Impacts of a *Green-New-Deal* Energy Plan on Grid Stability, Costs, Jobs, Health, and Climate in Northern Europe

The results here were derived from the LOADMATCH grid model using country-specific business-as-usual (BAU) and wind-water-solar (WWS) load data for 2050 and 30-second resolution WWS supply data from the GATOR-GCMOM weather-prediction model. Source*: Jacobson, M.Z., The cost of grid stability with 100% clean, renewable energy for all purposes when countries are isolated versus interconnected, Renewable Energy, 179, 1065-1075, doi:10.1016/j.renene.2021.07.115, 2021.*
https://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html

This infographic summarizes the changes in energy needs; in energy, health, and climate costs; and in jobs due to transitioning Northern Europe as one grid to 100% clean, renewable WWS energy for all energy purposes (the energy goal of the *Green New Deal*). The proposed transition timeline is 100% by no later than 2050, with at least 80% by 2030. Land needed for 100% WWS is also quantified.

Main results:

The energy portion of the Northern European *Green New Deal*

- **Assumes only wind-water-solar (WWS) energy (electricity from onshore + offshore wind, solar PV CSP, geothermal, hydro, tidal, and wave and heat from geothermal and solar); electricity, heat, cold, and hydrogen storage; demand response; and well-interconnected transmission. No fossil fuels, nuclear, bioenergy, or carbon capture.**
- **Has an upfront cost of $2.51 trillion (for WWS electricity, heat, H_2 generation; electricity, heat, cold, H_2 storage; short- and long-distance transmission; distribution). This pays for itself over time from energy sales**
- **Creates 1,360,000 more long-term, full-time jobs than lost**
- **Saves 27,400 lives from air pollution each year in 2050**
- **Eliminates Northern European energy emissions affecting global warming**
- **Reduces 2050 end-use energy requirements by 48.1%**
- **Reduces 2050 private energy costs by 61% (from $626 to $244 billion/yr)**
- **Reduces energy, health, and climate costs by $382, $288, and $805 billion/yr**
- **Reduces social energy costs by 86% (from $1,719 to $244 billion/yr)**
- **Requires 0.44% of Northern European land for footprint, 1.11% for spacing**

Table 1. Reduced End-Use Demand Upon a Transition From BAU to WWS in Northern Europe
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The Northern European grid includes Belgium, Denmark, Germany, Luxembourg, Netherlands, Norway, and Sweden

Table 1. Reduced End-Use Demand Upon a Transition From BAU to WWS in Northern Europe

This table shows 2016 BAU, 2050 BAU, and 2050 100% WWS annually averaged end-use power demand (GW) by sector. The last column shows the total percent reduction in 2050 BAU end-use power demand due to switching from BAU to WWS, including the effects of reduced energy use caused by (a) the higher work output to energy input ratio of electricity over combustion, (b) eliminating energy used to mine, transport, and/or refine coal, oil, natural gas, biofuels, bioenergy, and uranium, and (c) assumed policy-driven increases in end-use energy efficiency beyond those in the BAU case. Reduced energy use due to the higher work output to energy input of electricity over combustion is due to the higher work output to energy input of electric vehicles and hydrogen fuel cell vehicles powered by WWS over internal combustion vehicles, of high-temperature industrial processes powered by WWS, and of heat pumps over internal combustion heating for low-temperature heat.

Scenario	Total end-use dem-and (GW)	Resid-ential per-cent of total	Com-mercial percent of total	Indus-trial per-cent of total	Trans-port per-cent of total	Ag/for-estry/ fishing per-cent of total	Mili-tary/ other per-cent of total	(a) 2050 change in demand (percent) due to higher work: energy ratio of WWS	(b) 2050 change in demand (percent) due to eliminat-ing upstream w/WWS	(c) 2050 change in demand (percent) due to effic-iency beyond BAU w/WWS	Total 2050 change in demand (percent) w/WWS
BAU 2016	560.3	21.5	13.0	31.6	32.4	1.4	0.06				
BAU 2050	679.1	21.8	14.4	31.6	30.9	1.3	0.02				
WWS 2050	287.1	19.1	18.3	42.4	19.2	1.0	0.01	-33.83	-7.98	-6.27	-48.08

Table 2. 2050 WWS End-Use Demand by Sector

2050 annual average end-use electric plus heat load (GW) by sector after energy in all sectors has been converted to WWS. Instantaneous loads can be higher or lower than annual average loads.

