TECHNICAL ANNEX

Employment opportunities from a coal-to-renewables transition in South Korea

National and provincial level employment impacts of replacing coal-fired power generation with solar, wind and storage

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Find the underlying brief *Climate Analytics, Solutions for Our Climate (2021). Employment opportunities from a coal-to-renewables transition in South Korea* for download under: https://climateanalytics.org/publications/2021/employment-opportunities-from-a-coal-to-renewables-transition-in-south-korea/

1. Overview on methodological approach and steps of the analysis

Previous studies showed that a transition towards renewable energy would entail multiple economic benefits for South Korea, including **employment creation potential**. This study goes beyond the insights from previous studies. First, to our knowledge it is the first study for South Korea to assess the employment impacts of phasing out its coal power generation in line with the Paris Agreement and directly replacing coal power generation with renewable energy. These insights are relevant in the context of the need for increased ambition from countries in the lead up to COP26 later this year.
Second, it is the first study to provide not only national level estimates but also to look into province level employment impacts. Our subnational level estimates provide a valuable starting point for a discussion on potential alternative local employment options that are newly created, initialising a Just Transition process in South Korea.

Focus of the analysis

The analysis focuses on estimating the ***direct*** **employment impacts of an accelerated South Korean coal phase out in line with the Paris Agreement**, replacing coal power with solar and wind power as well as storage, and comparing this with a **Current Policy Scenario** based on the coal pathway as laid out in the 9th Basic Plan.

While other existing power generation technologies are considered in the underlying energy system modelling to capture the total energy mix and derive storage needs[1], **we limit our results to showing employment impacts only for those technologies directly related to the coal phase out and replacement with solar and wind as well as related storage capacity**. Power generation capacity and the related jobs that are the same in both scenarios, as they are not affected by the analysed shift replacing coal with solar and wind, are not shown in our results. This includes pre-existing jobs related to solar and wind which are not stemming from the analysed coal phase out. We do not conduct an assessment of the employment impacts for transitioning the whole South Korean energy system to 100% Renewable Energy, instead we focus on replacing coal only.

We focus our results on the period until 2030 to show the relevant period for the suggested coal phase out before 2030.

For estimating the employment impacts on the national as well as provincial level that would result from an accelerated phase out of South Korean coal power plants in line with the Paris Climate Agreement, we conduct the following steps. All parts of the analysis as well as the underlying assumptions are described in detail in section 3.

1. We build on previous work[2] in which we have derived a Paris Agreement-compatible power-generation-related pathway for South Korea based on downscaling the B2DS pathway[3] accounting for relevant policy constraints to obtain an emission pathway for South Korea using the model SIAMESE. For more information on the methodology see Sferra et al. (2019) [1].
2. Also building on previous work [2], we model a unit-by-unit phase out schedules that define a ranking which coal power plant units in South Korea should be shut down in which order to fulfil the Paris Agreement compatible emission pathway derived in step 1. For the analysis at hand, we chose the ranking criteria that most carbon emission-intensive units are prioritised for decommissioning (called 'regulator perspective' in previous work). For more information on the methodology see Technical Annex of this brief that this work builds on Climate Analytics (2021) [2]. This accelerated coal-phase out schedule is contrasted with the current policy plans in South Korea as described by the 9th Basic Plan for Electricity Supply and Demand [3].

To compensate for the electricity supplied by the phased-out power plants, we model a replacement of these coal power plants by renewable energy technologies and related storage. This part of the analysis is conducted in two separate steps:

3. We conduct an analysis of the South Korean subnational potentials for solar PV rooftop and PV open field (utility-scale) as well as for offshore wind and onshore wind based on modelling with high-resolution gridded data (see section 3.2 for more details). We exploit the obtained spatially explicit information on regional solar and wind potentials to identify in which provinces in South Korea solar and wind installations would be located for our scenarios.
4. We created an electricity system model for South Korea based on the "Python for Power System Analysis" (PyPSA) framework to assess the energy mix for the analysed respective scenarios. For this, we use the results from the modelling of solar and wind potential from step 3 as well as the unit-level coal-phase out schedule from step 2. The results of the PyPSA model provide us information on how much capacity of each technology (solar PV rooftop, PV open field, offshore wind and onshore wind as well as related storage needs) will need to be installed to replace phased out coal for the given developments for other power generation technologies. Moreover, exploiting the spatially explicit information on the solar and wind potentials (from step 3) as well as the information on which coal power plants is shut down in which year (from step 2) combined with information on its geolocation (from the Global Coal Plant Tracker [4]), we obtain capacity estimates and their developments over time for each province in South Korea for the different technologies.

Building on these previous steps, we conduct an analysis of the direct employment impacts by province associated with replacing coal power plants with solar and wind power as well as storage for an accelerated coal phase out in line with the Paris Agreement as compared to the current policy pathway. We build on an employment factor approach for assessing impacts on direct jobs. The employment factor approach is a very transparent and flexible methodology and has been commonly used in the literature (see, e.g. Rutovitz et al. (2015) [5], Ram et al. (2020) [6]). The general methodology and underlying assumptions are described in more detail in section 3.3. For our employment analysis, different steps are needed:

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[2] In a Climate Analytics study from 2020 a coal phase out pathway for South Korea under the Paris Agreement was derived [43]. In another study earlier this year, unit-level-phase out schedules for coal have been analysed assessing the impacts on air pollution and health [2].

[3] Climate Analytics modelled a Paris Agreement consistent emission reduction pathway for coal generation in South Korea based on a downscaling model applied to the IEA's Energy Technology Perspectives "Beyond 2°C Scenario", taking into account historical emissions until 2019. This pathway has been assessed by Climate Analytics to have characteristics that are consistent with the Long-Term Temperature Goal of the Paris Agreement. The Paris Agreement establishes a global commitment to limit warming "well below 2°C" and to pursue efforts to limit warming to 1.5°C.

5. Whenever data availability allows, we empirically derive own South-Korea specific employment factors for our analysis. In case this is not possible, we apply employment factors from the literature.
6. Using the results of the PyPSA model providing installed and added as well as retired capacity for each technology and province (step 4) and applying the employment factors from step 5, we estimate the resulting direct jobs differentiating between different job types (local manufacturing, construction and installation, operation and maintenance) and the different power generation technologies that are relevant for our analysis.
7. We assign the employment estimates to the province level exploiting information from the spatially explicit modelling of solar and wind potentials as well as the geolocation of coal power plants.

2. Scenario Description

In December 2020, the Korean Ministry of Trade, Industry and Energy published the 9th Basic Plan for Long-term Electricity Supply and Demand (short '9th Basic Plan') [3]. It provides projections for energy demand developments and defines policy plans for capacity developments for different electricity generation technology groups until the end of the planning period in 2034. While President Moon had announced in a speech in October 2020 that South Korea aims to become carbon neutral by 2050 and to replace coal power with renewable energy, the 9th Basic Plan still foresees that coal power generation capacity would amount to 29 GW at the end of the planning horizon in 2034.

To illustrate the job potential that could be created from an accelerated phase-out of coal-fired power generation compatible with the Paris Agreement, we model two scenarios that represent different trajectories with regard to the role and timing of phasing out coal-fired power generation in South Korea. The current policy plans for coal are modelled in the *Current Policy (CPol)* scenario. This is contrasted with *a Coal-to-Renewables (CtR)* scenario in which an accelerated coal phase-out occurs by 2029. The underlying assumptions for both scenarios are outlined in more detail below.

Focusing on the role of coal, both scenarios share a range of common assumptions. Electricity demand is identical in both scenarios and is assumed to follow the projections for demand[4] from the 9th Basic Plan. In both scenarios, it is assumed that electricity supply needs to cover demand plus a stability reserve, which increases from 17% to 22%. Transmission and distribution are not explicitly modelled. For the assumptions on renewable energy costs used as an input for the techno-economic optimisation of the electricity system, we assume medium renewable energy cost projections provided by IRENA. Moreover, the capacity development of power generation technologies not directly resulting from the suggested accelerated shift from coal to renewable energy follow the developments outlined in the 9th Basic Plan in both scenarios. While this other power generation capacity is taken into account in the optimisation in PyPSA, we assume these to be given exogenously, and thus no employment impacts are analysed with respect to this capacity. Since the respective capacity is exactly the same in both scenarios, these employment effects are also identical between scenarios.

[4] The electricity demand curve is rescaled to match the total electricity demand as well as peak demand forecast assumptions in demand scenario 1 of the 9th Basic Plan for Electricity Supply and Demand. We use the high demand scenario from the 9th Basic plan for our analysis to be conservative in the sense that the energy system would be able to cover higher demand projections.

Current Policy (*CPol*) Scenario

The ***Current Policy (CPol)* scenario** is based on assumptions largely derived based on the projections for energy demand developments as well as planned developments for different electricity generation technology aggregates from the 9th Basic Plan for Long-term Electricity Supply and Demand [3]. We highlight the main characteristics of the *CPol* scenario below.

Development of power generation capacity *in the CPol* scenario:

- ***Coal power generation capacity*** is exogenously defined by the coal trajectory given in the 9th Basic Plan defining envisioned shut down (or conversion) dates for specific units. 24 units of coal-fired power plants are defined to be replaced by natural gas by 2034, following the dates which coal power units are planned to be converted by which year as defined in the 9th Basic Plan.
- ***Natural gas power generation capacity*** is also exogenously given following the planned capacity developments defined in the 9th Basic Plan. Total installed natural gas capacity increases to 59 GW in 2034, including the natural gas capacity stemming from the conversion of coal-power capacity into natural gas power plants.
- ***Power generation capacity for renewable energy and related storage needs*** are derived by optimising wind (onshore and offshore) and solar PV (utility-scale and rooftop) capacity, as well as electricity storage, with a PyPSA model, which i) covers the electricity demand projections from the 9th Basic plan plus an additional stability reserve and ii) follows the total installed renewable energy capacity pathway defined in the 9th Basic Plan, which increases to 78 GW in 2034.
- ***Power generation capacity for other technologies*** are also modelled as defined in the 9th Basic plan. This includes the categories nuclear, pumped hydro, as well as other less relevant technologies.

Coal-to-Renewables (*CtR*) scenario of an accelerated coal phase-out in line with the Paris Agreement

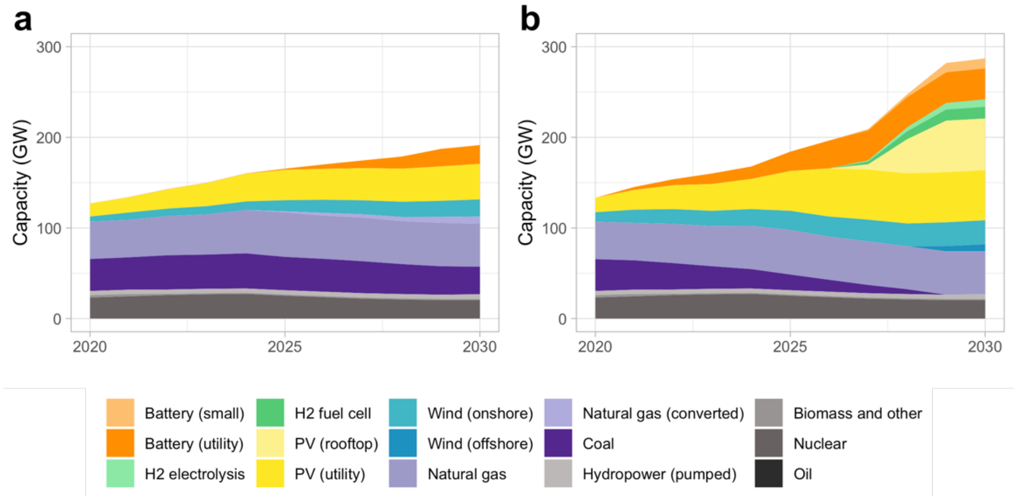
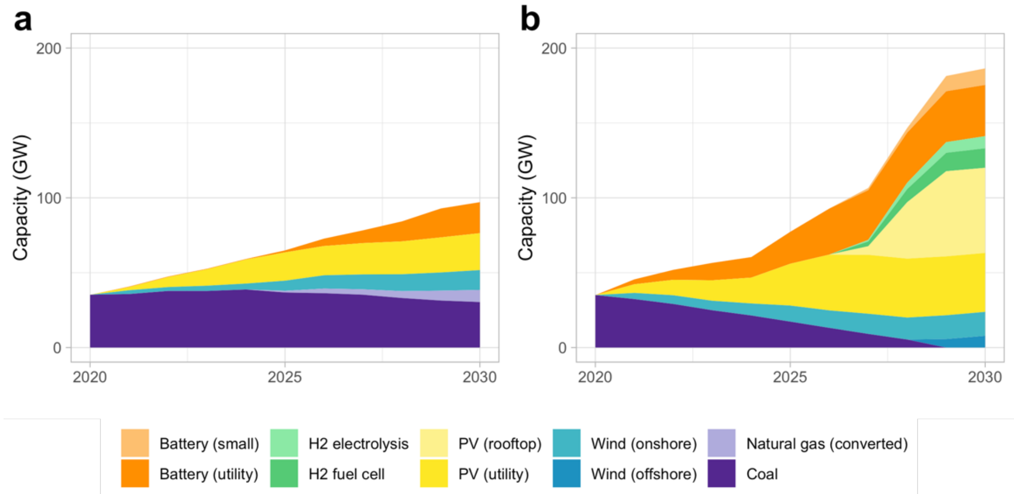
The **Coal-to-Renewables (*CtR*) scenario** sees coal phased out from the power system by 2029 (in line with benchmarks consistent with the Paris Agreement), and a direct replacement of phased-out coal capacity by renewables coupled with storage. The scenario is based on previous work[5] which derived a coal phase out schedule for South Korea in line with the long-term temperature limit as defined in the Paris Agreement. This is also in line with other work conducted by Climate Analytics and others on Paris-Agreement compatible pathways, finding that coal will need to be phased out before 2030 [7]. We highlight the main scenario characteristics of the *CtR* scenario below.

