l in operational node i ($l \in \mathcal{L}, i \in \mathcal{I}$) [MW]
X^{PMax}_{pz}	maximum installed capacity of technology p in region z ($p \in \mathcal{P}, z \in \mathcal{Z}$) [MW, MWh, kg]
X^{LMax}_{l}	maximum installed capacity of line l ($l \in \mathcal{L}$) [MW]
X^{PMaxb}_{pzi}	maximum built capacity of technology p in region z in investment node i ($p \in \mathcal{P}, z \in \mathcal{Z}, i \in \mathcal{I}_0$) [MW, MWh, kg]
X^{LMaxb}_{li}	maximum built capacity of line l in investment node i ($l \in \mathcal{L}, i \in \mathcal{I}_0$) [MW]
H^{P}_{p}	lifetime of technology p ($p \in \mathcal{P}$) [year]
H^{L}_{l}	lifetime of line l ($l \in \mathcal{L}$) [year]
W^{s}	weight of slice s ($s \in \mathcal{S}$)
C^{P}_{pi}	total operational costs (fuel costs and variable operational cost) of technology p in operational node i ($p \in \mathcal{P}, i \in \mathcal{I}$) [€/MW]
C^{LShed}	load shedding penalty cost [€/MW]
$Y^{D}_{z\omega ti}$	load in region z in scenario ω in period t in operational node i ($z \in \mathcal{Z}, \omega \in \Omega, t \in \mathcal{T}, i \in \mathcal{I}$) [MW]
A_{zl}	bus-line incidence matrix ($z \in \mathcal{Z}, l \in \mathcal{L}$)
ρ^{G}_{g}	CO_2 content of the fuel used by thermal generator g ($g \in \mathcal{G}$) [tonne/MWh]
$E^{CO_2}_{\omega i}$	CO_2 emission limit in scenario ω in operational node i ($\omega \in \omega, i \in \mathcal{I}$) [tonne/year]
η^{L}_{l}	efficiency of line l ($l \in \mathcal{L}$)
η^{G}_{gi}	efficiency of thermal generator g in operational node i ($g \in \mathcal{G}, i \in \mathcal{I}$)
η^{S}_{si}	charging efficiency of electricity storage s in operational node i ($s \in \mathcal{S}, i \in \mathcal{I}$)
η^{ES}	conversion factor from electrolyser to storage facility [MWh/kg]
η^{EF}	conversion factor from electrolyser to fuel cell [MWh/kg]

1. INTRODUCTION

Norway sets to reduce greenhouse gas emissions by at least 50-55% by 2030 compared to 1990 levels to contribute to the EU's climate target, and the Paris Agreement [1]. In 2020, offshore oil and gas extraction in the Norwegian Continental Shelf (NCS) produced 13.2 Mt CO_2 equivalent, which made up 26.8% of the total Norwegian greenhouse gases emissions [2]. The oil and gas industry has the highest emissions than any other industries in Norway. Therefore, decarbonising offshore oil and gas production is crucial to meet Norway's climate goal.

Energy provision of offshore platforms was responsible for nearly 85% of the total emissions in the NCS [3]. Nowadays, platform located gas turbines with low efficiency provide the most energy. Thus, replacing gas turbines with zero emission energy generation will cut offshore emissions. Power from shore is considered a feasible solution of clean energy provision due to the near zero emission power generation in the onshore energy system [4, 5]. Offshore wind is an alternative that draws more attention [6–8]. However, intermittent renewable energies cannot fulfil the security of supply requirements of the platforms. Energy storage may be needed to fully replace gas turbines. The space and weight limitations of platforms may make local energy storage infeasible. An offshore energy hub was proposed in [9] to support efficient wind power generation and distribution. In [9], a deterministic Mixed-Integer Linear Programming (MILP) model was developed for the investment planning towards a zero emission NCS energy system. However, there are some limitations in the analysis in [9]: (a) uncertainty is not considered in the model, (b) the onshore energy system expansion is not considered but analysed via sensitivity analysis, and (c) platforms are in isolated mode, and no interconnection among platforms is considered.

In this paper, we extend the deterministic MILP model in [9], including: (a) adding operational uncertainties in wind and solar capacity factors, energy load, platform production profiles, and hydro power production profile, (b) considering onshore power system expansion, (c) exploring different network topology, and (d) making multi-period investment planning towards 2050.

The outline of the paper is as follows: Section 2 gives the background knowledge of stochastic programming and energy hub modelling. Section 3 introduces the problem and modelling strategies. Section 4 presents the multi-horizon stochastic MILP model. Section 5 presents the preliminary results. Section 6 concludes the paper and suggests further research.

2. LITERATURE REVIEW

This paper uses stochastic programming to solve an investment planning problem for a decarbonised NCS energy system. Offshore energy hubs is an offshore investment option in addition to offshore wind, offshore solar, subsea cables, battery and electric boiler. In the following, we present background knowledge of stochastic programming and energy hubs modelling.