Region	Total	Resi-dential	Com-mercial	Trans-port	Industrial	Agricultur e/forest/fis hing	Military/ other
Northern Europe	287.1	54.70	52.72	55.04	121.71	2.88	0.07

Table 3. WWS End-Use Demand by Load Type

Annual average WWS all-sector inflexible and flexible loads (GW) for 2050. "Total load" is the sum of "inflexible load" and "flexible load." "Flexible load" is the sum of "cold load subject to storage," "low-temperature heat load subject to storage," "load subject to demand response (DR)", and "load for H_2" production, compression, and storage (accounting for leaks as well). Annual average loads are distributed in time as described in the text. Thus, instantaneous loads, either flexible or inflexible, can be much higher or lower than annual average loads. Also shown is the annual hydrogen mass needed in each region, estimated as the load multiplied by 8,760 hr/yr and divided by 59.01 kWh/kg-H_2.

Region	Total end-use load (GW)	Inflex-ible load (GW)	Flex-ible load (GW)	Cold load subject to storage (GW)	Low-temp-erature heat load subject to storage (GW)	Load sub-ject to DR	Load for H_2 (GW)	H_2 needed (Tg-H_2/yr)
Northern Europe	287.1	128.4	158.7	2.59	39.1	18.8	98.3	2.78

Table 4. Nameplate Capacities Needed by 2050 and Installed as of 2018 End in Northern Europe

Final (from LOADMATCH) 2050 total (existing plus new) nameplate capacity (GW) of WWS generators needed to match power demand with supply and storage continuously over time in 2050. Also provided are the nameplate capacities already installed as of 2018 end. Nameplate capacity equals the maximum possible instantaneous discharge rate.

Year	Onshore wind	Off-shore wind	Resi-dential roof-top PV	Comm /govt rooftop PV	Utility PV	CSP with stor-age	Geoth ermal -elec-tricity	Hydro power	Wave	Tidal	Solar therm al	Geoth ermal heat
2050	340.2	182.7	99.2	292.3	478.5	0	0.03	51.5	2.1	0.573	16.2	11.1
2018	71.97	10.28	11.15	11.15	33.44	0.002	0.03	51.5	0	0.003	16.24	11.10

Table 5. Characteristics of Storage Resulting in Matching Demand With 100% WWS Supply

Maximum charge rates, discharge rate, and storage capacity of all electricity, cold and heat storage needed for supply + storage to match demand in the region.

Storage type	Max charge rate (GW)	Max discharge rate (GW)	Storage (TWh)
PHS	40.2	40.2	0.562
CSP-elec.	0	0	--
CSP-PCM	0	--	0
Batteries	1400	1400	2.716
Hydropower	23.7	51.5	207.6
CW-STES	1.04	1.04	0.015
ICE	1.56	1.56	0.022
HW-STES	103.0	103.0	0.618
UTES-heat	16.2	103.0	37.08
UTES-elec.	154.5	--	--

PHS = pumped hydropower storage; PCM = Phase-change materials; CSP=concentrated solar power; CW-STES = Chilled-water sensible heat thermal energy storage; HW-STES = Hot water sensible heat thermal energy storage; and UTES = Underground thermal energy storage (either boreholes, water pits, or aquifers). The peak energy storage capacity equals the maximum discharge rate multiplied by the maximum number of hours of storage at the maximum discharge rate. Table S12 gives maximum storage times at the maximum discharge rate.

Heat captured by CSP solar collectors can either be used immediately to produce electricity, put in storage, or both. The maximum direct CSP electricity production rate (CSP-elec) equals the maximum electricity discharge rate, which equals the nameplate capacity of the generator. The maximum charge rate of CSP phase-change material storage (CSP-PCM) is set to 1.612 multiplied by the maximum electricity discharge rate, which allows more energy to be collected than discharged directly. Thus, the maximum overall simultaneous direct electricity plus storage CSP production rate is 2.612 multiplied by the discharge rate. The maximum energy storage capacity equals the maximum electricity discharge rate multiplied by the maximum number of hours of storage at full discharge, set to 22.6 hours, or 1.612 multiplied by the 14 hours required for CSP storage to charge when charging at its maximum rate.