Development of power generation capacity *in the CtR* scenario:

- ***Coal power generation capacity*** is defined by the coal capacity trajectory given by the unit-level phase out schedule in line with the Paris Agreement. Using the 'regulator perspective, this unit-level phase out schedule defines which coal power plants need to be taken offline in which year in order to be Paris Agreement compatible prioritising the shutdown of more carbon emission-intensive units.
- ***Natural gas power generation capacity*** follows the trajectory of the *CPol* scenario for those natural gas capacity additions that are *not* stemming from the conversion of coal power into natural gas power plants as defined in the 9th Basic Plan. In contrast to the *CPol* scenario, those power plant units that the 9th Basic Plan foresees to be converted into natural gas are shut down and are replaced with wind and solar capacity instead of being converted to natural gas. As a consequence, developments for natural gas capacity which is not related to the conversion of coal power plants into natural gas are assumed identical in the *CPol* scenario and in the accelerated coal phase out scenario, as this analysis focuses on the employment opportunities from phasing out coal-fired power generation.
- ***Power*** generation capacity for renewable ***energy and related storage needs*** are derived by optimising wind (onshore and offshore) and solar PV (open field and rooftop) capacity, as well as electricity storage, with a PyPSA model, which i) covers the electricity demand projections from the 9th Basic plan plus an additional stability reserve and ii) remains below a Paris Agreement compatible CO_2 emissions pathway of the power sector.
- ***Power generation capacity for other technologies***, including nuclear, biomass, and pumped hydro, are also modelled as defined in the 9th Basic plan and are thus following the same assumptions as in the *CPol* scenario. As a consequence, the employment impacts related to those technologies are neglected in this analysis as they are identical between both scenarios.

[5] In a Climate Analytics study from 2020 a coal phase out pathway for South Korea under the Paris Agreement was derived [43]. Based on this, in another study in 2021, unit-level-phase out schedules for coal have been analysed assessing the impacts on air pollution and health [2].

Table 1 Electricity generation capacity developments under the CPol and the CtR scenarios: Full capacity as included in the modelling (top) and capacity directly related to coal phaseout as considered in employment analysis (below)

	Current Policies (*CPol*) scenario	Coal-to-Renewable (CtR) scenario
Capacity as modelled (full power system)		
Capacity directly associated with coal phase out (as considered in employment analysis)		

Note: PyPSA models the power generation system until 2034, covering the whole period of the 9th Basic Plan. For the employment analysis, we focus on the time horizon until 2030, while the information from PyPSA on post-2030 capacity additions is taken into account for upstream jobs such as manufacturing or construction and installation. Hydrogen storage capacity (in MWh) is not shown.

3. Methodological steps and underlying assumptions in detail

[redacted] Unit-level phase out schedules for South Korean coal power plants

A detailed description of the methodology of how the unit-level-phase out schedule has been derived can be found in the Technical Annex of a previous brief [2]. For the employment analysis, we focus on the 'regulator perspective' unit-level phase out schedule. Table 2 shows the ranking in which the coal units are phase out in the Coal-to-Renewables (*CtR*) scenario as compared to the policy retirement (Current Policy (*CPol*) scenario).

Table 2: Unit-level coal power plant phase out schedule

Unit Name	Policy Retirement	CtR-Scenario Retirement	Emission Intensity ($g\ CO_2$ / kWh)
Boryeong #1	2020	2020	1045.552
Boryeong #2	2020	2020	1045.552
Donghae #1	2028	2020	1256.639
Donghae #2	2029	2021	1166.901
Honam #1	2021	2021	1175.02
Honam #2	2021	2021	1175.02
Samchonpo #1	2021	2021	1012.987
Samchonpo #2	2021	2021	1012.987
Taean #2	2025	2022	939.6995
Samchonpo #4	2024	2021	972.3855
Samchonpo #3	2024	2021	972.3855
Dangjin #3	2030	2023	861.3834
Yeosu #1	2046	2022	881.4979
Taean #4	2029	2022	939.6995
Dangjin #4	2030	2023	861.3834
Gangreung Anin #1	2052	2026	795.0736
Gangreung Anin #2	2052	2026	795.0736
Taean #3	2028	2022	939.6995
Dangjin #1	2029	2024	861.3834
Gosung Hai #1	2051	2026	795.0736
Gosung Hai #2	2051	2026	795.0736
Samcheok Greenpower #2	2047	2027	795.0736
Yeosu #2	2041	2021	1094.004
Taean #1	2025	2022	939.6995
Boryeong #3	2043	2021	969.909
Dangjin #9	2045	2028	770.3096
Yeongheung #1	2034	2024	861.3834
Dangjin #2	2029	2024	861.3834
Dangjin #8	2037	2024	847.3219
Dangjin #7	2037	2025	847.3219
Yeongheung #2	2034	2024	861.3834
Dangjin #10	2046	2029	770.3096

Taean #10	2047	2029	770.3096
Bukpyeong #2	2047	2023	867.3625
Bukpyeong #1	2047	2023	867.3625
Boryeong #4	2043	2021	969.909
Taean #7	2037	2025	847.3219
Boryeong #5	2025	2021	969.909
Boryeong #6	2025	2022	969.909
Dangjin #6	2036	2023	874.5617
Taean #5	2032	2024	861.3834
Hadong #1	2026	2022	939.6995
Hadong #2	2027	2022	939.6995
Dangjin #5	2035	2023	874.5617
Hadong #3	2028	2022	939.6995
Yeongheung #5	2044	2028	783.0674
Yeongheung #6	2044	2028	783.0674
Hadong #4	2028	2024	861.3834
Hadong #5	2031	2024	861.3834
Hadong #6	2031	2024	861.3834
Samchonpo #5	2027	2022	969.909
Shin-Seocheon	2051	2027	795.0736
Boryeong #8	2038	2023	874.5617
Samcheok Greenpower #1	2046	2027	795.0736
Sinboryeong #2	2047	2027	795.0736
Samchonpo #6	2028	2022	969.909
Samcheok PosPower #1	2054	2025	808.2415
Samcheok PosPower #2	2054	2025	808.2415
Yeongheung #4	2038	2029	770.3096
Sinboryeong #1	2047	2028	795.0736
Taean #8	2037	2025	847.3219
Taean #9	2046	2029	770.3096
Taean #6	2032	2024	861.3834
Boryeong #7	2038	2023	874.5617
Yeongheung #3	2038	2029	770.3096
Hadong #7	2038	2025	847.3219
Hadong #8	2039	2029	770.3096

[redacted] Modelling the transition from coal to renewable energy

MODELLING AND ASSESSMENT OF TECHNICAL POTENTIAL OF ELECTRICITY PRODUCTION FROM SOLAR AND WIND ENERGY

The technical potential has been assessed for different renewable energy sources including wind onshore, wind offshore, utility-scale and rooftop solar PV by applying the temporally and spatially resolved simulation models of the open-source python packages GLAES[6] (Geospatial Land Eligibility for Energy Systems) and RESKit[7] (Renewable Energy Simulation Toolkit) [8]. These models have been used and improved throughout recent studies to assess the future European wind onshore and offshore potential [9]–[11] as well as a wind energy potential analysis of Argentina's Patagonian area [12]. The renewable modelling framework provides for a regional context based on global data sets for land eligibility and weather data depending on a technology selection, maximum RES potentials (onshore/ offshore wind; rooftop/open-field PV), generation time series for each renewable group, and depending on cost projections a cost assessment (e.g. LCOE).

As the first step, the land eligibility analysis evaluates the amount and distribution of land which is eligible for renewable energy sources based on a comprehensive set of exclusion factors and constraints informed from the land eligibility literature review. These reflect the most common (socio-political, physical, conservation pseudo-economic) constraints for placement of wind turbines and PV modules commonly considered in renewable potential studies. Once the distinction is made between available and excluded areas, the placement algorithm identifies individual turbine/PV module locations within the eligible areas followed by hourly simulation of generation profiles. Table 3 provides an overview of exclusion factors applied through this analysis for different renewable technologies.

Table 3: Underlying assumptions and parameter choices for modelling of wind and solar potential

Technology	Aspect	Description	Assumption and parameter choice (exclusion limits)	Source
Wind onshore	Regional boundaries	500m buffer distance from regional boundaries excluded	≤ 500 m	Heuser et al. (2019) [12]
	Primary roads	500m buffer distance from primary roads excluded	≤ 500 m	Heuser et al. (2019) [12]
	Railways	500m buffer distance from railways excluded	≤ 500 m	Heuser et al. (2019) [12]
	Waterways (Rivers)	150m buffer distance from waterways excluded	≤ 150 m	Heuser et al. (2019) [12]
	Airports	5000m buffer distance from airports excluded	≤ 5000 m	Ryberg (2019), Ryberg et al. (2020), Ryberg et al. (2019), Heuser et al. (2019) [8]–[10], [12]
	Urban settlements	1000m buffer distance from urban settlements excluded	≤ 1000 m	Heuser et al. (2019) [12]

[6] Find more information on https://github.com/FZJ-IEK3-VSA/glaes

[7] Find more information on https://github.com/FZJ-IEK3-VSA/RESKit

	Woodlands	300m buffer distance from woodlands (tree cover, broadleaved, needle leaved, mixed leaf type) excluded	≤ 300 m	Heuser et al. (2019) [12]
	Water bodies	1000m buffer distance from water bodies excluded	≤ 1000 m	Heuser et al. (2019) [12]
	Protected areas	1000m buffer distance from protected parks, monuments, reserves, and wildernesses excluded	≤ 1000 m	Heuser et al. (2019) [12]
	Bird protected areas	1500m buffer distance from protected habitats and bird areas excluded	≤ 1500 m	Heuser et al. (2019) [12]
	Elevation	Terrain elevation above 1500 m excluded.	≥ 1500 m	Heuser et al. (2019) [12]
	Terrain Slope	Areas with a terrain slope angle above 17° excluded.	≥ 17°	Ryberg (2019), Ryberg et al. (2020), Ryberg et al. (2019) [8]–[10]
Wind offshore	Water depth	Water depths greater than the maximum (200m) excluded	≥ 200 m	RE White paper translation
	Distance to shore	5000 m buffer distance from shore excluded.	≤ 5000 m	Own assumption based on regional aspects and ranges given in literature [11], [13]
	Protected areas	3000 m buffer distance from protected areas excluded	≤ 3000 m	Caglayan et al. (2019) [11]
	Bird protected areas	5000 m buffer distance from bird protected areas excluded	≤ 5000 m	Caglayan et al. (2019) [11]
	Shipping routes	No data available	No exclusion applied	
Open-field PV	Primary roads	50m buffer distance from primary roads included	≤ 50 m	own assumption
	Railways	50m buffer distance from railways included	≤ 50 m	own assumption
	Airports	0m buffer distance from airports excluded	≤ 0 m	own assumption based on Ryberg (2019) [8]
	Urban settlements	500m buffer distance from urban area excluded	≤ 500 m	own assumption
	Woodlands	0m buffer distance from woodlands (tree cover, broadleaved, needle leaved, mixed leaf type) excluded	≤ 0 m	own assumption
	Water bodies	0m buffer distance from water bodies excluded	≤ 0 m	own assumption
	Protected areas	0m buffer distance from protected parks, monuments, reserves, and wildernesses excluded	≤ 0 m	Own assumption
	Agricultural areas	0m buffer distance from agriculture lands (cropland_rainfed, cropland_rainfed_tree_or_shrub_cover,cropland_irrigated, mosaic_cropland, mosaic_natural_vegetation) excluded	≤ 0 m	own assumption based on Ryberg (2019) [8]
	Elevation	Terrain elevation higher than 1750m excluded	≥ 1750 m	Ryberg (2019) [8]

	Slope: Total	Areas with a terrain slope angle above 10° excluded.	≥ 10°	Ryberg (2019) [8]
	Slope: North-ward	Areas with a north-facing slope angle above 3° excluded.	≥ 3°	Ryberg (2019) [8]
Rooftop PV	Population density	Only areas with a non-zero population density taken into account		Ryberg (2019) [8]

Table 4 provides an overview of assumptions made in this work regarding the baseline turbine design, which is meant to reflect the typical turbine configuration in 2020 based on the study conducted in IRENA (2019) [14]. The current range of costs for wind turbines are based on the global average values given in IRENA (2019, 2020) [14], [15]. Expected reduction in costs of wind turbines over 2030 time horizon have been obtained from IRENA (2019) [14]. The functions implemented in RESKit then derive corresponding scaling factors based on the given baseline turbine when different assumptions are made with respect to the turbine configuration for the region of interest and considered time horizon. In this study, turbine design parameters have been finally selected based on a sensitivity study, which is described in the following section.

Table 4: Underlying assumptions and parameter choices: baseline turbine technical design and economic parameters

Technology	Aspect	Assumption and parameter choice	Source
Wind onshore	Hub height	101m	BWE (2021) [16] and https://en.wind-turbine-models.com/turbines/1719-ge-general-electric-ge-4.8-158-cypress
	Rotor diameter	158m	IRENA (2019) [14]
	Capacity	4.8MW	IRENA (2019) [14]
	Specific power	245 W m^{-2}	IRENA (2019) [14]
	Capital Cost (2020)	1108 (Low) – 1473 (medium) 2019 USD/kW	IRENA (2019,2020) [14], [15]
	Capital Cost (2030)	800 (Low) – 1075 (medium) 2019 USD/kW	IRENA (2019) [14]
	Annual operating cost	2% capex	IRENA (2020) [15]
	Economic lifetime	20 years	https://www.nrel.gov/analysis/tech-footprint.html
Wind offshore	Hub height	120m	Wang et al. (2020), Onea & Rusu (2018) [17], [18]
	Rotor diameter	164m	IRENA (2019) [14]
	Capacity	10MW	IRENA (2019) [14]
	Specific power	473 W m^{-2}	IRENA (2019) [14]
	Foundation type	monopile	
	Capital Cost (2020)	2890 (Low) – 3800 (medium) 2019 USD/kW	IRENA (2019, 2020) [14], [15]
	Capital Cost (2030)	1700 (Low) – 3200 (medium) 2019 USD/kW	IRENA (2019) [14]
	Annual operating cost	2% capex	IRENA (2020) [15]
	Economic lifetime	20 years	https://www.nrel.gov/analysis/tech-footprint.html

Table 5 provides the characteristics of the PV module selected in this study for open-field and roof-top applications as well as the economic assumptions. The current range of costs for photovoltaic technology is based on the global average values given in IRENA (2019, 2020) [14], [15]. Expected reduction in costs over 2030 time horizon have been derived from IRENA (2019, 2020) [14].