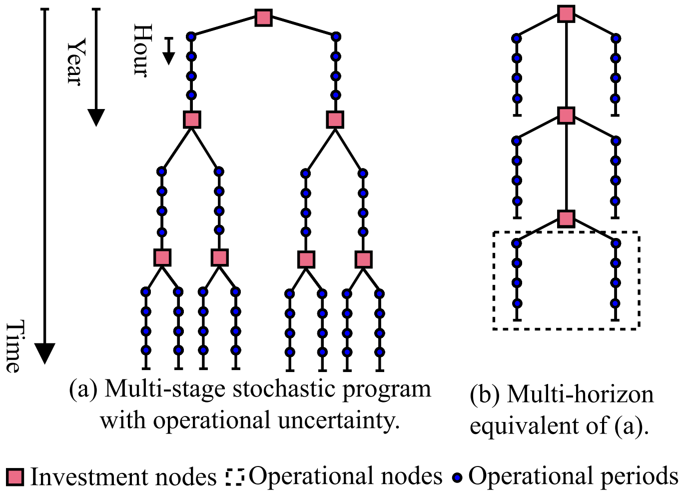
2.1 Stochastic programming

Considering operational uncertainty while conducting long-term investment planning is important for an energy system with higher penetration of renewable energies. The electricity system in regulated markets is the best developed area for the use of stochastic programming in energy [10]. Stochastic programming is widely used in power system [11–15], natural gas system [16], offshore oil and gas infrastructure planning [17], hydrogen network [18], among others.

Using traditional stochastic programming in an investment planning problem may result in a large scenario tree. A multi-horizon formulation was proposed in [19] that reduces the problem sizes drastically. The scenario tree reduces in size by embedding operational nodes into their respective strategic nodes, see Figure 1 for a comparison between traditional multi-stage stochastic programming scenario tree and multi-horizon programming scenario tree. There are two conditions for applying multi-horizon stochastic programming, (1) strategic uncertainty is independent of the operational uncertainty, and (2) the last operational decision in a strategic node has no impact on the first operational decision in the following strategic node [19]. This approach is widely used in energy system planning, see [9, 11, 20, 21]. This paper uses the multi-horizon approach to model a multi-period investment planning problem with short-term uncertainties. We define the entire operational problem succeeding an investment node as an operational node. There are some scenarios generated from certain scenario generation routines for each operational node, and each scenario has some operational periods. We do not consider multi-stage operational trees in the operational node. Therefore, such a problem is a two-stage stochastic programming.

2.2 Offshore energy hubs modelling

An energy hub is a physical connection point with energy storage where multiple energy carriers can be converted, conditioned, and stored [23]. Conversion means converting energy in one form to another, such as converting electricity to hydrogen. Conditioning means to change the operating parameter of energy carriers, e.g., change voltage of electricity. The energy can then store in a storage unit of energy hubs. Energy hubs may have quite different components depending on their functions. We refer the reader to [24] for a comprehensive review of applications and models of energy hubs. The previous work using the energy hub concept mainly focus on the onshore energy system integration. More specifically, sector coupling of electricity, natural gas and heat. In real life, the energy hub concept is broadened, such as [25, 26] where the hubs can be simply a wind power generation and distribution hub. The offshore energy hubs are mainly planned to use offshore wind power as energy input and convert and distribute wind power. However, as more offshore wind is available [27], offshore energy hubs can also convert surplus wind power, for example, to hydrogen for clean energy export or energy storage. We consider energy hubs both in onshore and offshore energy systems. This paper considers energy hubs with converter, electrolysers, fuel cells, and hydrogen storage facilities. The hubs produce green hydrogen from surplus wind power and store it. Furthermore, energy hubs can be deployed both onshore and offshore. An illustration of the energy hubs considered in this paper is presented in Figure 2.



(a) Multi-stage stochastic program with operational uncertainty.

(b) Multi-horizon equivalent of (a).

FIGURE 1: ILLUSTRATION OF SCENARIO TREES OF MULTISTAGE STOCHASTIC PROGRAMMING AND ITS MULTI-HORIZON COUNTERPART (WITH OPERATIONAL UNCERTAINTY), ADAPTED FROM [19, 22].

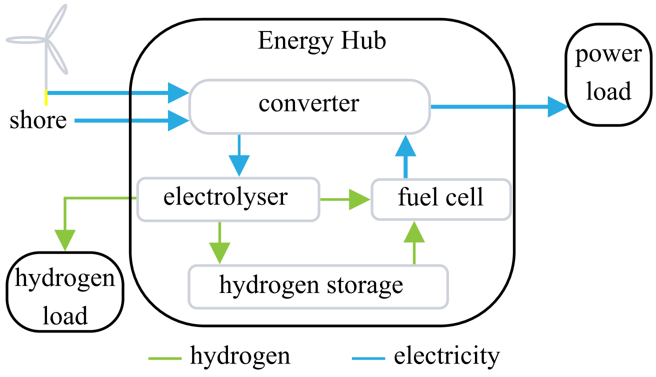


FIGURE 2: ILLUSTRATION OF AN ENERGY HUB, ADAPTED FROM [9].