Hydropower can be charged only naturally, but its annual-average charge rate must equal at least its annual energy output divided by the number of hours per year. It is assumed simplistically here that hydro is recharged at that rate, where its annual energy output in 2050 is close to its current value. Hydropower's maximum discharge rate in 2050 is its 2018 nameplate capacity. The maximum storage capacity is set equal to the 2050 annual energy output of hydro.

The CW-STES charge/discharge rate is set equal to 40% of the maximum daily averaged cold load subject to storage, which itself is calculated as the maximum of Equation S32 during the period of simulation. The ICE storage charge/discharge rate is set to 60% of the same peak cold load subject to storage.

The HW-STES charge and discharge rates are set equal to the maximum daily-averaged heat load subject to storage, calculated as the maximum value during the period of simulation from Equation S29.

UTES heat stored in underground soil can be charged by either solar or geothermal heat or excess electricity. The maximum charge rate of heat to UTES storage (UTES-heat) is set to the nameplate capacity of the solar thermal collectors. In several regions, no solar thermal collectors are used. Instead, UTES is charged only with excess grid electricity. The maximum charge rate of excess grid electricity converted to heat stored in UTES (UTES-elec.) is set by trial and error for each country. The maximum UTES heat discharge rate is set to that of HW-STES storage, which is limited by the warm storage load.

Figure 1. Keeping the Electric Grid Stable From 2050-2052 With 100% WWS + Storage + Demand Response

Time-series comparison during 2050 for Northern Europe. First row: modeled one-year time-dependent total wind-water-solar (WWS) power generation versus load plus losses plus changes in storage plus shedding. Second row: same as first row, but for a 100-day window during the year. Third row: a breakdown of WWS power generation by source during the window. Fourth row: a breakdown of inflexible load; flexible electric, heat, and cold load; flexible hydrogen load; losses in and out of storage; transmission and distribution losses; changes in storage; and shedding. The model was run at 30-s resolution. Results are shown hourly. No load loss occurred during any 30-s interval.

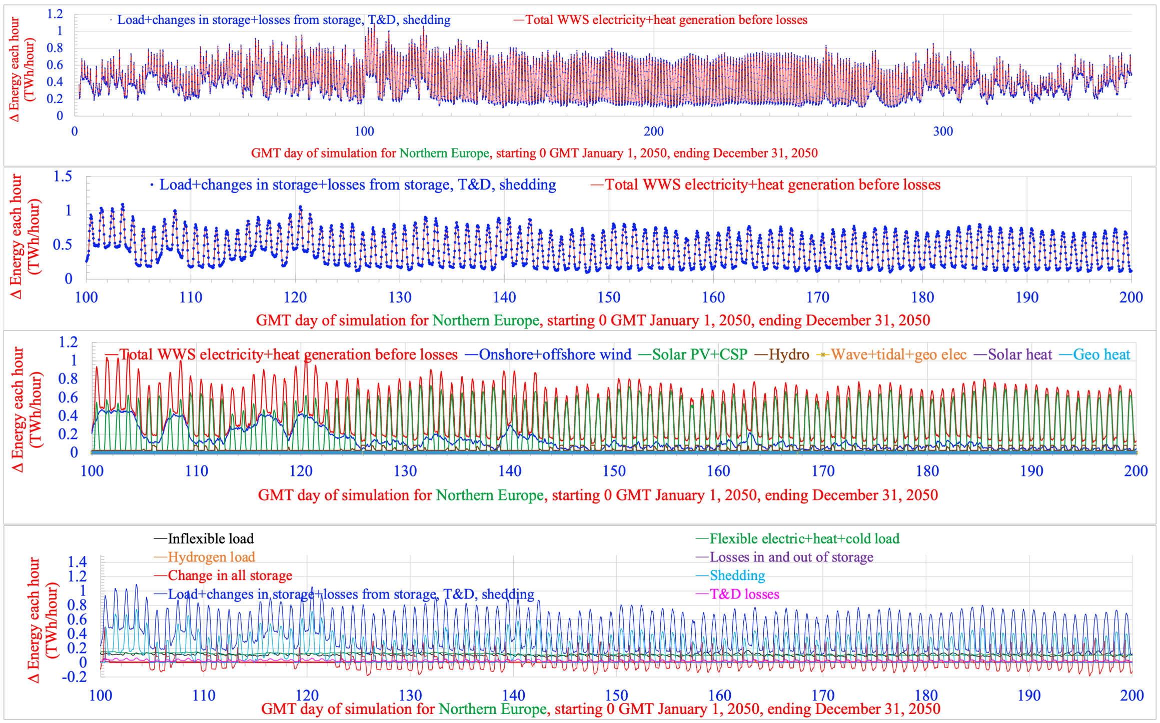

Table 6. End-Use Load, Capital Cost, Cost of Energy, and BAU vs. 100% WWS Annual Social Costs