Table 5: Underlying assumptions and parameter choices: selected PV module characteristics for open-field and roof-top applications

Technology	Aspect	Assumption and parameter choice	Source
PV open-field	Module name	Winaico WSx-240P6	Ryberg (2019) [8]
	P_{mp}	240.4 W	Ryberg (2019) [8]
	Area	1.663 m^2	Ryberg (2019) [8]
	Efficiency	24%	Ryberg (2019) [8]
	Technology	Polycrystalline	Ryberg (2019) [8]
	Coverage	30 m^2_{land} kWp^{-1}	Own assumption based on the insights from Ryberg (2019) [8]
	Type (fixed tilt/single axis tracking)	Fixed-tilt	
	Capital Cost (2020)	714 (Low) – 995 (medium) 2019 USD/kWp	IRENA (2020) [15]
	Capital Cost (2030)	340 (Low) – 587 (medium) 2019 USD/kWp	IRENA (2019) [19]
	Operating Cost	1.7% capex	Ryberg (2019) [8]
	Economic lifetime	25 years	https://www.nrel.gov/analysis/tech-footprint.html
PV Rooftop	Module name	LG 360Q1C-A5	Ryberg (2019) [8]
	P_{mp}	379.4 W	Ryberg (2019) [8]
	Area	1.673 m^2	Ryberg (2019) [8]
	Efficiency	30%	Ryberg (2019) [8]
	Technology	Mono-crystalline	Ryberg (2019) [8]
	Coverage	9.1 m^2_{land} kWp^{-1}	Own assumption based on the insights from Ryberg (2019) [8]
	Type (fixed tilt/single axis tracking	Fixed-tilt	
	Capital Cost[8] (2020)	821 (Low) – 1144 (medium) 2019 USD/kWp	IRENA (2020) [15]
	Capital Cost (2030)	391 (Low) – 675 (medium) 2019 USD/kWp	IRENA (2019) [19]
	Operating Cost	1.7% capex	IRENA (2020) [15]
	Economic lifetime	25 years	https://www.nrel.gov/analysis/tech-footprint.html

[8] Costs for PV rooftop are calculated based on the ratio between PV utility and rooftop costs given both for South Korea in 2019 according to [15]

SENSTIVITY ANALYSIS ON RENEWABLE ENERGY MODELLING - OPTIMAL TURBINE DESIGN SELECTION

We perform a sensitivity analysis by varying the turbine technical design parameters over a given range to derive the cost-optimal level for hub height and rotor diameter which lead to the minimum LCOE. Table 6 provides the assumed range of turbine design parameters as well as the selected cost-optimal level obtained from the sensitivity analysis.

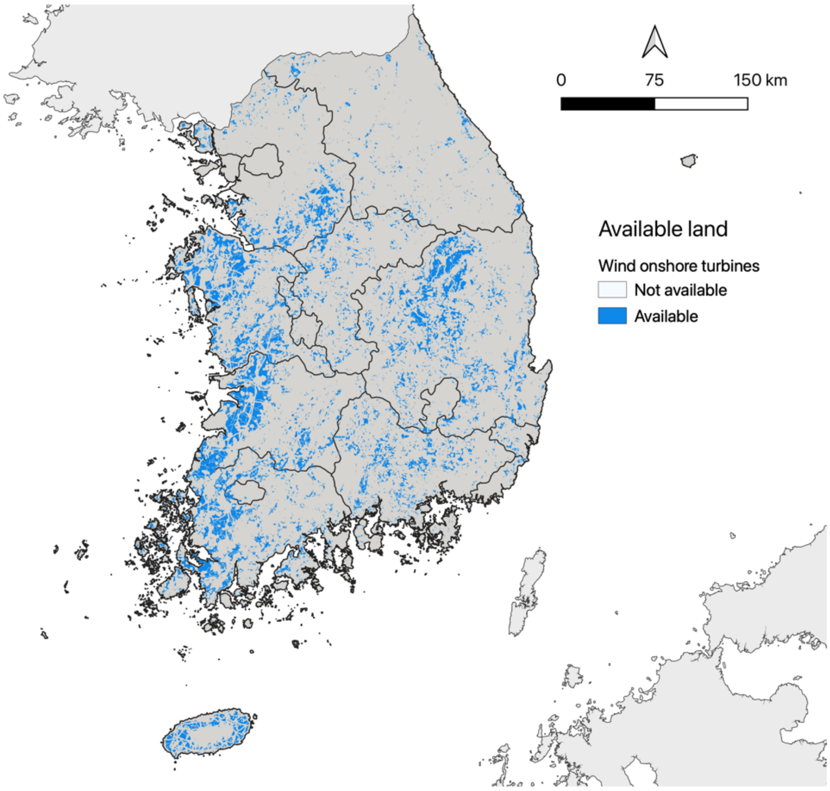
Table 6: Underlying assumptions and parameter choices: range of assumptions and selected optimal level in bold

Technology	Aspect	Assumption and parameter choice (optimal level)	Source
Wind on-shore	Hub height	80m, 88m, **99m**, 101m, 121m, 149m	Own assumptions based on the typical ranges and the optimal value derived from sensitivity analysis
	Rotor diameters	117m, 125m, 136m, 141m, **158m**	Same as above
	Capacity	1MW, 2MW, **2.4MW**, 3MW, 3.4MW, 4.2MW, 4.8MW	Same as above
Wind off-shore	Hub height	105m, 110m, 120m, 130m, 140m, 150m	Same as above
	Rotor diameter	180m, **200m**	Same as above
	Capacity	3MW, 5MW, 7MW, **9MW**, 11MW, 13MW	Same a above
	Foundation type	Fixed foundation (<100 m depth), floating foundation (≥ 100m depth)	Own assumption

VISUALISATION OF LAND / OCEAN AVAILABILITY AND LEVELISED COST OF ELECTRICITY (LCOE)

The graphical visualizations of the land availability analysis as well as the distribution of the levelized cost of electricity in 2020 are given for all four investigated renewable technologies in the following.

Wind onshore turbines



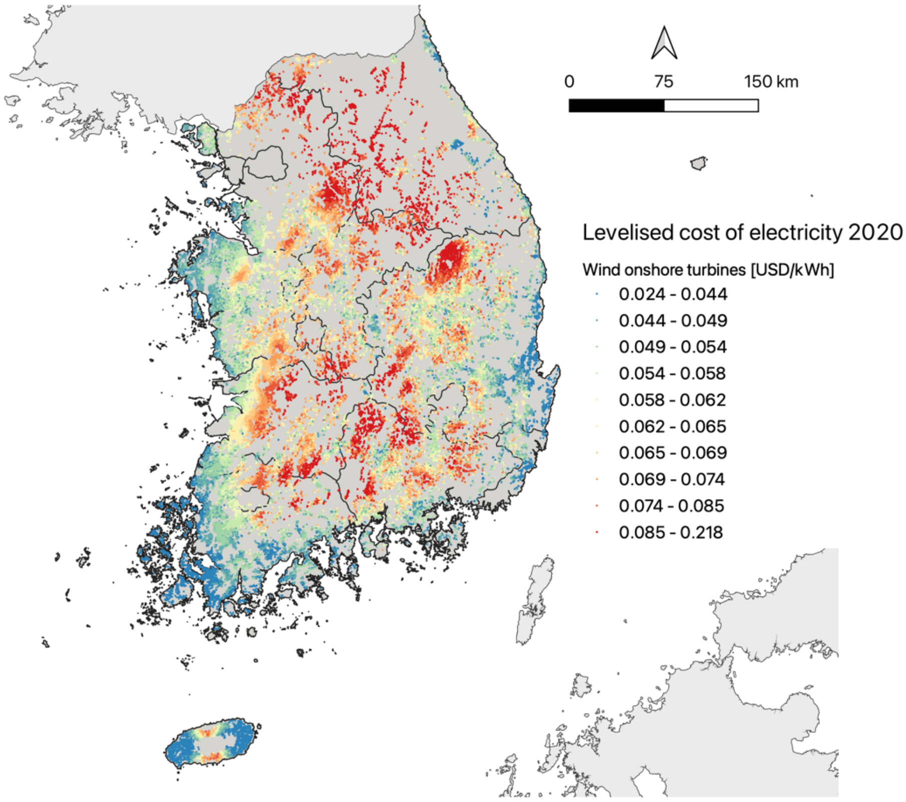


Figure 1 Available land and levelised cost of electricity (LCOE) for onshore wind turbines. The size of the individual turbine locations is enlarged to increase visibility.

Wind offshore turbines

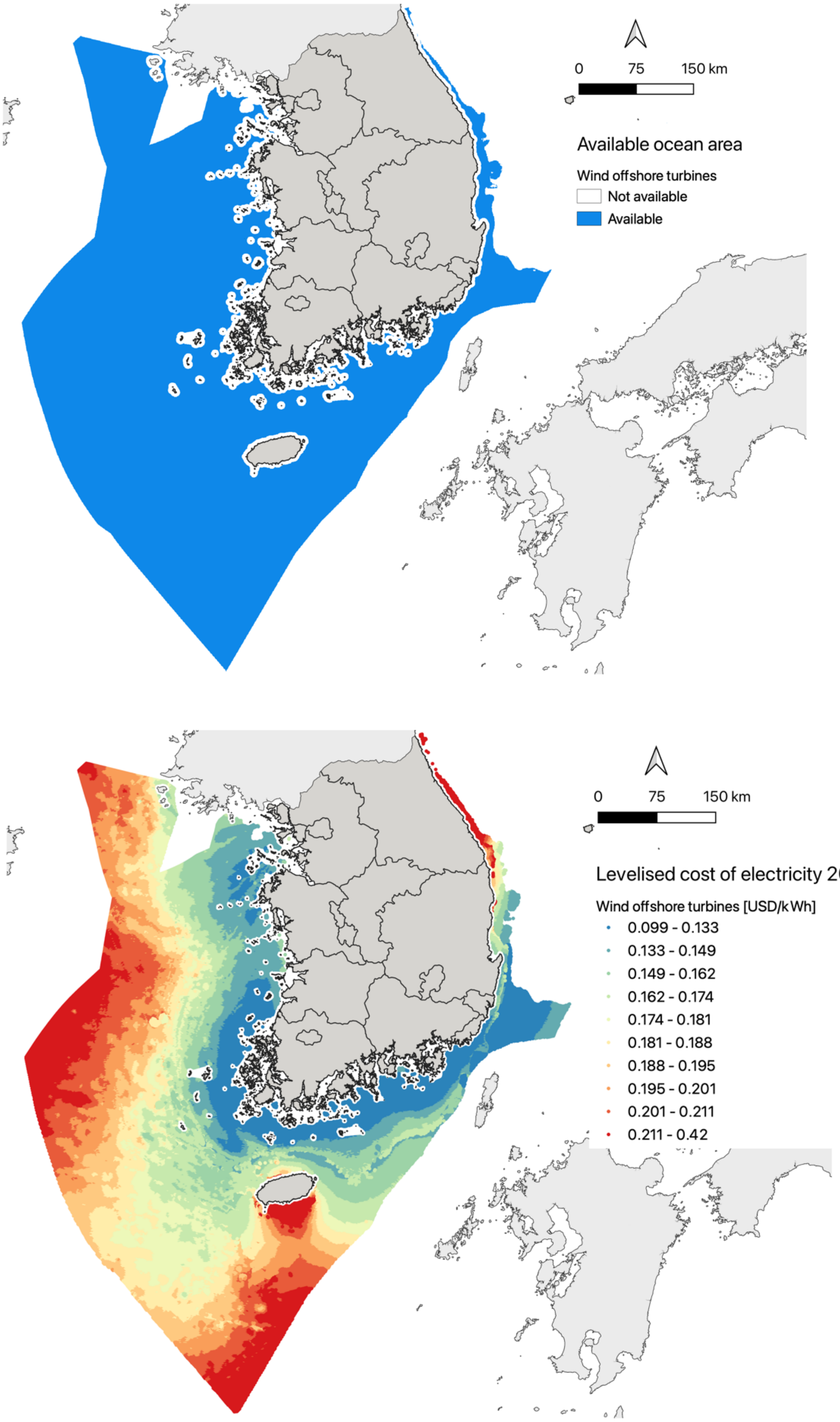
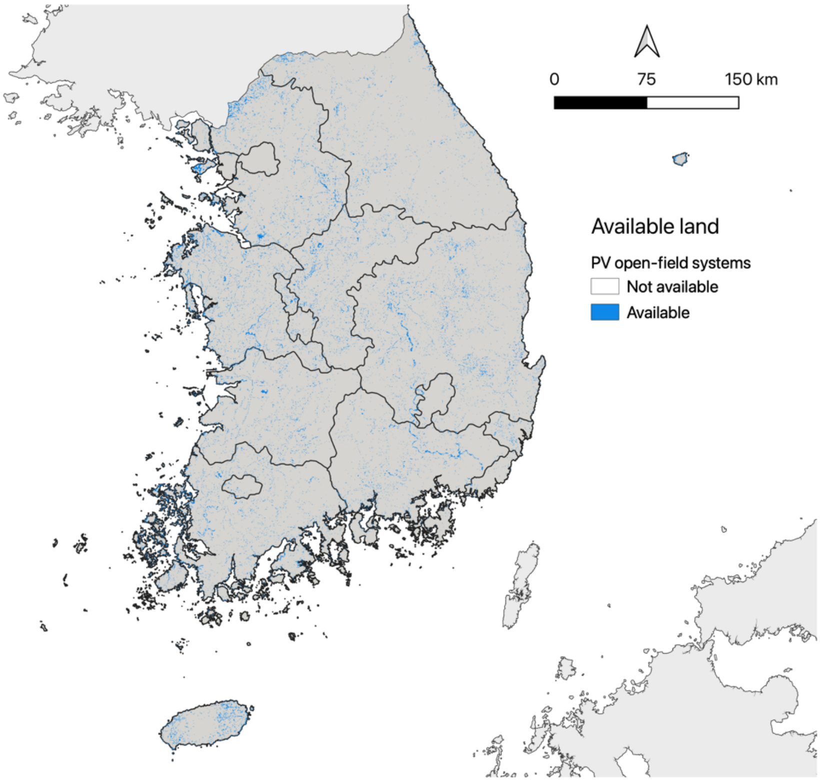


Figure 2 Available ocean area and levelised cost of electricity (LCOE) for offshore wind turbines. The size of the individual turbine locations is enlarged to increase visibility.