3. PROBLEM DESCRIPTION AND MODELLING STRATEGIES

This section first introduces the proposed NCS energy system planning problem. Then we present the temporal and spatial representation of such a problem. Finally, we give the modelling

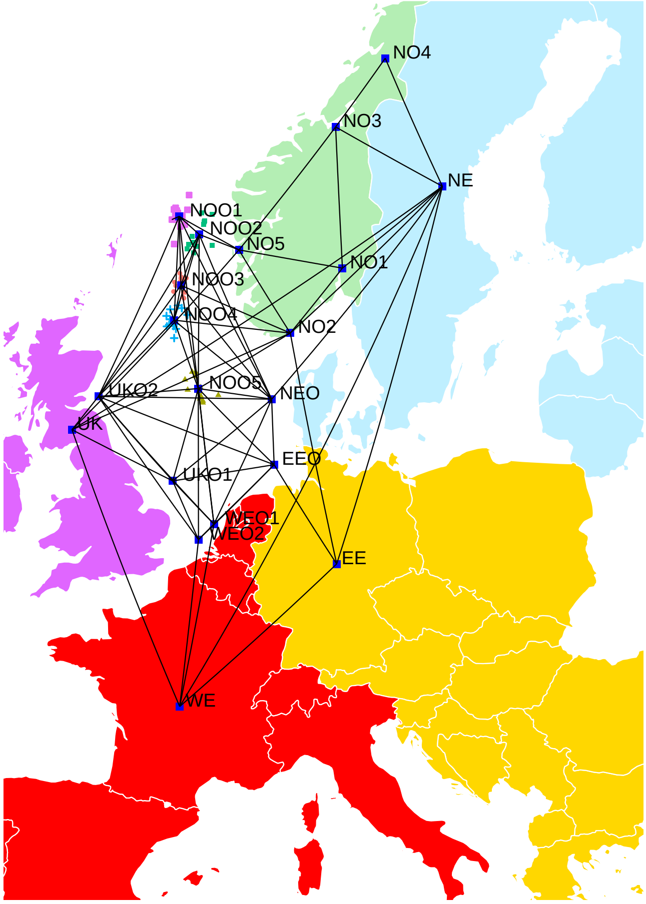


FIGURE 3: THE NORTH SEA GRID (NOX REPRESENT NORWEGIAN ONSHORE NODES AND NOOX REPRESENT NORWEGIAN OFFSHORE NODES.

assumptions.

The problem aims to make optimal investment decisions for a set of offshore and onshore technologies. Although the focus is on the NCS energy system, including onshore system expansion is important. The onshore load still needs to be fulfilled after part of the generation is distributed offshore. The offshore technologies include: (a) platform located devices (electric boiler, battery), (b) offshore renewables (offshore wind and offshore solar), (c) offshore energy hubs (converters, electrolysers, fuel cells, and hydrogen storage facilities) and subsea cables (HVAC and HVDC). The onshore technologies include: (a) 22 kinds of generators, (b) onshore energy hubs, (c) energy storage (hydro pump storage and battery) and (d) overhead HVAC and HVDC cables. The development of capital expenditures, fixed operational costs are assumed to be known.

The problem is a cost minimisation problem, including investment and operational costs aiming to determine: (a) the optimal capacities of technologies and (b) optimal operational scheduling of generators, storage and approximate power flow among regions under stochastic operational scenarios.

3.1 Temporal representation

The investment planning problem can span over a few decades, whereas the operational problem is optimised with an hourly time horizon using representative hours. Combining strategic and operational time horizons in the same model and including short-term uncertainty can make the problem intractable. Therefore, we choose to make investment planning every κ year in the strategic time horizon instead of yearly.

In the operational time horizon, we choose S representative slices from the sample space and scale them up to represent a whole operational year. We also assume the operational status will not change between two successive investment nodes and scale the expected operational cost up by κ times to represent the total operational costs of an operational node.

3.2 Spatial representation

We include detailed modelling of the NCS and keep a part of the information of the European onshore system. The European countries are aggregated into representative nodes and connected by representative transmission lines to keep such a problem reasonable size. The platforms on the NCS are clustered and aggregated into some representative platforms [9]. The resulted network topology is presented in Figure 3.

3.3 Modelling assumption

We assume a κ years investment delay meaning that the investment made at one investment node start affecting the system operation from the following investment nodes onwards. For simplicity, we assume the pressure levels and temperatures to take typical values on the North Sea, leading to a linear formulation. Kirchhoff voltage law is omitted, and the model is an energy flow model. We assume no mass loss during production. We assume linear costs models for transnational transmission lines and onshore technologies due to their large size and aggregated representation. The linear costs model also applies for offshore wind and solar because of the potentially large size and the flexibility of their unit size. However, step-wise cost models are assumed for offshore energy hubs and transmission lines in the NCS.

4. MATHEMATICAL MODEL

4.1 Objective function

$$\min f(\mathbf{x}) + \kappa \sum_{i \in \mathcal{I}} \delta_i^I \pi_i g(x_i, c_i) \tag{1}$$

The objective function Equation (1) is to minimise the total investment ($f(\mathbf{x})$) and the expected operational ($\kappa \sum_{i\in\mathcal{I}} g(x_i, c_i)$) costs over the planning horizon. The expected operational cost $g(x_i, c_i)$ is described in Section 4.3, where x_i and c_i are vectors containing capacities and costs information respectively.