2050 regional annual-average end-use (a) BAU and (b) WWS loads; (c) present values of the mean total capital cost for new WWS electricity, heat, cold, and hydrogen generation and storage and long-distance transmission; mean levelized private costs of all (d) BAU and (e) WWS energy (¢/kWh-all-energy-sectors, averaged between today and 2050, in USD 2013); (f) mean aggregate WWS private (equals social) energy costs per year (2013 USD $billion/yr), and mean aggregate BAU (g) private energy cost, (h) health cost, (i) climate cost, and (j) total social cost per year (2013 USD $billion/yr).

Region	(a) Annual average BAU end-use load (GW)	(b) Annual average WWS end-use load (GW)	(c) Mean WWS Total capital cost ($tril 2013)	(d) Mean BAU (¢/kWh -all energy)	(e) Mean WWS (¢/kWh -all energy)	(f) Mean annual WWS all-energy private and social cost ($bil/yr)	(g) Mean annual BAU all-energy private cost ($bil/yr)	(h) Mean annual BAU health cost ($bil/yr)	(i) Mean annual BAU climate cost ($bil/yr)	(j) =g+h+i Mean annual BAU total social cost ($bil/yr)
Northern Europe	679.2	287.1	2.509	10.52	9.70	243.9	626	288	804	1,718

Footnote. Aggregate private energy cost (Columns f or g) equals annual average end use load (Column a or b) multiplied by the mean cost per unit energy (Column d or e) and by 8760 hours per year. Tables S14, S16, and S18 of Jacobson et al. (2019) give parameters for determining the costs of energy, health damage, and climate avoided, respectively. Table S13 of Jacobson et al. (2019) gives the lifecycle costs and efficiencies of storage for each storage type. The discount rate used for generation, storage, transmission/distribution, and social costs is a social discount rate of 2 (1-3)%[1].

Table 7. Breakdown of Energy Costs Required to Keep Grid Stable

Summary of 2050 WWS mean capital costs of new electricity plus heat generators and storage ($ trillion in 2013 USD) and mean levelized private costs of energy (LCOE) (USD ¢/kWh-all-energy or ¢/kWh-electricity-replacing-BAU-electricity) averaged over the 1-year simulations. Also shown are the energy consumed per year in each case and the resulting aggregate annual energy cost to the region.

	Northern Europe
Capital cost new generators only ($trillion)	2.10
Cap cost new generators + storage ($trillion)	2.51
Components of total LCOE (¢/kWh-all-energy)	
Short-dist. transmission (¢/kWh-all-energy)	1.05
Long-distance transmission	0.12
Distribution	2.38
Electricity generators	5.10
Additional hydro turbines	0
Solar thermal collectors	0.13
CSP-PCM+PHS+battery storage	0.56
CW-STES+ICE storage	0.002
HW-STES storage	0.009
UTES storage	0.08
H_2 production/compression/storage	0.27
Total LCOE (¢/kWh-all-energy)	**9.70**
LCOE (¢/kWh-replacing BAU electricity)	9.33
GW annual avg. end-use demand (Table S10)	287.1
TWh/y end-use demand (GW x 8,760 h/y)	2,515
Annual energy cost ($billion/yr)	**243.9**

The LCOEs are derived from capital costs assuming a social discount rate for an intergenerational project of 2.0 (1 to 3) percent and lifetimes, annual O&M, and end-of-life decommissioning costs that vary by technology, all divided by the total annualized end-use demand met, given in the present table. Capital costs are an estimated average of those between 2015 and 2050 and are a mean (in USD $1 million/MW) of 1.27 for onshore wind, 3.06 for offshore wind, 2.97 for residential rooftop PV, 2.06 for commercial/government PV, 1.32 for utility PV, 4.33 for CSP with storage, 3.83 for geothermal electricity and heat, 2.81 for hydropower, 3.57 for tidal, 4.01 for wave, and 1.22 for solar thermal for heat.