PV open-field systems



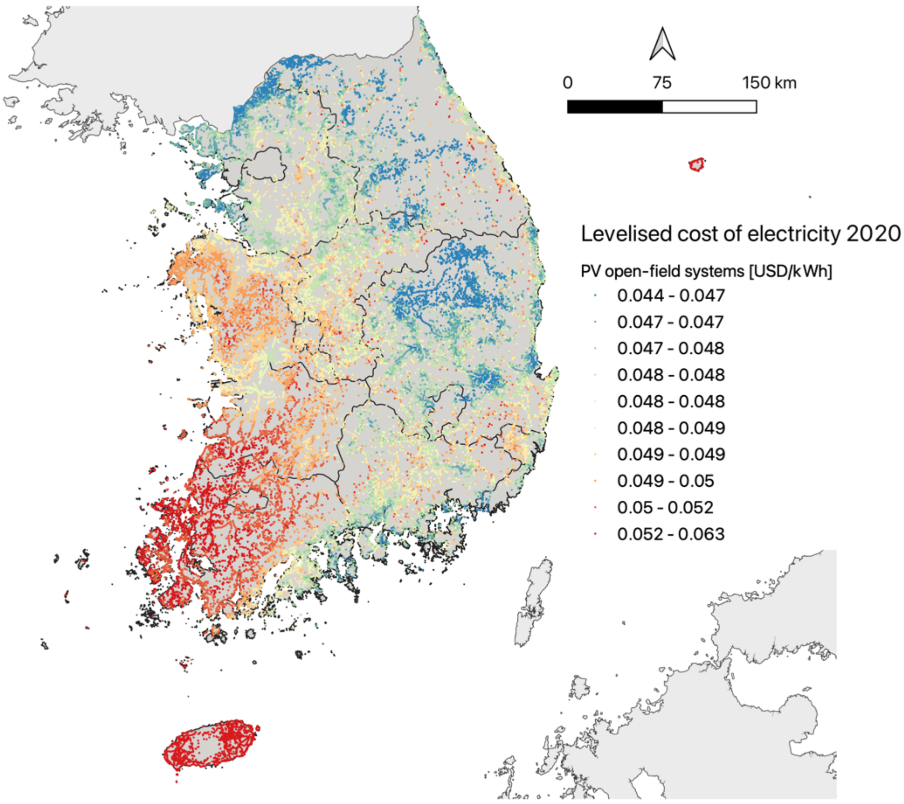
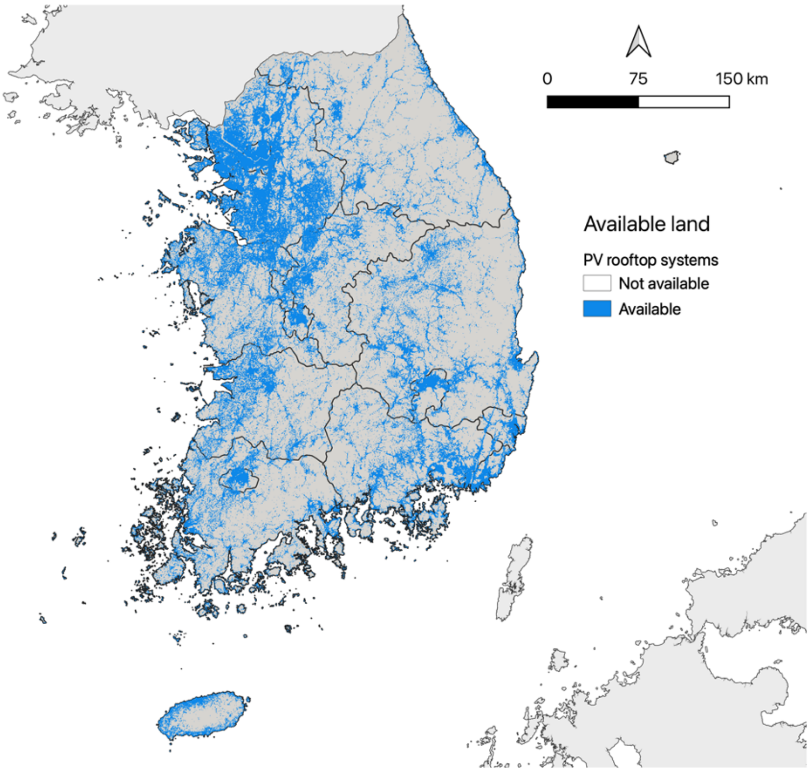


Figure 3 Available land and levelised cost of electricity (LCOE) for PV open-field systems. The size of the individual parks is enlarged to increase visibility.

PV rooftop systems



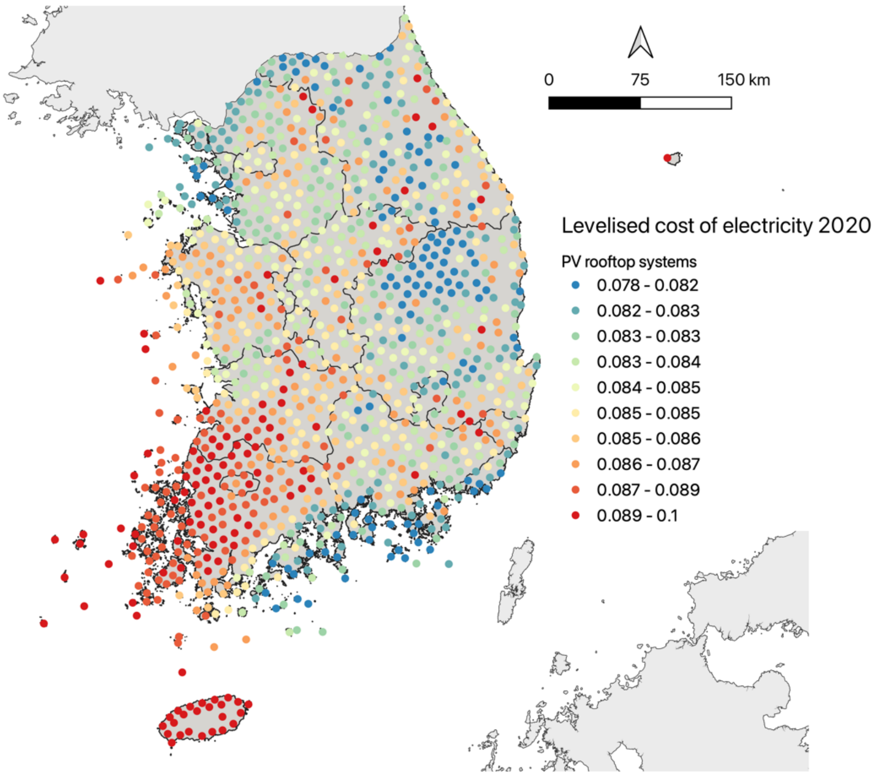


Figure 4 Available land and levelised cost of electricity (LCOE) for PV rooftop systems. The indicated spots in the lower figure only indicate the geographical distribution of the cost and do not represent individual panel distributions which are spread across residential rooftops.

ENERGY SYSTEM MODELLING WITH PYPSA

Overview

In both scenarios (*CPol* and *CtR*) a techno-economic electricity system model based on the energy system modelling framework PyPSA (Python for Power System Analysis) (see [20]) determines the cost-optimal renewable capacity, as well as the storage infrastructure, for replacing the coal plant units which are retired. PyPSA is run as a recursive-dynamic partial equilibrium model with a one-year horizon and an hourly resolution. For each given year an optimisation problem chooses capacity additions and a power generation schedule, which minimises the total system costs composed of capital, operational and fuel costs:

1. Capacity additions of the wind and solar potentials, as well as new capacity of a short-term and a long-term storage technology are chosen.
2. The renewable power generation is combined with a power generation schedule for the coal, nuclear, gas, pumped hydro storage and other technologies which settles electricity demand in each hour of the year including a reserve margin to cover stability concerns [21].
3. In the *CtR* scenario, additionally, the CO_2 emissions must be below the South Korean part of the electricity system emissions pathway of the IEA B2DS scenario.
4. In the *CPol* scenario, the renewable capacity additions must add up to the capacity of the renewable category.

The existing power generation capacity for technologies other than solar and wind are not available for retirement or extension, instead they generally follow the development in the 9th Basic Plan (see also the section "Scenario description"). *For coal capacity,* PyPSA defines the added and retired capacity over time depending on the respective scenario based on i) the information given in the Paris agreement compatible unit-level-phase out scenarios (*CtR*) ii) the phase out plan for coal is given by the coal plans from the 9th Basic Plan which foresees a slower phase out of coal as well as a partial transformation of coal power plants to natural gas power plants (*CPol*). For combined-cycle gas turbine capacity, the additions of the 9th Basic Plan are followed, except that in the *CtR* scenario, no retired coal plants are converted to natural gas plants. For the other generation technologies, i.e. nuclear reactors, pumped hydro storage, waste incineration and oil plants (grouped together as *Other*), the governmental capacity plan is adopted.

The integration of weather-dependent renewable energy generation depends on the availability of flexibility from dispatchable thermal generation technologies (gas turbines) and more importantly storage systems for smoothing short-term misbalances, like battery storage and pumped hydro storage, with an energy-to-power ratio of a few hours (1-6 hours), as well as long-term storage to move energy between weeks and seasons. The model can control the existing pumped hydro storage and additionally install utility-scale lithium-ion based batteries and home-batteries, as well as a hydrogen storage solution, consisting of an electrolyser, a pipe storage and a fuel cell.

The transmission and distribution system is not represented in the model due to limited data availability of the current capacity and topology, but also importantly, since the concrete investment needs into the distribution system depend strongly on the electrification rate of mobility and heating, which were outside of the scope of this work.

The individual components and their mathematical representation in the model are described in detail in the following subsections.

Optimisation formulation in PyPSA

The optimisation model for determining the necessary renewable generation capacity and storage configuration to replace coal is run separately for each year between 2020 and 2034, while the thermal generation capacity, as well as demand time-series changes in each year.

Table 7: Nomenclature for PyPSA

Variable	***Units***	***Definition***
n		Region labels
f		Thermal generator fuel labels (e.g. gas, coal, etc.)
s		Storage energy technology labels (e.g. battery, hydrogen, etc.)
a		Renewable generation label (open-field PV, rooftop PV, onshore wind, offshore wind)
t		Snapshot / time point labels
y		Year labels
e_f	tCO_2eq/MWh_{th}	CO_2-equivalent emissions of fuel type f
$g_{f,t,y}$	MW	Dispatch of thermal generator type f at time t in year y
$G_{f,y}$	MW	Power capacity of generator f in year y
$r_{n,a,t,y}$	MW	Dispatch of renewable generator in region n of type a at time t in year y
$R_{n,a,y}$	MW	Installed capacity of renewable generator in region n of type a in year y
$\bar{R}_{n,a}$	MW	Installable potential of renewable generation in region n of type a
$\bar{r}_{n,a,t}$	MW/MW	Power availability per unit of generator capacity
η_f	MW_{el}/MW_{th}	Efficiency of fuel type
$c^r_{n,a}$	€/MW	Generator capital (fixed) cost
$o^r_{n,a}$	€/MW	Renewable generator operating (variable) cost
o^g_f	€/MWh	Thermal Generator operating (variable) cost
$h_{s,t,y}$	MW	Dispatch of storage with carrier s at time t in year y
$H_{s,y}$	MW	Power capacity of storage s in year y
$e_{s,t,y}$	MWh	Storage state of charge (energy level)
$E_{s,y}$	MWh	Storage energy capacity
c^h_s	€/MW	Storage power capacity cost
$\hat{c}^h_s$	€/MWh	Storage energy capacity cost
$d_{t,y}$	MW	Electrical load at time t in year y
ν		Reserve margin

Objective function of PyPSA

PyPSA minimises total electricity system costs, which include the variable and fixed costs of generation, storage and transmission, given technical and physical constraints.

The objective function is given by;

$$\min_{R_{n,a,y},H_{s,y},E_{s,y}\, g_{f,t,y},r_{n,a,t,y},h_{s,t,y}} \Big[\sum_{n,r} c^{r}_{n,a} \cdot R_{n,a,y} + \sum_{s} c^{h}_{s} \cdot H_{s,y} + \hat{c}^{h}_{s} \cdot E_{s,y}$$
$$+ \sum_{n,a,t} o^{r}_{n,a} \cdot r_{n,a,t,y} + \sum_{f,t} o^{g}_{f} \cdot g_{f,t,y} \Big]$$

It consists of the renewable generator capacity $R_{n,a,y}$ in each region n for technology a and their annuitised fixed costs per capacity $c^{r}_{n,a}$, the storage unit power capacity $H_{s,y}$ and store energy capacity $E_{s,y}$ for storage technology s and their associated fixed costs c^{s}_{s} and $\hat{c}^{s}_{n,s}$, the dispatch $r_{n,a,t,y}$ of the renewable technology a at time t and the associated variable costs $o^{r}_{n,a}$, the dispatch $g_{f,t,y}$ of the thermal generation for fuel f at time t and the associated variable costs o^{g}_{f}. The optimisation is run over multiple time periods t representing different weather and demand conditions. The investment costs are annuitised for the total period (8760 hours of a full year).

Table 8: Cost and technology assumptions for thermal generators

Technology	Variable O&M Euro / MWh_{el}	Fuel Euro / MWh_{th}	Efficiency	CO_2 intensity kg CO_2 / MWh_{th}
Coal	3.5 [a]	8.15 [b]	0.33 [a]	0.34 [c]
Nuclear	3.5 [a]	2.6 [a]	0.33 [a]	
CCGT	4.4 [a]	20.1 [b]	0.47 [c]	0.2 [c]
Other (Oil/Waste)	2.1 (25.9) [d,e]	7 (-) [d,e]	0.3 (0.23) [d,e]	0.4 [c]

[a.] [22]. [b.] [23]. [c.] [24]. [d.] [25]. [e.] In our modelling *Other* was attributed to Biomass instead of *Waste/Oil*. As this is only a very minor share of the overall capacity, the influence on results is negligible. However, in parentheses we added a suggested alternative parameter choice.

Constraints implemented in PyPSA

Generation

The dispatch of thermal generators $g_{f,t,y}$ is constrained by their capacity $G_{f,y}$

$$0 \leq g_{f,t,y} \leq G_{f,y} \qquad \forall\, f, t \;(1)$$

The capacity for all fuel types is fixed exogenously for the optimisation. They are based on the 9th Basic Plan, except for coal and gas in the *CtR* scenario as described in the overview subsection and the Scenario description.

The dispatch of renewable generation in each region n $r_{n,a,t,y}$ is also constrained by their capacity $R_{n,a,y}$, but additionally by their time-dependent availabilities $\bar{r}_{n,a,t}$, which are given per unit of the capacity $R_{n,a,y}$:

$$0 \leq r_{n,a,t,y} \leq \bar{r}_{n,a,t} \cdot R_{n,a,y} \qquad \forall\, n, a, t, y \;(2)$$

For variable renewable generators such as wind and solar, $\bar{r}_{n,r,t}$ represents the weather-dependent power availability.

The renewable power capacity $R_{n,a,y}$ is optimised up to a maximum installable potential $\bar{R}_{n,a}$ and can only be increased from year to year:

$$R_{n,a,y-1} \leq R_{n,a,y} \leq \bar{R}_{n,a} \qquad \forall\, n, r, y \ (3)$$

Renewable power availability and potential are inputs from the renewable potential and generation assessment described in the previous section and are determined separately for each region n.

In the *CPol* scenario an additional constraint ensures that the total renewable generation capacity follow the pathway of the 9th Basic Plan, R_y^{9th}:

$$\sum_{n,a} R_{n,a,y} = R_y^{9th} \qquad \forall\, y \ (4)$$

Storage

The dispatch of storage units $h_{s,t,y}$, whose energy carriers are labelled by s, is constrained by a similar equation to that for generators:

$$-H_{s,y} \leq h_{s,t,y} \leq H_{s,y} \qquad \forall\, s, t \ (5)$$

except that dispatch $h_{s,t,y}$ can be both positive when discharging into the grid and negative when absorbing power from the grid. The power capacity $H_{s,y}$ can also be optimised within installable potentials.