4.2 Investment planning constraints

Equation (2a) calculates the expected total discounted capacity dependent investment costs, fixed operating and maintenance costs and fixed capacity independent investment costs. For each investment node, the investment costs parameters are adjusted if the lifetimes of technologies exceed the remaining planning horizon to account for salvage value. We define $\mathbf{x}$ to be a vector collecting available capacities of all technologies ($\mathcal{P}$) and lines ($\mathcal{L}$) for all operational nodes ($\mathcal{I}$). Constraints (2b) and (2c) represent that the available capacity of a technology (x_{pzi}^{PAcc}) or a line (x_{li}^{LAcc}) at an operational node equals to its historical capacity (X_{pz}^{PHist} or X_l^{LHist}) and the sum of newly invested capacities

(x_{pzi}^{PInst} or x_{li}^{LInst}) in its ancestor investment nodes ($\mathcal{I}_i$) that are not retired. A binary variable γ_{pzi}^{P} decides whether technology $p \in \mathcal{P}$, in location $z \in \mathcal{Z}$ is built investment period $i \in \mathcal{I}_0$. A binary variable γ_{li}^{L} indicates whether line $l \in \mathcal{L}$ is built in investment period $i \in \mathcal{I}_0$. Constraint (2d) and (2e) restrict the maximum capacity that can be invested in an investment node. Constraint (2d) and (2e) state the maximum installed capacity in an operation node.

$$f(\mathbf{x}) = \sum_{i \in \mathcal{I}_0} \delta_i^{I_0} \pi_i^{I_0} \left(\sum_{p \in \mathcal{P}} \sum_{z \in \mathcal{Z}} \left(C_{pi}^{PInv} x_{pzi}^{PInst} + C_{pi}^{PFInv} \gamma_{pzi}^{P} \right) + \sum_{l \in \mathcal{L}} \left(C_{li}^{LInv} x_{li}^{LInst} + C_{li}^{LFinv} \gamma_{li}^{L} \right) \right) + \kappa \delta_i^{I} \pi_i^{I} \sum_{i \in \mathcal{I}} \left(\sum_{p \in \mathcal{P}} \sum_{z \in \mathcal{Z}} C_{pi}^{PFix} x_{pzi}^{PAcc} + \sum_{l \in \mathcal{L}} C_{li}^{LFix} x_{li}^{LAcc} \right) \tag{2a}$$

$$x_{pzi}^{PAcc} = X_{pz}^{PHist} + \sum_{i_0 \in \mathcal{I}_i | \kappa(i-i_0) \leq H_p} x_{pzi}^{PInst}, \quad p \in \mathcal{P}, z \in \mathcal{Z}, i \in \mathcal{I} \tag{2b}$$

$$x_{li}^{LAcc} = X_{l}^{LHist} + \sum_{i_0 \in \mathcal{I}_i | \kappa(i-i_0) \leq H_l} x_{li}^{LInst}, \quad l \in \mathcal{L}, i \in \mathcal{I} \tag{2c}$$

$$0 \leq x_{pzi}^{PInst} \leq X_{pzi}^{PMaxb} \gamma_{pzi}^{P}, \quad p \in \mathcal{P}, z \in \mathcal{Z}, i \in \mathcal{I}_0 \tag{2d}$$

$$0 \leq x_{li}^{LInst} \leq X_{li}^{LMaxb} \gamma_{lzi}^{L}, \quad l \in \mathcal{L}, i \in \mathcal{I}_0 \tag{2e}$$

$$0 \leq x_{pzi}^{PAcc} \leq X_{pz}^{PMax}, \quad p \in \mathcal{P}, z \in \mathcal{Z}, i \in \mathcal{I} \tag{2f}$$

$$0 \leq x_{li}^{LAcc} \leq X_{l}^{LMax}, \quad l \in \mathcal{L}, i \in \mathcal{I} \tag{2g}$$

$$\gamma_{pzi}^{P}, \gamma_{li}^{L} \in \{0, 1\}, \tag{2h}$$

$$x_{pzi}^{PInst}, x_{li}^{LInst}, x_{pzi}^{PAcc}, x_{li}^{LAcc} \in \mathbb{R}_0^+. \tag{2i}$$

4.3 Operational constraints

The operational cost function $g(x,c)$, which is included in the objective function Equation (1) for each operational node i, is described by Equation (3a) that includes total operating costs of all devices and energy load shedding costs. Equation (3a) calculates the expected operational costs over scenarios Ω. All variables are indexed by operational node i and scenario ω, and we omit them for ease of notation. Vectors x and c contain capacities and costs information, respectively. Constraints (3b) and (3c) ensure devices (y_{pzt}^{P}) and transmission lines (y_{lt}^{L}) are within their capacities ($x_{pz}^{PAcc}, x_{l}^{LAcc}$). Constraint (3d) gives the energy balance at each region, where y_{gt}^{G}, y_{fzt}^{F} and y_{rzt}^{R} are power generation of generators, fuel cells and renewables respectively. Moreover, we define y_{ezt}^{E} to be the power that goes into electrolysers and $l_{szt}^{S}, y_{szt}^{S+}$ and y_{szt}^{S-} represent the storage level, input and output energy of storage facilities. The energy demand Y_{zt}^{D} can be modelled corresponding to the specific sector, such as offshore platforms. The modelling of offshore platforms is described in details in [9]. Constraint (3e) states the storage balance of electricity storage facilities. Constraint (3g) states the storage balance of hydrogen storage facilities. Constraint (3g) gives the hydrogen nodal balance of offshore energy hubs, where v_{szt}^{SHy-} and v_{szt}^{SHy+} are the hydrogen output and input of hydrogen storage facilities. Constraint (3h) restricts the total emissions. The complete stochastic MILP problem consists of Equations (1)-(3).