Since the total end-use load includes heat, cold, hydrogen, and electricity loads (all energy), the "electricity generator" cost, for example, is a cost per unit all energy rather than per unit electricity alone. The 'Total LCOE' gives the overall cost of energy, and the 'Electricity LCOE' gives the cost of energy for the electricity portion of load replacing BAU electricity end use. It is the total LCOE less the costs for UTES and HW-STES storage, H_2, and less the portion of long-distance transmission associated with H_2.

Long-distance transmission costs are provided in the footnote to Table S14.

Storage costs are derived as described in Table S13.

H_2 costs are derived as in Note S38 and Note S43. These costs exclude electricity costs, which are included separately in the present table.

Table 8. Energy Balances Resulting in Grid Stability

Summary of WWS energy requirements met, energy losses, energy supplies, and changes in storage, during the 3-year (26,291.5 hour) simulations for 24 world regions. All units are TWh over the 3-year simulation. Table 1 identifies the countries within each region.

	Northern Europe
A1. Total end use demand	**2,512**
Electricity for electricity inflexible demand	1,139
Electricity for electricity, heat, cold storage + DR	1,208
Electricity for H_2 direct use + H_2 storage	164
A2. Total end use demand	**2,512**
Electricity for direct use, electricity storage, + H_2	2,166
Low-T heat load met by heat storage	342
Cold load met by cold storage	3.98
A3. Total end use demand	**2,512**
Electricity for direct use, electricity storage, DR	1,984
Electricity for H_2 direct use + H_2 storage	164
Electricity + heat for heat subject to storage	342
Electricity for cold load subject to storage	22.68
B. Total losses	**977**
Transmission, distribution, downtime losses	222
Losses CSP storage	0.00
Losses PHS storage	20.1
Losses battery storage	12.16
Losses CW-STES + ICE storage	0.72
Losses HW-STES storage	46.78
Losses UTES storage	63.58
Losses from shedding	611
Net end-use demand plus losses (A1 + B)	***3,489***
C. Total WWS supply before T&D losses	**3,466**
Onshore + offshore wind electricity	1,666
Rooftop + utility PV+ CSP electricity	1,443
Hydropower electricity	325
Wave electricity	3
Geothermal electricity	0.255
Tidal electricity	1.226
Solar heat	3.586
Geothermal heat	23.613
D. Net taken from (+) or added to (-) storage	**22.505**
CSP storage	0
PHS storage	-0.056
Battery storage	-0.272
CW-STES+ICE storage	-0.004
HW-STES storage	-0.062
UTES storage	17.455
H_2 storage	5.444
Energy supplied plus taken from storage (C+D)	***3,489***

End-use demands in A1, A2, A3 should be identical. Transmission/distribution/maintenance losses are given in Table S14. Round-trip storage efficiencies are given in Table S13. Generated electricity is shed when it exceeds the sum of electricity demand, cold storage capacity, heat storage capacity, and H_2 storage capacity. Onshore and offshore wind turbines in the climate model are assumed to be Senvion (formerly Repower) 5 MW turbines with 126-m diameter rotors, 100 m hub heights, a cut-in wind speed of 3.5 m/s, and a cut-out wind speed of 30 m/s. Rooftop PV panels in GATOR-GCMOM were modeled as fixed-tilt panels at the optimal tilt angle of the country they resided in; utility PV panels were modeled as half fixed optimal tilt and half single-axis horizontal tracking. All panels were assumed to have a nameplate capacity of 390 W and a panel area of 1.629668 m^2, which gives a 2050 panel efficiency (Watts of power output per Watt of solar radiation incident on the panel) of 23.9%, which is an increase from the 2015 value of 20.1%. Each CSP plant before storage is assumed to have the mirror and land characteristics of the Ivanpah solar plant, which has 646,457 m^2 of mirrors and 2.17 km^2 of land per 100 MW nameplate capacity and a CSP efficiency (fraction of incident solar radiation that is converted to electricity) of 15.796%, calculated as the product of the reflection efficiency of 55% and the steam plant efficiency of 28.72%. The efficiency of the solar thermal for heat hot fluid collection (energy in fluid divided by incident radiation) is 34%.