The energy levels $e_{s,t,y}$ of all storage units have to be consistent between all hours and are limited by the storage energy capacity $E_{s,y}$

$$e_{s,t,y} = e_{s,t-1,y} + \eta_{s,+}\left[h_{s,t,y}\right]^{+} - \eta_{s,-}^{-1}\left[h_{s,t,y}\right]^{-}$$

$$0 \leq e_{s,t,y} \leq E_{s,y} \qquad \forall\, s, t \ \ (6)$$

Positive and negative parts of a value are denoted as $[\cdot]^{+} = max(\cdot\,,0)$, $[\cdot]^{-} = -min(\cdot\,,0)$. The storage units have a charging efficiency $\eta_{s,+}$ and a discharging efficiency $\eta_{s,-}$. The energy level is assumed to be cyclic, i.e. $e_{s,t=0,y} = e_{s,t=T,y}$.

The energy capacity $E_{s,y}$ can also be optimised within installable potentials, which have not been constrained for this study.

There are two types of storage technology: Lithium-ion batteries provide high-efficiency flexibility on daily time-scales while hydrogen conversion, hydrogen pipe storage and re-electrification in fuel cells provides low-efficiency seasonal flexibility.

To assess regional storage capacity expansion without explicitly modelling the transmission and distribution grids, the power flow topology for renewable generation is represented as in Figure 5. *Battery (small)* represents consumer lithium-ion home batteries, which can only be charged from *PV (rooftop)* generation. *Battery (utility)* is preferably charged with renewable generation from the same region, while energy from remote renewable capacity incurs 2% transmission loss. Electricity used for electrolysis in the hydrogen storage is exclusively generated by wind turbines or solar PV.

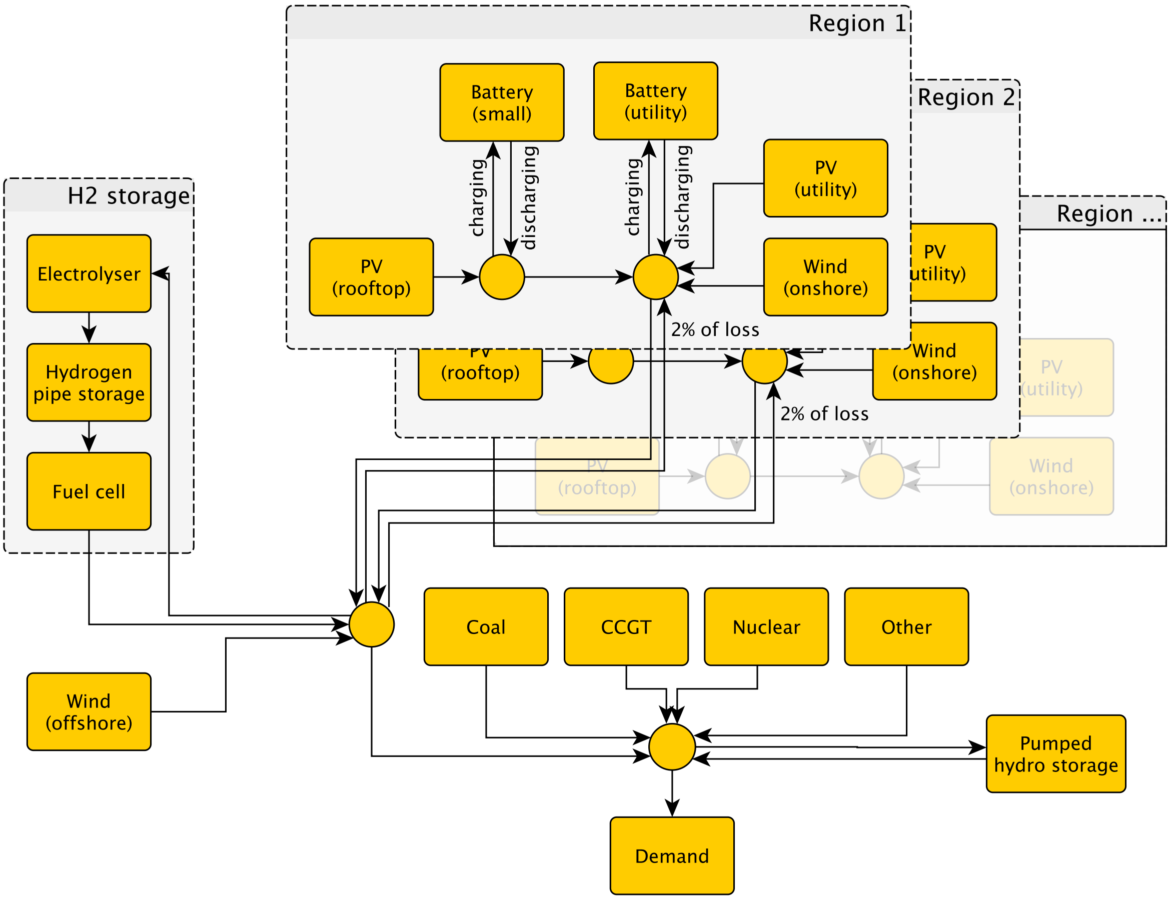


Figure 5: Power flow topology in the model. Boxes represent technologies generating, converting or consuming power and arrows show the studied energy flows and their directions.

Table 9: Cost and technology assumptions for storage options

Technology	CAPEX [a] 2020	2025	2030	Fixed O&M % of CAPEX / year	Lifetime year	Efficiency
H_2 electrolyser [b]	600	575	550	5	25	0.64 – 0.66 [c]
H_2 pipe storage [d]	7	7	7	1	30	
H_2 fuel cell [b]	1300	1200	1100	5	10	0.5
Battery storage [b]	232	187	142	-	20 – 25 [c]	
Battery inverter [b]	270	215	160	0.2 – 0.34 [c]	10	0.95 – 0.96 [c]

[a] CAPEX in Euro/kW$_e$ for power capacity and in Euro/kWh for storage capacity. [b] [25]. [c] Lower value in 2020 and higher value in 2030. [d] Own considerations based on techno-economic data for natural gas pipelines, [26] and hydrogen compressors [27], as well as on information of existing pipe storage systems, [28] and [29].

CO_2 emissions

CO_2 emissions are limited by those of a power sector emissions pathway P_y, implemented using the specific emissions e_f in tCO_2/MWh_{th} of the fuel f and the efficiency η_f of the generator:

$$\sum_{f,t} \frac{1}{\eta_f} g_{f,t,y} \cdot e_f \leq P_y \quad (7)$$

The reference emissions pathway P_y is derived by harmonising the emissions due to fuel combustion for electricity generation from the downscaled B2DS pathway. A similar harmonisation method (harmonising to latest historical (2019) CO_2 emissions from fuel combustion (IEA), while conserving the total allowed emissions) is applied to all fuels in addition to coal to ensure consistency with previous work [30].

Electricity demand

The (inelastic) electricity demand $d_{t,y}$ must be met at each time t by either thermal generators, renewable generation or storage

$$\sum_{n,a} r_{n,a,t,y} + \sum_f g_{f,t,y} + \sum_s h_{s,t,y} = d_{t,y} \qquad \forall\, t \text{ (8).}$$

The hourly electricity demand curve is derived by concatenating hourly load profiles for a day in each season scaled according to daily peak demand published at EPSIS. The hourly load profiles have been modelled by Kim et al. 2020 [21].

The electricity demand curve is rescaled to match the total electricity demand as well as peak demand forecast assumptions in demand scenario 1 of the 9th Basic Plan for Electricity Supply and Demand.

Reserve margin

A reserve margin of an additional increasing ratio ν [9] of the electricity demand $d_{t,y}$ must be potentially met as a safety precaution at each time t by either thermal generators, renewable generation or storage:

$$\sum_{n,a} \bar{r}_{n,a,t} \cdot R_{n,a,y} + \sum_f G_{f,y} + \sum_s H^{reserve}_{s,t,y} \geq (1+\nu) d_{t,y} \qquad \forall\, t, y \text{ (9)}$$

$$H^{reserve}_{s,t,y} \leq H_{s,y} \quad and \quad H^{reserve}_{s,t,y} \leq \eta_{s,+} e_{s,t,y} \quad \forall\, t, s, y \text{ (10)}$$

Where the additional variable $H^{reserve}_{s,t,y}$ prevents an empty storage from contributing to fulfilling the reserve demand.

[9] The reserve margin increases as in the 9th Basic plan from 17% until 2024, 18% until 2028 to 22%.

[redacted] Estimating the employment impacts of an accelerated coal phase out

OVERVIEW ON BASIC EMPLOYMENT FACTOR APPROACH

We apply the general approach proposed by Rutovitz and co-authors [5] which has for example been used in the Energy [R]evolution Report by Greenpeace International, Global Wind Energy Council and Solar Power Europe, assessing job opportunities from energy transition round the world [31]. The basic methodology proposes to use employment factors to assess the employment impacts of an energy transition. The general approach has been applied and extended more recently. Ram et al. (2020) explicitly include jobs in transmission and also in decommissioning of power plants [6]. In the book on achieving the Paris Agreement Climate Goals [32], Dominish et al. extend the approach by adding more detailed occupational dimensions [33]. Apart from global analyses, the approach has also been applied for specific countries with country-specific employment factors (e.g. Australia [34] or South Africa [35]). Advantages of the approach are that assumptions can be made very transparent and impact chains are clearly laid out. Moreover, it is very flexible as the employment factors can be adjusted based on local data if available.

The approach estimates direct jobs associated with electricity generation and includes jobs in manufacturing, construction & installation, operations & maintenance. Moreover, jobs in fuel supply, transmission and decommissioning can be added if relevant.

The underlying basic (simplified) rational is illustrated in Figure 6. Newly installed capacity for electricity generation in a given year create jobs in manufacturing of technology parts (to the degree these are produced with the country as defined by the local share, these are local jobs) and jobs in construction and installation of these added capacity over the construction period. The total capacity that is in place and running in a given year is contributing to jobs in operation and maintenance over the lifetime of the respective installation. To reflect 'learning', e.g. improvements in technology efficiency and maturing production techniques leading to increasing the efficiency, the employment factor can be adjusted over time with a so-called decline factor.

For the calculation of local employment in manufacturing, the share of technology parts that is manufactured within the country or region of interest has to be defined. If relevant to a country-specific context, local share assumptions can also be applied to other sectors if – for example – expertise on installation and construction or operation and maintenance cannot be covered by the country and experts from abroad are involved.

The calculation is conducted for each relevant technology for electricity generation with technology-specific employment factors and assumptions on lifetime and construction duration.

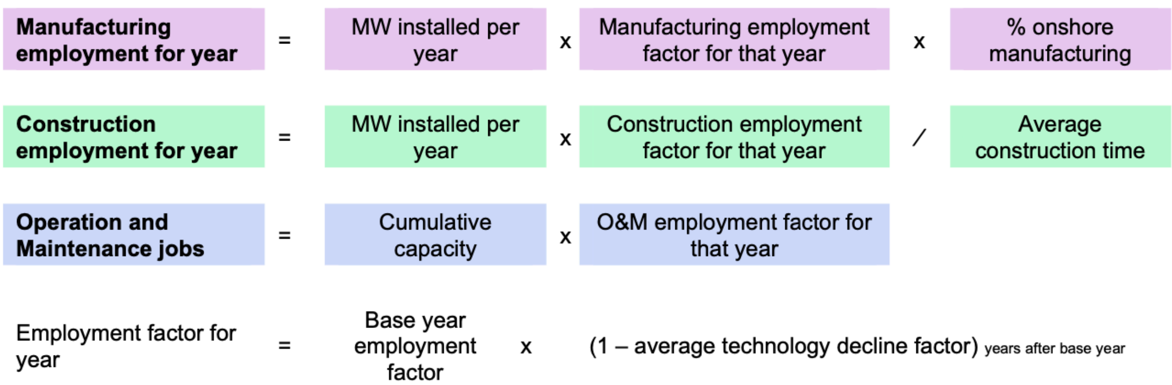


Figure 6 General overview on methodology. Source: [34]

As Ram et al. (2020) and Rutovitz et al. (2015) estimate employment impacts globally, they apply regional employment multipliers to adjust the 'base' employment factors for each technology and job activity with regional adjustment factors to account for differences in productivity between regions.

Note that the employment factor approach typically focuses on ***direct employment*** only, and does not quantify indirect employment further down the supply chain nor employment induced by the spending of wages throughout the economy. Still, a comparison of jobs for the different technologies over time can yield an indicative picture of the overall developments and employment effects for the analysed scenarios. However, the estimates should not be interpreted as a projection of net employment effects.

APPLYING OF THE EMPLOYMENT FACTOR APPROACH IN THIS STUDY

Focus of this study

For our analysis, we focus on estimating the employment impacts of phasing out South Korean coal power plants in line with the Paris Agreement temperature target and replacing these coal power plants with renewable energy installations of solar PV (rooftop and utility-scale installations) as well as wind (onshore and offshore installations). As explained above, we build on previous work[10] on Paris Agreement-compatible unit-level decommissioning schedules for South Korea.

Note that while the energy modelling takes into account the entire energy mix in terms of existing capacity for *all* power generation technologies, we do not assess the employment impacts for transitioning the whole South Korean energy system to 100% renewable energy. More specifically, the analysis focuses on the employment implications of **replacing coal-fired power capacity** with solar and wind renewable energy capacity as well as storage in South Korea. We do not assess the employment related to other renewable energy technologies such as hydro, marine, biomass or waste capacity.[11] In addition, we compare the employment effects of replacing coal-fired power capacity with solar and wind renewable energy capacity to a 'current policy' scenario derived based on coal decommissioning schedule from the 9th Basic Plan For Electricity Supply & Demand. This 'current policy' scenario envisages the conversion of selected coal-fired power plants to natural gas-fired power plants while it also builds up renewable energy capacity. Correspondingly, we only assess employment related to the transformation of coal power plants to natural gas and disregard employment in other natural gas-fired power plants. We limit our analysis to showing results until 2030, as, first, this is the timeline relevant for the Paris Agreement-compatible phase out date in 2029 and second, the uncertainty increases the further into the future the analysis is conducted.

Extensions of the basic approach developed in this study

While we build on the basic employment factor approach suggested by Rutovitz et al. (2015) [5] and updated and extended by Ram et al. (2020) [6], we extend this basic approach in three ways.

First, whenever suitable local data is available, we derive South Korea-specific employment factors and parameters. This is explained in detail below.

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10 In a Climate Analytics study from 2020 a coal phase out pathway for South Korea under the Paris Agreement was derived [43]. In another study earlier this year, unit-level-phase out schedules for coal have been analysed assessing the impacts on air pollution and health [2].

11 We do however take the current energy mix in terms of existing capacity for all power generation technologies into account for modelling the amount of solar and wind capacity to replace coal for the given energy system structure as described above.