$$g(x,c) = \sum_{\omega \in \Omega} \pi_{\omega}^{\Omega} \sum_{s \in \mathcal{S}^T} \sum_{t \in \mathcal{T}} \sum_{z \in \mathcal{Z}} W_s \left(\sum_{p \in \mathcal{P}} C_p^P y_{pzt}^P + C^{Shed} y_{zt}^{LShed} \right) \tag{3a}$$

$$0 \leq y_{pzt}^{P} \leq x_{pz}^{PAcc}, \quad p \in \mathcal{P}, z \in \mathcal{Z}, t \in \mathcal{T} \tag{3b}$$

$$-x_{l}^{LAcc} \leq y_{lt}^{L} \leq x_{l}^{LAcc}, \quad l \in \mathcal{L}, t \in \mathcal{T} \tag{3c}$$

$$\sum_{g \in \mathcal{G}} y_{gt}^{G} + \sum_{l \in \mathcal{L}} A_{zl} y_{lt}^{L} + \sum_{f \in \mathcal{F}} y_{fzt}^{F} + y_{zt}^{LShed} + \sum_{r \in \mathcal{R}} y_{rzt}^{R} = Y_{zt}^{D} + \sum_{s \in \mathcal{S}} (y_{szt}^{S+} - y_{szt}^{S-}) + \sum_{e \in \mathcal{E}} y_{ezt}^{E}, \quad z \in \mathcal{Z}, t \in \mathcal{T} \tag{3d}$$

$$l_{sz(t+1)}^{S} - l_{szt}^{S} = \eta_s^S y_{szt}^{S+} - y_{szt}^{S-}, \quad s \in \mathcal{S}, z \in \mathcal{Z}, t \in \mathcal{T} \tag{3e}$$

$$l_{sz(t+1)}^{SHy} - l_{szt}^{SHy} = v_{szt}^{SHy+} - v_{szt}^{SHy-}, \quad s \in \mathcal{S}^{Hy}, z \in \mathcal{Z}, t \in \mathcal{T} \tag{3f}$$

$$\sum_{e \in \mathcal{E}} y_{ezt}^{E} + \sum_{s \in \mathcal{S}^{Hy}} \eta^{EF} v_{szt}^{SHy-} = \sum_{s \in \mathcal{S}^{Hy}} \eta^{ES} v_{szt}^{SHy+} + \sum_{f \in \mathcal{F}} \eta^{EF} y_{fzt}^{F}, \quad z \in \mathcal{Z}, t \in \mathcal{T} \tag{3g}$$

$$\sum_{s \in \mathcal{S}^T} \sum_{z \in \mathcal{Z}} \sum_{t \in \mathcal{T}} \sum_{g \in \mathcal{G}} \frac{W_s \rho_g^G y_{gzt}^G}{\eta_g^G} \leq E^{\mathrm{CO}_2}, \tag{3h}$$

$$y_{lt}^{L} \in \mathbb{R}_0, \tag{3i}$$

$$y_{pz}^{P}, y_{gzt}^{G}, y_{fzt}^{F}, y_{zt}^{LShed}, y_{rzt}^{R}, y_{szt}^{S+}, y_{szt}^{S-}, y_{ezt}^{E}, l_{szt}^{S}, l_{szt}^{SHy}, v_{szt}^{SHy-}, v_{szt}^{SHy+}, x_{pz}^{PAcc}, x_{l}^{LAcc} \in \mathbb{R}_0^+. \tag{3j}$$

5. RESULTS

We demonstrate the results of the multi-period investment planning and operational problem given by Equations (1)-(3) towards 2050. The problem consists of 1,072,525 continuous variables, 186 binary variables and 12,843,006 constraints. We implemented the model in Julia 1.7.1 using JuMP [28] and solved it with Gurobi 9.5.0 [29] on a computer cluster with a 2x 3.6GHz 8 core Intel Xeon Gold 6244 CPU and 384 GB of RAM, running on CentOS Linux 7.9.2009.

5.1 Case study

The case study is carried out on the European energy system with detailed modelling of the NCS. After applying the aggregation strategy described in Section 3.2, the system is represented by 25 regions and 73 candidate transmission lines. In each operational node, we generate three scenarios. In each scenario, we randomly select one day with hourly resolution from four seasons and scale them up to represent a whole operational year. Onshore system data, including costs, historical capacities of technologies and time-series data, are collected and aggregated from [30]. The costs and historical capacities of technologies are presented in A. Platform production and hydrogen system data are included in [9]. The full model given by Equations (1)-(3) takes approximately 5.4 hours to solve.

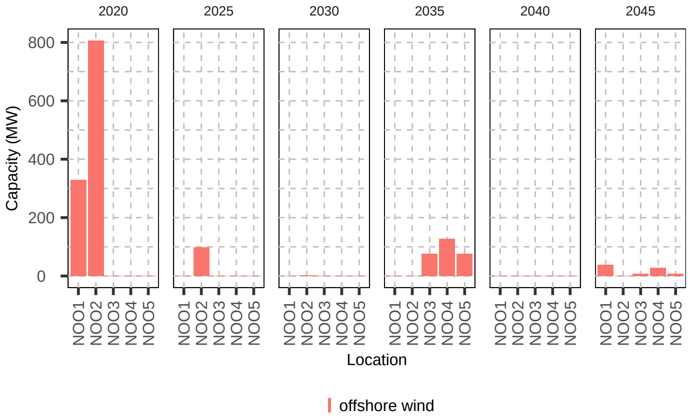


FIGURE 4: INVESTMENT OF OFFSHORE ENERGY HUBS.

FIGURE 5: INVESTED CAPACITY OF PLATFORM LOCATED TECHNOLOGIES. NO INVESTMENT ARE MADE IN BATTERY AND GAS TURBINE.