Table 9. Summary of the Private and Social Costs of a Northern European *Green New Deal*
2050 Northern European WWS versus BAU mean social cost per unit energy. Also shown is the WWS-to-BAU aggregate social cost ratio and the components of its derivation (Equation 5 of paper).

a) BAU electricity private cost per unit energy (¢/kWh)[1]	10.5
b) BAU health cost per unit energy (¢/kWh)	4.84
c) BAU climate cost per unit energy (¢/kWh)	13.5
d) BAU social cost per unit energy (¢/kWh) (a+b+c)	**28.9**
e) WWS private and social cost per unit energy (¢/kWh)[1]	**9.70**
f) BAU end-use power demand (GW)[2]	679.2
g) WWS end-use power demand (GW)[2]	287.1
h) BAU aggregate annual energy private cost ($bil/yr) (af)	626
i) BAU health cost ($bil/yr) (bf)	288
j) BAU climate cost ($bil/yr) (cf)	805
k) BAU social cost ($bil/yr) (df)	**1,719**
l) WWS private and social cost ($bil/yr) (eg)	**244**
m) WWS-to-BAU energy private cost/kWh ratio ($R_{WWS:BAU-E}$) (e/a)	0.92
n) BAU-energy-private-cost/kWh-to-BAU-social-cost/kWh ratio ($R_{BAU-S:E}$) (a/d)	0.36
o) WWS-kWh-used-to-BAU-kWh-used ratio ($R_{WWS:BAU-C}$) (g/f)	0.42
WWS-to-BAU aggregate social cost ratio (R_{ASC}) (mno)	**0.14**
WWS-to-BAU aggregate private cost ratio (R_{APC}) (mo)	**0.39**
WWS-to-BAU social cost per unit energy ratio (R_{SCE}) (mn)	**0.34**

[1]This is the BAU electricity-sector cost of energy per unit energy. It is assumed to equal the BAU all-energy cost of energy per unit energy. The WWS cost per unit energy is for all energy, which is almost all electricity (plus a small amount of direct heat).
[2]Multiply GW by 8,760 hr/yr to obtain GWh/yr.

Table 10. Land Areas Needed

Spacing areas for new onshore wind turbines, and footprint areas for new utility PV, CSP, solar thermal for heat, geothermal for electricity and heat, and hydropower in each grid region. Spacing areas are areas between wind turbines needed to avoid interference of the wake of one turbine with the next. Such spacing area can be used for multiple purposes, including farmland, rangeland, open space, or utility PV. Footprint areas are land areas on the ground that cannot be used for multiple purposes. Rooftop PV is not included because it does not take up new land. Conventional hydro new footprint is zero because no new dams are proposed as part of these roadmaps. Offshore wind, wave, and tidal are not included because they don't take up new land. Table S25 gives the installed power densities assumed. Areas are given both as an absolute area and as a percentage of the region land area, which excludes inland or coastal water bodies. For comparison, the total area and land area of Earth are 510.1 and 144.6 million km^2, respectively.

Region	Region land area (km^2)	Footprint Area (km^2)	Spacing area (km^2)	Footprint area as percentage of region land area (%)	Spacing area as a percentage of region land area (%)
Northern Europe	1,230,168	5,438	13,681	0.44	1.11

Table 11. Changes in the Numbers of Long-Term, Full-Time Jobs

Estimated long-term, full-time jobs created and lost due to transitioning from BAU energy to WWS across all energy sectors. The job creation accounts for new jobs in the electricity, heat, cold, and hydrogen generation, storage, and transmission (including HVDC transmission) industries. However, it does not account for changes in jobs in the production of electric appliances, vehicles, and machines or in increasing building energy efficiency. Construction jobs are for new WWS devices only. Operation jobs are for new and existing devices. The losses are due to eliminating jobs for mining, transporting, processing, and using fossil fuels, biofuels, and uranium. Fossil-fuel jobs due to non-energy uses of petroleum, such as lubricants, asphalt, petrochemical feedstock, and petroleum coke, are retained. For transportation sectors, the jobs lost are those due to transporting fossil fuels (e.g., through truck, train, barge, ship, or pipeline); the jobs not lost are those for transporting other goods. The table does not account for jobs lost in the manufacture of combustion appliances, including automobiles, ships, or industrial machines.

Region	Construction jobs produced	Operation jobs produced	Total jobs produced	Jobs lost	Net change in jobs
Northern Europe	909,377	1,185,268	2,094,645	730,546	1,364,099