Second, we assess the employment impacts of different coal phase out scenarios based on unit-level specific phase out schedules that are compatible with the Paris Agreement and compare the results to the 'current policy' scenario reflecting the current policy plan as represented by the 9th Basic Plan. For the analysis of coal phase out in South Korea, data on historical installed capacity as well as future capacity scenarios are based on results from the PyPSA model on the technology mix and storage needs using inputs from the unit-level coal phase out scheduled as well as the modelling of RE potentials in South Korea (see section 3.2). Based on this, the data on (future) newly installed capacity as well as total already installed capacity for the relevant technologies are derived for the employment analysis.

Third, we exploit spatially explicit data and modelling results to provide employment estimates on the subnational level for South Korea. The underlying methodology for this subnational disaggregation is explained in more detail below.

EXTENDING THE GENERAL APPROACH TO THE SUBNATIONAL LEVEL

While Ram et al. (2020) [6] and Rutovitz et al. (2015) [4] typically provide aggregated employment estimates on the national level, we extend the analysis to obtain estimates for the subnational level such as on province levels. For this, we make use of the spatially explicit information of the coal power plant locations as well as of the spatially explicit modelling of the potentials for solar and wind in South Korea described above. This is explained in more detail below.

Assigning coal- and natural gas-related jobs to the subnational level

We make use of information on longitude and latitude of coal power plant locations as provided by the Global Coal Plant Tracker [4] to assign the respective direct employment related to the coal power plant, such as construction and installation, operation and maintenance as well as decommissioning jobs to the respective district the coal power plant is located in. For jobs related to coal where the location of where the work is carried out is not necessarily linked to location of the power plant itself, such as manufacturing of coal power plant related technology parts, we report those separately without assigning them to a specific region – while also being included in the aggregated national-level estimates.

With respect to natural gas, we only consider those natural gas power plants that are planned to be transformed from coal- to natural gas-power plants according to the 9th Basic Plan for Electricity Demand and Supply (in the *Current Policies* scenario), and do not account for pre-existing or planned natural gas power plants other than those, as our analysis specifically focuses on the employment impacts of phasing out coal. As a consequence, in our analysis employment in natural gas only plays a role for the current policy scenario. For the location of the natural gas-power plant that had been resulting for the transformation of existing coal power plants, we assume that the location of the respective coal power plant as provided by Global Coal Plant Tracker applies also to the natural gas power plant replacing this coal power plant [4].

Assigning RE-related jobs to the subnational level

The modelling of potentials for solar PV rooftop and open field (utility-scale) as well as for onshore and offshore wind potentials in South Korea (as described in section 3.2) provides explicit geospatial information of where those identified potentials lie in South Korea. Based on this information, we assign the RE-related jobs that are directly bound to the location to the respective subnational level. These include jobs in construction and installation, and operation and maintenance of solar and wind, differentiating the locations of the respective sub-technologies (onshore wind and PV rooftop and open field). For offshore wind, the geolocation where the capacity are built up are located in the sea, so their location is not directly bound to a specific province. Likewise, employment in local manufacturing of technology parts is not directly bound to the location of the installations and thus not directly attributable to the province level. For these, we report the jobs separately without being assigned to a specific region – while also being included in the aggregated national-level estimates.

Assigning battery storage related jobs to the subnational level
For employment related to battery storage, we assume that the storage capacity that is modelled by PyPSA South Korea (see section 3.2) is linked to certain technologies and their respective locations. We assume that prosumer-size battery storage is linked to PV rooftop installations and their locations, while large scale battery storage is linked to PV open field (utility-scale) and the respective locations. Again, the related employment that is directly bound to the location, such as construction and installation and operation and maintenance are assigned to the respective location. Employment that is not locally bound, such as manufacturing of battery technology parts is reported separately without being assigned to a specific region – while also being included in the aggregated national-level estimates. The same approach if taken for hydrogen-related storage.

Employment in transmission and distribution are not considered, as this would require a detailed modelling of the power grid and transmission lines which is beyond the scope of this study.

DERIVING EMPLOYMENT FACTORS FOR SOUTH KOREA

A core strength of the employment factor approach as described above is that it provides a flexible and transparent framework with basic parameters that have been empirically derived and can serve as a benchmark. At the same time, these factors suggested by the literature can be replaced if better local data is available to derive own employment factors.

Whenever we could *not* obtain better local data to derive own employment factors for South Korea, we use the employment factors as suggested by Ram et al. (2020) [6].[12]
In their global assessment, Ram et al. (2020) provide regional multipliers to account for differences in labour intensity. Regional multipliers are provided for both the OECD and Northeast Asia region. Given the country's high labour productivity comparable with other OECD countries, we choose to assign South Korea along with in the OECD country grouping. Note that this represents more conservative job creation estimates.

To derive the employment factors for South Korea, we make use of available information on recent employment data as well as data on historic and current capacity by technology. This is used to calculate ratios of how many jobs per added capacity (for local manufacturing and construction and installation), total installed capacity (for operation and maintenance) have been observed in the recent past. For historic capacity, we use capacity information provided by EPSIS [24] to determine employment factors for both fossil and renewable sources. We use EPSIS generation capacity 'by fuel' as opposed to generation capacity 'by source' as this includes generation capacity for both electricity and heating; while at the same time this is the only disaggregated information by renewable technology available from EPSIS.

[12] To obtain the employment factors from Ram et al. (2020) for the year 2020, we are adjusting the 2015 base factors from Ram et al. to the year 2020 applying the decline factors provided by Ram et al. (2020) to reflect learning over time. Note that for solar and wind after 2020, we apply decline factors based on CAPEX developments as described in section 1.3.2 (RE modelling) to be consistent with the assumptions made for modelling the potentials for wind and solar (see description of decline factors below).

Employment statistics for solar PV and wind are taken from the Korea Energy Agency [36], [37], however, this information is generally not available differentiated by sub-technology (i.e. differentiating between jobs related to rooftop and utility-scale for PV and between onshore and offshore for wind-related employment). Employment factors from the literature such as Ram et al. (2020) however suggest, that the employment intensity differs between these sub-technologies. For example, it is suggested that offshore wind is more employment intensive compared to onshore with regard to construction and installation while it is relatively less employment intensive in terms of operation and maintenance. For solar PV, the Ram et al. (2020) employment factors indicate that rooftop PV is twice as employment intensive both with regard to C&I as well as with regard to O&M compared to utility-scale PV measured in terms of jobs or jobs years per MW. To calculate the employment ratios per sub-technology based on historic data for South Korea, we approximate the historic installed and added capacity for rooftop solar PV and utility-scale solar PV as well as onshore wind and offshore wind based on historic shares from IRENA[13] applied to the total installed capacity for solar and wind from EPSIS. For the calculation of South-Korea specific employment factors for the sub-technologies wind offshore and onshore as well as solar PV rooftop and utility-scale, we assume that the relative ratio of employment factors by sub-technology from Ram et al. (2020) holds for South Korea and apply this to derive the respective employment factor that matches the given statistics on employment and installed and added capacity by technology.

To account for efficiency improvements resulting from learning effects over time, we apply *decline factors*. The decline factors related to construction and installation as well as local manufacturing employment have been derived based on assumptions on the development of technology-specific capital expenditures (CAPEX). Decline factors related to operation and maintenance are based on technology-specific operational expenditures (OPEX). The decline factors by technology are shown in Table 10.

Table 10: Decline factors to represent learning and efficiency improvements

Technology	Annual decline factor derived from CAPEX (%)	Annual decline factor derived from OPEX (%)	Source
Battery (small)	0.094 (2021-2025) 0.065 (2026-2030)	0.128 (2021-2025) 0.062 (2026-2030)	Ram et al. (2020) [6]
Battery (utility)	0.076 (2021-2025) 0.059 (2026-2030)	0.111 (2021-2025) 0.056 (2026-2030)	Ram et al. (2020) [6]
Coal	0	0	Ram et al. (2020) [6]
H2 electrolysis	0	0	Ram et al. (2020) [6] (Power-to-Gas)
H2 fuel cell	0.017	0.017	Table 9
H2 storage	0	0	Ram et al. (2020) [6] (Gas storage)
Natural gas (converted)	0	0	Ram et al. (2020) [6]
PV (rooftop)	0.051	0.051	Table 4
PV (utility)	0.051	0.051	Table 4
Wind (offshore)	0.017	0.017	Table 5
Wind (onshore)	0.031	0.031	Table 5

Note: A decline factor of 0 means that the employment factor remains constant over time.

[13] International Renewable Energy Agency 2021. Statistics Time Series. https://irena.org/Statistics/View-Data-by-Topic/Capacity-and-Generation/Statistics-Time-Series.

Below, we explain in more detail which employment factors have been used and how these have been derived. Table 11 provides the respective technology-specific factors used for the analysis and their development over time (taking the decline factors into account).

Table 11: Overview on employment factors used for the analysis

Technology	Job type	2020	2025	2030	Comment	Ram et al.(2020) EF 2020
Battery (small)	C&I (job-years/MW)	16.31	9.98	7.13	EF and CAPEX from Ram et al. [6]	See "2020" column
Battery (small)	Manufacturing (job-years/MW)	12.76	7.81	5.58	EF and CAPEX from Ram et al. [6]	See "2020" column
Battery (small)	O&M (jobs/MW)	0.34	0.17	0.12	EF and OPEX from Ram et al. [6]	See "2020" column
Battery (utility)	C&I (job-years/MW)	7.29	4.91	3.62	EF and CAPEX from Ram et al. [6]	See "2020" column
Battery (utility)	Manufacturing (job-years/MW)	11.41	7.69	5.66	EF and CAPEX from Ram et al. [6]	See "2020" column
Battery (utility)	O&M (jobs/MW)	0.15	0.08	0.06	EF and OPEX from Ram et al. [6]	See "2020" column
Coal	C&I (job-years/MW)	5.26	5.26	5.26	Local EF, CAPEX from Ram et al. [6]	11.2
Coal	Decommission-ing (job-years/MW)	1.65	1.65	1.65	EF from Ram et al. [6]; jobs not part of the employment assess-ment but reported sep-arately in the Box on Decommissioning.	See "2020" column
Coal	Manufacturing (job-years/MW)	5.4	5.4	5.4	EF and CAPEX from Ram et al. [6]	See "2020" column
Coal	O&M (jobs/MW)	0.17	0.17	0.17	EF and OPEX from Ram et al. [6]	See "2020" column
H2 electrolysis	C&I (job-years/MW)	2.6	2.6	2.6	EF and CAPEX from Ram et al. [6]: Power-to-Gas	See "2020" column
H2 electrolysis	Manufacturing (job-years/MW)	1.86	1.86	1.86	EF and CAPEX from Ram et al [6].: Power-to-Gas	See "2020" column

H2 electrolysis	O&M (jobs/MW)	0.28	0.28	0.28	EF and OPEX from Ram et al. [6]: Power-to-Gas	See "2020" column
H2 fuel cell	C&I (job-years/MW)	2.78	2.56	2.35	Local EF; CAPEX from Table 9	NA
H2 fuel cell	Manufacturing (job-years/MW)	2.8	2.58	2.37	Local EF ; CAPEX from Table 9	NA
H2 fuel cell	O&M (jobs/MW)	0.6	0.55	0.51	Local EF; OPEX from Table 9	NA
H2 storage	C&I (job-years/MWh)	$6x10^{-5}$	$6x10^{-5}$	$6x10^{-5}$	EF and CAPEX from Ram et al [6].: gas storage (underground)	See "2020" column
H2 storage	Manufacturing (job-years/MWh)	0	0	0	EF and CAPEX from Ram et al. [6]: gas storage (underground)	See "2020" column
H2 storage	O&M (jobs/MWh)	$4x10^{-6}$	$4x10^{-6}$	$4x10^{-6}$	EF and OPEX from Ram et al. [6]: gas storage (underground)	See "2020" column
Natural gas (converted)	C&I (job-years/MW)	1.3	1.3	1.3	EF and CAPEX from Ram et al. [6]	See "2020" column
Natural gas (converted)	Manufacturing (job-years/MW)	0.93	0.93	0.93	EF and CAPEX from Ram et al. [6]	See "2020" column
Natural gas (converted)	O&M (jobs/MW)	0.19	0.19	0.19	Local EF, OPEX from Ram et al. [6]	0.14
PV (rooftop)	C&I (job-years/MW)	2.8	2.15	1.65	Local EF; CAPEX from Table 4	17.37
PV (rooftop)	Manufacturing (job-years/MW)	1.64	1.26	0.97	Local EF; CAPEX from Table 4	4.48
PV (rooftop)	O&M (jobs/MW)	0.57	0.44	0.34	Local EF; OPEX from Table 4	1.21
PV (utility)	C&I (job-years/MW)	1.4	1.08	0.83	Local EF; CAPEX from Table 4	7.21
PV (utility)	Manufacturing (job-years/MW)	1.64	1.26	0.97	Local EF; CAPEX from Table 4	3.72
PV (utility)	O&M (jobs/MW)	0.29	0.22	0.17	Local EF; OPEX from Table 4	0.46
Wind (offshore)	C&I (job-years/MW)	7.16	6.57	6.03	EF from Ram et al. [6]; CAPEX from Table 5	See "2020" column
Wind (offshore)	Manufacturing (job-years/MW)	13.95	12.80	11.75	EF from Ram et al. [6]; CAPEX from Table 5	See "2020" column
Wind (offshore)	O&M (jobs/MW)	0.08	0.08	0.07	Local EF; OPEX from Table 5	0.16
Wind (onshore)	C&I (job-years/MW)	2.94	2.52	2.15	EF from Ram et al.; CAPEX from Table 5	See "2020" column

Wind (on-shore)	Manufacturing (job-years/MW)	4.32	3.69	3.16	EF from Ram et al.; CAPEX from Table 5	See "2020" column
Wind (on-shore)	O&M (jobs/MW)	0.12	0.1	0.09	Local EF; OPEX from Table 5	0.28

Note: The last column provides the employment factors from Ram et al. (2020) for comparison in case own employment factors have been derived based on local data.