TABLE 1: YEARLY EMISSIONS IN EACH OFFSHORE FIELDS CLUSTER [9].

	NOO1	NOO2	NOO3	NOO4	NOO5
Emission (Mt)	1.72	2.46	0.40	0.62	0.30

5.1.1 Offshore energy hubs. The invested capacities in offshore energy hubs are shown in Figure 4. From Table 1, we can see that offshore regions NOO2 and NOO1 have the highest emissions among platform clusters on the NCS. We only consider the emissions from the gas turbines that are used for the energy provision of platforms. The model decides to invest in approximately 800 MW and 300 MW offshore wind around NOO2 and NOO1, respectively. In addition, from Figure 7, we can see that the investments in cables connecting these two regions and cables for taking power from onshore node NO5. Therefore, a combination of offshore wind and power from shore is needed for decarbonisation. Moreover, transmission is needed for compensating for the wind variation in those regions. An extra 100 MW offshore wind is added to region NOO2 in 2025. In 2030, nearly no investments are made in the offshore energy hubs. However, a cable connecting NO2 and NOO3 is invested in decarbonising NOO3. In 2035, offshore wind is invested in the rest NCS nodes to cope with the emissions target in 2040. From 2035 to 2040, we see a significant increase in cables connecting the Norwegian offshore regions. Each region are connected with an onshore system and surrounded by offshore wind farms in 2040. Because no hydrogen market or demand is considered in the model, no investments are made in hydrogen-related technologies. This suggests that a hydrogen system is costly if it is only used as energy storage. Connecting the regions with cables is a cheaper alternative for compensating renewable volatility.

5.1.2 Platform located technologies. Figure 5 shows the investments in platform located devices. As gas turbines are replaced by clean power, heat recovery of gas turbines are not enough to meet the heat load of the separation process. Therefore, electric boilers are needed. The major investments in electric boilers take place in 2030 in all NCS regions.

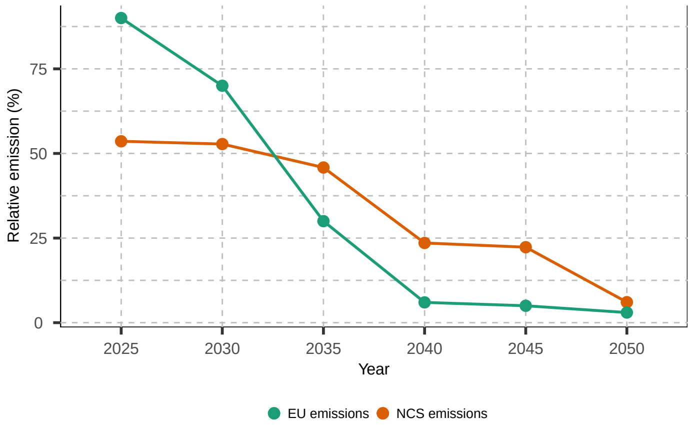


FIGURE 6: EMISSIONS OF THE NCS AND THE EUROPEAN ENERGY SYSTEMS.

5.1.3 Emissions. The relative changes in emissions in the EU and the NCS are presented in Figure 6. The reference initial emissions in 2020 are 5.51 Mt/yr [9] and 1,100 Mt/yr [22] for the NCS and the Europe respectively. All regions are governed by one emission constraint. EU emissions show the European emissions reduction relative to the initial total European emissions. Furthermore, NCS emissions show the emissions reduction of the NCS relative to initial NCS emissions. We can see that the NCS relative emissions decrease faster than Europe in 2025 and 2030. This result shows that almost half of the NCS emissions can be cut by 2030, aligning with stated climate goals. However, after 2030 the relative emission of Europe reduces faster than that of NCS. This may suggest that the first half of the NCS emission is cheaper to cut than the first half of the EU emissions. However, achieving zero emission in the NCS offshore energy system is more expensive than in the European onshore system in terms of costs per CO_2 reduced. Because of that, the model chooses to cut more emissions from the European onshore system to align with the predefined emission target in the later planning horizon. We also notice that the emissions target binds nearly all the time, and no extra emissions are cut.

5.1.4 NCS offshore grid connection. From Figure 7, we can see a possible development of an NCS grid towards zero emission. Until 2035, the offshore platform clusters mainly operate in isolation except for one connection between NOO1 and NOO2. However, starting from 2040, each platform cluster

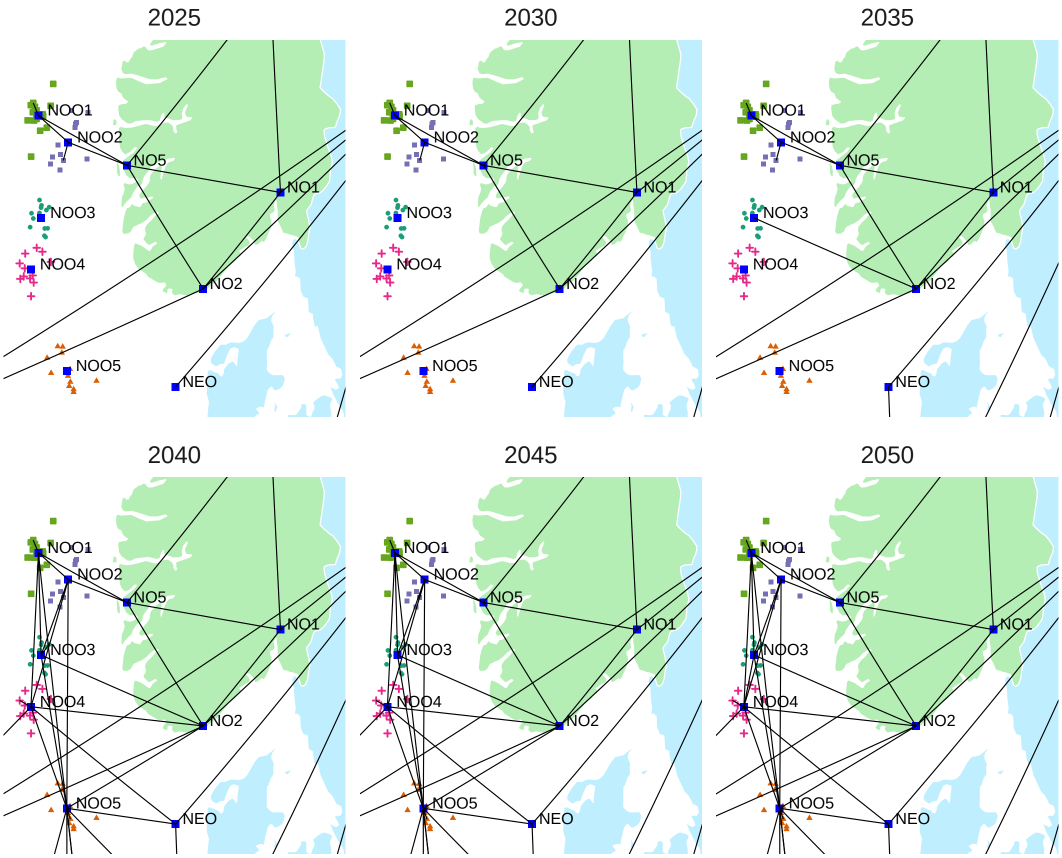


FIGURE 7: THE NCS GRID DESIGN TOWARDS 2050.

is connected to at least three other clusters. This may suggest that offshore grid design is essential for decarbonising the system towards zero emission. In 2050, the five platform clusters are fully connected. In addition, we notice that NOO4 and NOO5 are also connected with other offshore regions such as NEO and WEO. We do not include analysis of those connections due to the scope of the paper. Note that hydrogen storage is not seen in this case because no hydrogen load or hydrogen market is included. The platform clusters may be less connected when hydrogen storage is locally deployed to balance out the wind variation.

6. SUMMARY AND FUTURE WORK

This paper has presented a multi-horizon stochastic MILP model for the multi-period investment planning of a decarbonised NCS energy system. Operational uncertainties, including wind and solar capacity factors, oil and gas platforms production, onshore power load and hydro power production limits, were considered. Future hydrogen market or demand is not considered. We used the multi-horizon approach to reduce the problem size. The main conclusions are: (a) offshore energy hubs are essentially wind power generation, conversion and distribution hubs, (b) a combination of offshore wind and power from shore may be a cost efficient way for the decarbonisation of the NCS energy system, and a total of 1.6 GW offshore wind may be deployed in the NCS for a near zero emission system, (c) offshore grid design is crucial for offshore decarbonisation by distributing wind power efficiently; 2040 may be a turning point that large-scale interconnections among platform clusters become necessary and the platform clusters may be fully connected by 2050, and (d) the emissions reduce faster in the NCS energy system than in the European power system in the first planning stages but opposite in the later stages; by 2050, 94% and 97% emissions are cut in the NCS energy system and the European power system compared with their emissions in 2020.

Although the current model with short-term uncertainty can help make investment decisions that can better cope with short-term system variation, long-term uncertainty affects investment planning. Therefore, in future studies, we aim to consider long-term uncertainty such as CO_2 tax and CO_2 budget. Additionally, we noticed the large computational burden when solving the planning problem using a commercial solver. Including long-term uncertainty will make such a problem essentially a multi-stage stochastic MILP that can be intractable. Therefore, applying decomposition schemes may be necessary to solve such planning models incorporating both long-term and short-term uncertainty.

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APPENDIX A. HISTORICAL CAPACITIES AND COSTS OF TECHNOLOGIES

TABLE 2: CAPEX, VAROM AND FIXOM OF TECHNOLOGIES [30].