Employment factors for coal-related jobs in South Korea

- Local manufacturing of technology parts: We do not account for local manufacturing of coal power plants as we assume that manufacturing of parts relevant to coal power plants currently under construction has already been completed before our period of analysis.
- Construction and installation (C&I): We account for jobs related to the coal power plants that are already under construction in South Korea applying employment factors derived from local employment involved in the construction of the Shin Seocheon Thermal Power Plant as reported by the power plant owners to the parliament member's office of the National Assembly[14]. The resulting employment factor applied in the analysis is 5.26 job-years/MW (including employees in contractors and sub-contractors). In comparison, Ram et al. (2020) suggest a factor of 11.2 job-years/MW in 2020.
- Operation and maintenance (O&M): We have derived a local employment factor based on employment in operation and maintenance of existing coal power plants in South Korea as reported by the power plant owners to the parliament member's office of the National Assembly[15]. The derived employment factor corresponds to 0.17 jobs/MW, slightly larger than the factor of 0.14 jobs/MW suggested by Ram et al. (2020).
- Decommissioning: We do not account for jobs related to the decommissioning of coal power plants in South Korea in the main analysis. We indicate the overall job-creation potential from the decommissioning of coal power plants applying the employment factor of 1.65 job-years/MW from Ram et al. (2020) due to limited data availability for jobs in already decommissioned coal-fired power plants in South Korea.
- Transforming coal plants to natural gas power plants: We are not aware of data that would allow estimating the jobs related to converting an existing coal power plant into a natural gas power plant. We therefore apply the employment factor for construction and installation of natural gas power plants as suggested by Ram et al. (2020) of 1.3 job-years/MW to proxy the conversion-related jobs, and disregard decommissioning of coal-specific infrastructure for the main analysis.
- Fuel supply: We are not accounting for jobs related to coal supply.
- Province-level estimates: As described above, we assign the estimated jobs to the provincial level based on the location of the power plant.

Employment factors for natural gas-related jobs in South Korea

- Local manufacturing of technology parts: South Korea has recently made successful efforts to enter the business of manufacturing own gas turbines, however currently manufacturers from

[14] The data has been shared with the authors by a national assembly member who is part of the Trade, Industry, Energy, SMEs and Start-ups Committee.

[15] See previous footnote.

the US, Germany and Japan still have a market share of about 96%.[16] For our analysis, we assume a local share for manufacturing gas turbines for the gas power plants that are transformed from coal power plants to be 30%, linearly increasing to 50% by 2030. We apply the employment factor provided by Ram et al. (2020) of 0.93 job-years/MW.

- Refurbishing from coal/ construction and installation (C&I): Our analysis does not consider natural gas power plants other than those that are transformed from previous coal power plants according to the 9th power plan (BAU scenario). For the natural power plants planned to replace coal power plants, the calculation of related jobs is described under 'Transforming coal plants to natural gas power plants' above.
- Operation and maintenance (O&M): We have derived a local employment factor based on employment in operation and maintenance of existing natural gas power plants in South Korea as reported by the power plant owners to the parliament member's office of the National Assembly. The derived employment factor corresponds to 0.19 jobs/MW, slightly larger than the factor of 0.14 jobs/MW suggested by Ram et al. (2020). We apply this factor to the transformed natural gas power plants, assuming that the latter has the same capacity as the previous coal power plant that has been transformed.
- Decommissioning: Since our analysis ends in 2030 and we only consider natural gas plants converted from coal-fired power plants in this decade, the decommissioning of natural gas power plants is not relevant for our analysis.
- Fuel supply: We do not account for jobs related to natural gas supply.
- Province-level estimates: As described above, we assign the estimated jobs to the provincial level based on the location of the converted power plant whenever information allows.

Employment factors for solar PV related jobs in South Korea

- For our analysis, we differentiate between rooftop solar PV and open field solar PV (utility-scale). The differentiation is applied with regard to the modelling of the respective potential and the resulting locations as well as with regard to the employment intensity, i.e. applying different employment factors for rooftop solar PV than for utility-scale solar PV.
- Local manufacturing of solar PV technology parts:
    - Local shares: To estimate the local jobs related to manufacturing of PV technology parts for PV installations installed within South Korea, we need to make assumptions in the development of the local share for PV module manufacturing until 2030. Sources suggest that the domestic market share of the of PV modules produced in South Korea has been 72% in 2016, 73.5% in 2017, 72.5% in 2018 and even 78.7% in 2019.[17] While there is strong demand for Korean-made solar modules for small to medium-sized PV systems, for large-sized modules customers less costly Chinese products also play a major role.[18] For our scenario analysis, we therefore differentiate the local shares for (small-sized) rooftop PV and utility-scale PV, assuming a local share of 80% for rooftop PV installations and 50% for utility-scale PV installations that remain constant from 2020 to 2030.
    - Derived employment factors: We used data on historic employment in PV manufacturing for South Korea from the Human Resource Development Service of Korea (for

[16] http://www.businesskorea.co.kr/news/articleView.html?idxno=55984
[17] https://www.pv-magazine.com/2020/01/14/south-korean-government-reassures-domestic-pv-industry/
[18] http://koreabizwire.com/imports-of-chinese-solar-modules-surge-as-s-korean-renewable-energy-market-grows/165029

2017) [38] and the Korean Energy Agency [39], [40]. For information on historic installed PV capacity, we use data from EPSIS[19]. To account for the fact, that South Korea has also manufactured solar PV technology parts for exporting, we use data from the KITA database[20] on the ratio of export to import value for South Korea for 2017 to 2019 to approximate how many MW of solar PV have been manufactured in South Korea in total (for domestic use and export), assuming that the price for exported capacity is the same as for those sold domestically. To account for the fact that a part of the locally installed PV installations has been imported (mainly from China), we make use of information on historic local shares as described above. The manufacturing process happens before the added capacity is installed and show up in the EPSIS statistics. As we cannot say for certain, how far in advance the added capacity has been manufactured, we have to make necessary simplifications. While the historic employment in PV manufacturing is relatively constant over time, there are jumps in the number of calculated capacity. To deal with this uncertainty, we average available information on newly installed capacity, jobs in manufacturing, local shares and export-to-import ratio for the years 2017-2019 to determine a nationally representative employment factor. The resulting calculated employment factors for domestic solar PV manufacturing is 1.64 job-years/MW in 2020, assuming an identical employment factor for the manufacturing of rooftop solar PV and utility-scale PV systems. For comparison, the corresponding employment factor from Ram et al. (2020) is 3.72 job-years/MW (for 2020).

  - Decline factors: CAPEX-based decline factors are applied to adjust employment factors over time as explained above (see Table 10).
  - Estimating employment impacts: To estimate the jobs related to local manufacturing of PV installations in South Korea, we multiply the added capacity (in MW) of the respective solar PV technology (rooftop vs. utility-scale) obtained from PyPSA with the local share and then multiply the respective technology- and year-specific employment factors for local PV manufacturing.
  - Employment related to export or import: Note that in our analysis, we do not take local manufacturing for exporting solar PV technology parts into account as we aim to analyse the job implications of replacing South Korean coal power plants with RE locally. Jobs generated abroad from imported PV technology parts are also not considered as we focus on employment in South Korea.

- Construction and Installation (C&I):
  - Derived employment factors: As described above, employment factors for C&I differentiating between rooftop and utility-scale solar PV are derived based on historic data on added capacity from EPSIS differentiated into sub-technology assuming shares from the Renewable Energy 3020 Implementation Plan [41] and energy employment statistics for South Korea [39] assuming that the ratio of relative employment intensity from Ram et al. (2020) holds for South Korea. We average added capacity (2017-2019) and jobs (2017-2018) to determine a nationally representative employment factor. The resulting derived C&I employment factors for South Korea are 2.8 job-years/MW for rooftop PV systems and 1.4 job-years/MW for utility-scale PV installations. For comparison, the corresponding employment factors from Ram et al. (2020) for 2020 are 17.37 job-years/MW for rooftop PV and 7.21 job-years/MW for utility-scale PV installations for 2020.

[19] We use EPSIS 'by fuel' capacity (as opposed to EPSIS 'by source') to determine employment factors for both fossil and renewable sources. For renewables this is the only disaggregated information available from EPSIS.

[20] http://www.kita.org/kStat/byCom_SpeCom.do

- Construction duration: For solar PV we assume a construction duration of one year for both rooftop and utility-scale systems.
- Decline factors: CAPEX-based decline factors are applied to adjust employment factors over time as explained above.
- Estimating employment impacts: To estimate the jobs related to C&I of PV installations for rooftop and utility-scale respectively, we multiply the scenario data on added capacity (in MW) of the respective solar PV technology (rooftop vs. utility-scale) obtained from PyPSA with the respective derived technology- and year-specific employment factors for C&I. To calculate estimated jobs for each year, we distribute the estimated job-years over the construction duration.

- Operation and maintenance (O&M):
  - Deriving employment factors: As described above, employment factors for O&M differentiating between rooftop and utility-scale solar PV are derived based on historic data on total capacity from EPSIS differentiated into sub-technology assuming shares from the Renewable Energy 3020 Implementation Plan [41] and employment statistics for South Korea [39] assuming that the ratio of relative employment intensity from Ram et al. (2020) O&M employment factors holds for South Korea. We average both capacity and jobs for the years 2017-2018 to determine a nationally representative employment factor. The resulting derived current O&M employment factors for South Korea are 0.57 jobs/MW for rooftop PV and 0.29 jobs/MW for utility-scale PV. For comparison, the corresponding employment factors from Ram et al. (2020) for 2020 are 1.21 jobs/MW for rooftop PV and 0.46 jobs/MW for utility-scale PV, respectively.
  - Decline factors: OPEX-based decline factors are applied to adjust employment factors over time as explained above.
  - Estimating employment impacts: To estimate the jobs related to O&M of PV installations for rooftops and utility-scale, respectively, we multiply the scenario data on total capacity (in MW) of the respective solar PV technology (rooftop vs. utility-scale) obtained from PyPSA with the respective derived technology- and year-specific employment factors for O&M. These jobs are assumed to be permanent remaining over the lifetime of the installations.
- Lifetime and replacement: We assume that replacement of solar PV installations and related jobs can be neglected for our analysis given the long lifetime of PV installations (which is typically 25 years) and the comparably short time horizon of our analysis.
- Province-level estimates: As described above, we assign the estimated jobs to the provincial level whenever information allows.

Employment factors for wind related jobs in South Korea

- Local Manufacturing of technology parts:
  - Local shares: We assume a share of 20% of local manufacturing of wind turbines (both onshore and offshore), approximating Korea South-East Power Co. "Local Contents Rules" (LCRs) for the most relevant technology parts (blades, towers).[21] We assume this share to remain constant.
  - Employment factors: Due to significant uncertainties in the domestically manufactured capacity in recent years, we use employment factors provided by Ram et al.

[21] http://www.epj.co.kr/news/articleView.html?idxno=27311

(2020) for both on- and offshore wind. These correspond to 13.95 job-years/MW for offshore wind, and 4.32 job-years/MW for onshore wind (2020).

- Decline factors: CAPEX-based decline factors are applied to adjust employment factors over time as explained above.
- Estimating employment impacts: To estimate the jobs related to local manufacturing of wind installations in South Korea, we multiply the added capacity (in MW) of the respective wind technology (onshore vs. offshore) obtained from PyPSA with the local share and then multiply the respective technology- and year-specific employment factors for local wind manufacturing.
- Employment related to export or import: Note that in our analysis, we do not take local manufacturing for exporting wind technology components into account.

- Construction and Installation (C&I):
    - Deriving employment factors: We use employment factors from Ram et al. (2020) for 2020 corresponding to 2.94 job-years/MW for onshore wind and 7.16 job-years/MW for offshore wind installations. These are more conservative estimates than those derived from local employment and capacity data.
    - Construction duration: For onshore (offshore) wind we assume a construction duration of one (four) years.
    - Decline factors: CAPEX-based decline factors are applied to adjust employment factors over time as explained above.
    - Estimating employment impacts: To estimate the jobs related to C&I of onshore and offshore wind, respectively, we multiply the scenario data on added capacity (in MW) of the respective wind technology (onshore vs. offshore) obtained from PyPSA with the respective derived technology- and year-specific employment factors for C&I. To calculate estimated jobs for each year, we distribute the estimated job-years over the construction duration.

- Operation and maintenance (O&M):
    - Deriving employment factors: As described above, employment factors for O&M differentiating between onshore wind and offshore wind are derived based on historic data on total capacity from EPSIS differentiated into sub-technology based on shares from IRENA[22] and employment statistics for South Korea [39] assuming that the ratio of relative employment intensity from Ram et al. (2020) O&M employment factors between on- and offshore wind holds for South Korea. We average both capacity and jobs for the years 2017-2018 to determine a nationally representative employment factor. The resulting derived current O&M employment factors for South Korea are 0.12 jobs/MW for onshore wind and 0.08 jobs/MW for offshore wind, respectively. For comparison, the corresponding employment factors from Ram et al. (2020) for 2020 are 0.28 jobs/MW for onshore wind and 0.16 jobs/MW for offshore wind, respectively.
    - Decline factors: OPEX-based decline factors are applied to adjust employment factors over time as explained above.

[22] International Renewable Energy Agency 2021. Statistics Time Series. https://irena.org/Statistics/View-Data-by-Topic/Capacity-and-Generation/Statistics-Time-Series .

  - Estimating employment impacts: To estimate the jobs related to O&M of on- and off-shore wind turbines, we multiply the scenario data on total capacity (in MW) of the respective wind technology (onshore vs. offshore) obtained from PyPSA with the respective derived technology- and year-specific employment factors for O&M. These jobs are assumed to be permanent remaining over the lifetime of the installations.
- Lifetime and replacement: We assume that replacement of wind installations and related jobs can be neglected for our analysis given the long lifetime of wind installations (typically around 20 years) and the comparably short time horizon of our analysis.

Employment factors for battery storage related jobs in South Korea
The currently available data on employment in South Korea related to battery storage for the power sector is very limited and does not allow deriving own employment factors for this study. We therefore apply the employment factors from Ram et al. (2020) differentiating between small-scale 'prosumer' battery storage and large-scale battery storage.

- Local manufacturing of technology parts:
  - Local shares: Given the strong market position of South Korean battery manufacturers[23], we assume a share of 80% for both small- and utility-scale batteries, which remains constant over the period of analysis.
  - Employment factors: We account for jobs related to the manufacturing of small- and large-scale batteries in South Korea applying the respective employment factors from Ram et al. (2020) due to limited data availability on local jobs in battery manufacturing. In 2020, these correspond to 12.76 job-years/MW for small-scale batteries, and 11.41 job-years/MW for utility-scale batteries.
  - Decline factors: CAPEX-based decline factors are applied to adjust employment factors over time as explained above.
  - Estimating employment impacts: To estimate the jobs related to local manufacturing of battery storage systems in South Korea, we multiply the added capacity (in MW) of the respective storage technology (small- vs. large-scale) obtained from PyPSA with the local share and then multiply the respective technology- and year-specific employment factors for local battery manufacturing.
  - Employment related to export or import: Note that in our analysis, we do not take local manufacturing for exporting battery storage systems into account.
- Construction and installation (C&I):
  - Employment factors: We account for jobs related to the construction and installation of both prosumer and large-scale batteries in South Korea applying the respective employment factors from Ram et al. (2020) due to limited data availability on local jobs in power system battery construction and installation. In 2020, these correspond to 16.31 job-years/MW for small-scale batteries, and 7.29 job-years/MW for utility-scale batteries.
  - Decline factors: CAPEX-based decline factors are applied to adjust employment factors over time as explained above.