Technology	CaPeX (MEUR/GW, MEUR/GW/km for transmission lines)						VarOM (€/MWh)	FixOM (€/MW)
	2020	2025	2030	2035	2040	2045		
Lignite	1800.00	1800.00	1800.00	1800.00	1800.00	1800.00	3.00	5% of CaPeX
Lignite CCS adv	2600.00	2600.00	2530.00	2470.00	2400.00	2330.00	3.28	
Lignite CCS sup	3799.23	3799.23	3799.23	3799.23	3799.23	3799.23	1.18	
Coal	1600.00	1600.00	1600.00	1600.00	1600.00	1600.00	2.40	
Coal CCS adv	2500.00	2500.00	2430.00	2370.00	2300.00	2230.00	2.46	
Coal CCS	3550.00	3550.00	3350.00	3350.00	3250.00	3250.00	7.30	
Gas OCGT	400.00	400.00	400.00	400.00	400.00	400.00	2.31	
Gas CCGT	720.00	720.00	690.00	690.00	660.00	660.00	2.31	
Gas CCS adv	1350.00	1350.00	1330.00	1310.00	1290.00	1270.00	1.85	
Gas CCS	1750.00	1750.00	1625.00	1625.00	1500.00	1500.00	2.90	
Oil	320.00	320.00	320.00	320.00	320.00	320.00	2.76	
Bio 10 cofiring	1600.00	1600.00	1600.00	1600.00	1600.00	1600.00	0.48	
Bio 10 cofiring CCS	2600.00	2600.00	2530.00	2470.00	2400.00	2330.00	3.28	
Nuclear	6000.00	6000.00	6000.00	6000.00	6000.00	6000.00	7.50	
Wave	6100.00	6100.00	3100.00	3100.00	2025.00	2025.00	0.10	
Geo	4970.00	4970.00	4586.00	4586.00	3749.00	3749.00	0.32	
Hydro regulated	3000.00	3000.00	3000.00	3000.00	3000.00	3000.00	0.32	
Hydro run-of-the-river	2450.00	2450.00	2400.00	2400.00	2350.00	2350.00	0.00	
Bio	2000.00	2000.00	1800.00	1800.00	1700.00	1700.00	3.56	
Wind onshore	1295.00	1295.00	1161.00	1161.00	1010.00	1010.00	0.18	
Solar	710.00	710.00	663.00	663.00	519.00	519.00	0.00	
Waste	2030.00	2030.00	2013.00	2013.00	2005.00	2005.00	0.82	
HVAC	0.66	0.66	0.60	0.60	0.60	0.60	0.00	
HVDC	2.77	2.77	2.16	2.16	1.55	1.55	0.00	

TABLE 3: FUEL COSTS OF TECHNOLOGIES [30].

Technology	Fuel cost (€/MWh)					
	2025	2030	2035	2040	2045	2050
Lignite	5.04	5.04	5.40	5.40	5.40	5.40
Lignite CCS adv	5.04	5.04	5.40	5.40	5.40	5.40
Lignite CCS sup	5.04	5.04	5.40	5.40	5.40	5.40
Coal	8.59	10.26	12.31	13.04	13.59	14.08
Coal CCS adv	8.59	10.26	12.31	13.04	13.59	14.08
Coal CCS	8.59	10.26	12.31	13.04	13.59	14.08
Gas OCGT	28.96	31.34	34.08	36.40	37.62	38.39
Gas CCGT	28.96	31.34	34.08	36.40	37.62	38.39
Gas CCS adv	28.96	31.34	34.08	36.40	37.62	38.39
Gas CCS	28.96	31.34	34.08	36.40	37.62	38.39
Oil	45.00	51.12	56.16	58.68	62.28	63.72
Bio 10 cofiring	10.69	12.49	14.67	15.68	16.57	17.44
Bio 10 cofiring CCS	10.69	12.49	14.67	15.68	16.57	17.44
Nuclear	3.75	3.82	3.90	3.97	4.05	4.14
Bio	29.62	32.58	35.84	39.43	43.37	47.70

TABLE 4: AGGREGATED HISTORICAL CAPACITIES OF TECHNOLOGIES [30].

Technology	Historical capacity (MW)								
	NO1	NO2	NO3	NO4	NO5	NE	EE	WE	UK
Lignite	0.00	0.00	0.00	0.00	0.00	1229.00	61317.00	1124.00	228.00
Coal	0.00	0.00	0.00	0.00	0.00	7772.00	5554.00	27126.00	11715.00
Gas OCGT	35.23	89.43	4.65	48.78	56.91	3239.50	27383.50	61355.00	17195.50
Gas CCGT	35.23	89.43	4.65	48.78	56.91	3239.50	27383.50	61355.00	17195.50
Oil	0.00	0.00	0.00	0.00	0.00	7298.00	6165.00	15693.00	1798.00
Nuclear	0.00	0.00	0.00	0.00	0.00	11399.00	21341.00	79985.00	916.00
Wave	0.00	0.00	0.00	0.00	0.00	0.00	0.00	24.00	0.00
Geo	0.00	0.00	0.00	0.00	0.00	0.00	43.00	962.00	0.00
Hydro regulated	33.50	8377.50	387.75	4569.30	533.85	1663.00	17995.00	2516.00	86.00
Hydro run-of-the-river	754.13	1914.33	87.15	144.18	1218.21	4848.00	1877.00	42898.00	121.00
Bio	7.80	19.80	9.00	1.80	12.60	7531.00	11629.00	8842.00	2524.00
Wind onshore	227.37	577.17	262.35	314.82	367.29	14592.00	67628.00	59983.00	16684.00
Solar	5.85	14.85	6.75	8.10	9.45	1617.00	53534.00	43228.00	13322.00
Waste	0.00	0.00	0.00	0.00	0.00	966.00	1996.00	349.00	85.00

TABLE 5: AGGREGATED HISTORICAL CAPACITIES OF TRANSMISSION LINES [30].

From	To	Historical capacity (MW)
NO2	NE	1640.00
NO2	UK	1400.00
NO2	NO1	2000.00
NO3	NO1	100.00
NO4	NO3	350.00
NO5	NO1	1600.00
NO5	NO2	300.00
NO5	NO3	160.00
NE	EE	2450.00
NE	NO1	1200.00
NE	NO3	650.00
NE	NO4	600.00
EE	WE	12513.00
WE	UK	3000.00
UK	NE	1400.00
NEO	NE	1120.00
EEO	EE	7166.00
WEO1	WE	357.00
WEO2	WE	3739.30
UKO1	UK	1218.00
UKO2	UK	93.20

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