[23] Hwang I, Jung Y. Korea's Energy Storage System Development: The Synergy of Public Pull and Private Push [Internet]. 2020 [cited 2021 Jun 11]. Available from: https://documents1.worldbank.org/curated/en/152501583149273660/pdf/Koreas-Energy-Storage-System-Development-The-Synergy-of-Public-Pull-and-Private-Push.pdf

    - Construction duration: We assume a construction duration of one year for both small- and utility-scale battery storage.
    - Estimating employment impacts: To estimate the jobs related to construction and installation of battery storage systems in South Korea, we multiply the added capacity (in MW) of the respective storage technology (small-scale vs. large-scale) obtained from PyPSA with the respective technology- and year-specific employment factors.
- Operation and maintenance (O&M):
    - Employment factors: We account for jobs related to the operation and maintenance of both prosumer and large-scale batteries in South Korea applying the respective employment factors from Ram et al. (2020) due to limited data availability on local jobs in battery operation and maintenance. In 2020, these correspond to 0.34 jobs/MW for small-scale batteries, and 0.15 jobs/MW for utility-scale batteries.
    - Decline factors: OPEX-based decline factors are applied to adjust employment factors over time as explained above.
    - Estimating employment impacts: To estimate the jobs related to operation and maintenance of battery storage systems in South Korea, we multiply the total yearly capacity (in MW) of the respective storage technology (small- vs. large-scale) obtained from PyPSA with the respective technology- and year-specific employment factors.
- Lifetime and replacement: We assume that replacement of batteries and related jobs can be neglected for our analysis.

Employment factors for hydrogen-related jobs in South Korea

We differentiate between hydrogen electrolysis, hydrogen storage and hydrogen fuel cells. Given the limits of currently available data on employment globally related to hydrogen technologies, we apply employment factors from Ram et al. (2020) for similar technologies in order to approximate the employment factors for hydrogen electrolysis and hydrogen storage. For hydrogen fuel cells, we derive country-specific employment factors based on available data.

- Local manufacturing of technology parts:
    - Local shares: For hydrogen electrolysis, we assume a local share of 50%, which remains constant over the analysis period. For hydrogen fuel cells, we assume a local share of 50% in 2020, linearly increasing to 70% in 2030.[24] This reflects both the domestic experience in producing fuel cells for power generation and the still existing dependence on foreign technologies.[25] Hydrogen storage capacity are assumed underground, and therefore not associated with manufacturing employment.[26]
    - Employment factors: We account for jobs related to the manufacturing of electrolysers by applying the employment factor provided by Ram et al. (2020) for Power-to-Gas (PtG) manufacturing, corresponding to 1.86 job-years/MW. For hydrogen fuel cells, we account for jobs related to their manufacturing based on data from a local fuel cell

[24] As announced in the Hydrogen Economy Roadmap, Korea aims to expand local manufacturing of fuel cells [42]. The assumed local shares are chosen to reflect this.

[25] https://www.ifri.org/en/publications/editoriaux-de-lifri/edito-energie/south-koreas-hydrogen-strategy-and-industrial

[26] Underground storage facilities may not be realistic in Korea if no suitable geological formations are available. If other forms of storage (e.g. pipes, tanks) need to be built, additional jobs may be created in the manufacture of these storage facilities. Our employment estimates may therefore be viewed as conservative.

manufacturer. We approximate the employment factor based on manufactured capacity information[27] and employment information[28], assuming constant employment. The resulting employment factor is 2.8 job-years/MW. Hydrogen storage capacity is assumed underground, and therefore not associated with manufacturing employment as described above.

  - Decline factors: CAPEX-based decline factors are applied to adjust employment factors over time as explained above.
  - Estimating employment impacts: To estimate the jobs related to local manufacturing of hydrogen-related employment in South Korea, we multiply the added capacity (in MW for electrolysis and fuel cells, in MWh for hydrogen storage) of the respective hydrogen technology (electrolysis, hydrogen storage and hydrogen fuel cells) obtained from PyPSA with the local share and then multiply the respective technology- and year-specific employment factors for manufacturing described above.
  - Employment related to export or import: Note that in our analysis, we do not take local manufacturing for exporting hydrogen-related technologies into account.

- Construction and installation (C&I):
  - Employment factors: We account for jobs related to the construction and installation of electrolysers by applying the employment factor provided by Ram et al. (2020) for Power to Gas (PtG) construction and installation corresponding to 2.6 job-years/MW in 2020. For hydrogen storage, we apply the employment factor for gas storage construction and installation also provided by Ram et al. (2020) corresponding to 0.00006 job-years/MWh. For hydrogen fuel cells, C&I employment factors are derived based on historic data on added capacity from EPSIS and employment statistics for South Korea [39]. We average added capacity and jobs for the years 2017-2019 (2017-2018, respectively) to determine a nationally representative employment factor. The resulting derived C&I employment factors for South Korea are 2.78 job-years/MW.
  - Decline factors: CAPEX-based decline factors are applied to adjust employment factors over time as explained above.
  - Estimating employment impacts: To estimate the jobs related to construction and installation of hydrogen-related technologies in South Korea, we multiply the added capacity (in MW for electrolysis and fuel cells, in MWh for hydrogen storage) of the respective hydrogen technology (electrolysis, hydrogen storage and fuel cells) obtained from PyPSA with the respective technology- and year-specific employment factors for construction and installation described above

- Operation and maintenance (O&M):
  - Employment factors: We account for jobs related to the operation and maintenance of electrolysers by applying the employment factor provided by Ram et al. (2020) for Power-to-Gas (PtG) operation and maintenance corresponding to 0.28 jobs/MW in 2020. For hydrogen storage, we apply the employment factor for gas storage operation and maintenance also provided by Ram et al. (2020) corresponding to 0.000004 jobs/MWh in 2020. For hydrogen fuel cells, we apply a locally derived operation and maintenance employment factor based on information on expected jobs in a Korean

[27] https://www.doosan.com/en/media-center/press-release_view/?id=20172197&page=3&

[28] https://www.marketscreener.com/quote/stock/DOOSAN-FUEL-CELL-CO-LTD-103508980/company/

hydrogen fuel cell power plant currently under construction.[29] The resulting employment factor corresponds to 0.6 jobs/MW.

- Decline factors: OPEX-based decline factors are applied to adjust employment factors over time as explained above.
- Estimating employment impacts: To estimate the jobs related to operation and maintenance of hydrogen-related technologies in South Korea, we multiply the total annual capacity (in MW for electrolysis and fuel cells, in MWh for hydrogen storage) of the respective hydrogen technology (electrolysis, hydrogen storage and hydrogen fuel cells) obtained from PyPSA with the respective technology- and year-specific employment factors for operation and maintenance described above

- Lifetime and replacement: We assume that replacement of electrolysers, hydrogen storage and hydrogen fuel cells as well as related jobs can be neglected for the time horizon considered in our analysis.

Table 12: Underlying assumptions for lifetimes of installations and construction time

Technology	Construction time in years	Source
Battery (small)	1	Ram et al. (2020)
Battery (utility)	1	Ram et al. (2020)
Coal	5	Ram et al. (2020)
H2 electrolysis	2	Ram et al. (2020)
H2 fuel cell	2	Own assumption
H2 storage	2	Ram et al. (2020)
Natural gas (converted)	1	Own assumption
PV (rooftop)	1	Ram et al. (2020)
PV (utility)	1	Ram et al. (2020)
Wind (offshore)	4	Ram et al. (2020)
Wind (onshore)	1	Own assumption

Table 13 Underlying assumptions on local share of manufacturing

Technology	2020	2025	2030
Battery (small)	80%	80%	80%
Battery (utility)	80%	80%	80%
Coal	0%	0%	0%
H2 electrolysis	50%	50%	50%
H2 fuel cell	50%	60%	70%
Natural gas (converted)	30%	40%	50%
PV (rooftop)	80%	80%	80%
PV (utility)	50%	50%	50%
Wind (offshore)	20%	20%	20%
Wind (onshore)	20%	20%	20%

SENSITIVITY ANALYSES FOR THE EMPLOYMENT IMPACTS

[29] https://www.gb.go.kr/Main/open_contents/section/invest_eng/page.do?mnu_uid=4419&BD_CODE=bbs_gongji&cmd=2&B_NUM=73421401&B_STEP=73421400&V_NUM=

Estimates when assuming a restricted role of green hydrogen

While no hydrogen development is envisaged in the *CPol* scenario, the *CtR* scenario foresees the buildout of green hydrogen production, storage, utilization as a cost-effective technology to improve the power system's flexibility. In combination with medium renewable cost projections as provided by IRENA [14], [19], green hydrogen already plays an important role in providing the power system with cost-effective long-term storage from 2025 onwards. However, given the uncertainty around political support, investment and cost improvements of hydrogen technologies in the short-term, we here provide an analysis that restricts the amount of hydrogen to be in line with the Hydrogen Economy Roadmap announced by the Korean government in 2019 [42]. Specifically, fuel cells are defined to follow a constant growth path in line with the target of 1.5 GW of fuel cell power plants in 2040, with electrolyser and storage capacity developed accordingly.[30] Compared to the *CtR* scenario, the lower buildout of hydrogen taking place from 2025 onwards needs to be compensated by an additional buildout of small- and utility-scale battery storage capacity, accompanied by a substantially greater buildout of offshore wind turbines. Total employment effects reflect these developments, with less than a third of total hydrogen-related jobs retained while on average more than 20,000 additional jobs per year associated with batteries and offshore wind alone are created (see Figure 7). While the overall impact of limiting hydrogen development on jobs is beneficial, it should be noted that this comes at the cost of a non-cost-optimal energy system under the assumptions made in PyPSA.
The employment analysis at the province level also shows similar results to those of the main analysis (see Figure 8). While employment is partially reallocated between provinces, all provinces continue to benefit from replacing coal with renewable energy and storage, including those where coal power plants are located.

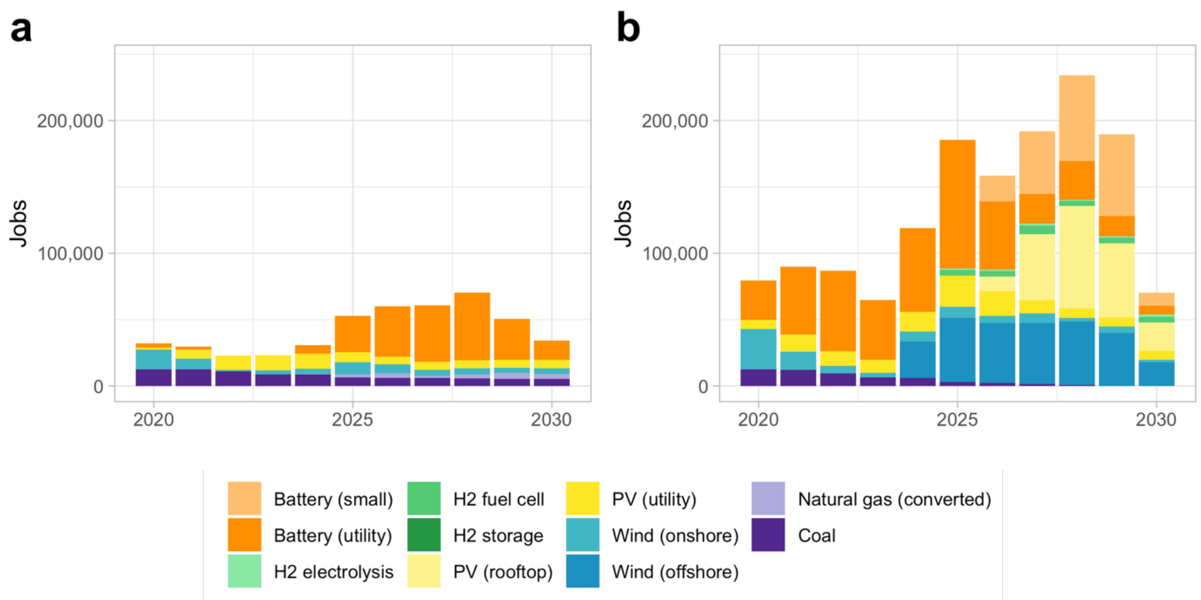

Figure 7 ***Sensitivity Analysis: Aggregated total employment impacts*** *by power generation technology aggregated over job types, comparing job estimates for the CPol scenario (Panel a) and a variant of the CtR scenario (Panel b) with* ***restricted hydrogen development****.*

30 The restricted hydrogen path results in 1.4 GW electrolyser capacity in the restricted hydrogen *CtR* scenario in 2030, compared to 8.1 GW in the *CtR* scenario in the main analysis.

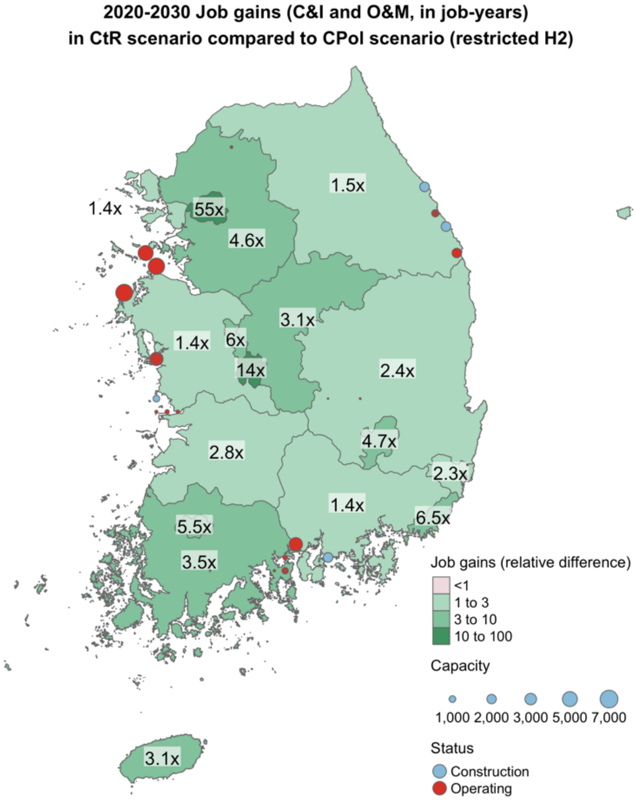

Figure 8 ***Sensitivity analysis**: **Difference in overall job-years between a variant of the CtR scenario which restricts H2 and CPol scenario*** *including jobs in C&I and O&M of coal, natural gas (converted), solar PV, onshore wind and battery storage. Factors shown indicate how the province-level job potential compares between scenarios, with for example 2x meaning that the variant of the CtR scenario supports twice the number of job years than estimated for the Current Policy Scenario. Note that additional jobs that have not been assigned to provinces (local manufacturing, offshore wind and hydrogen) are not included in these numbers. Coal power plant capacity and location are shown by circles.*

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