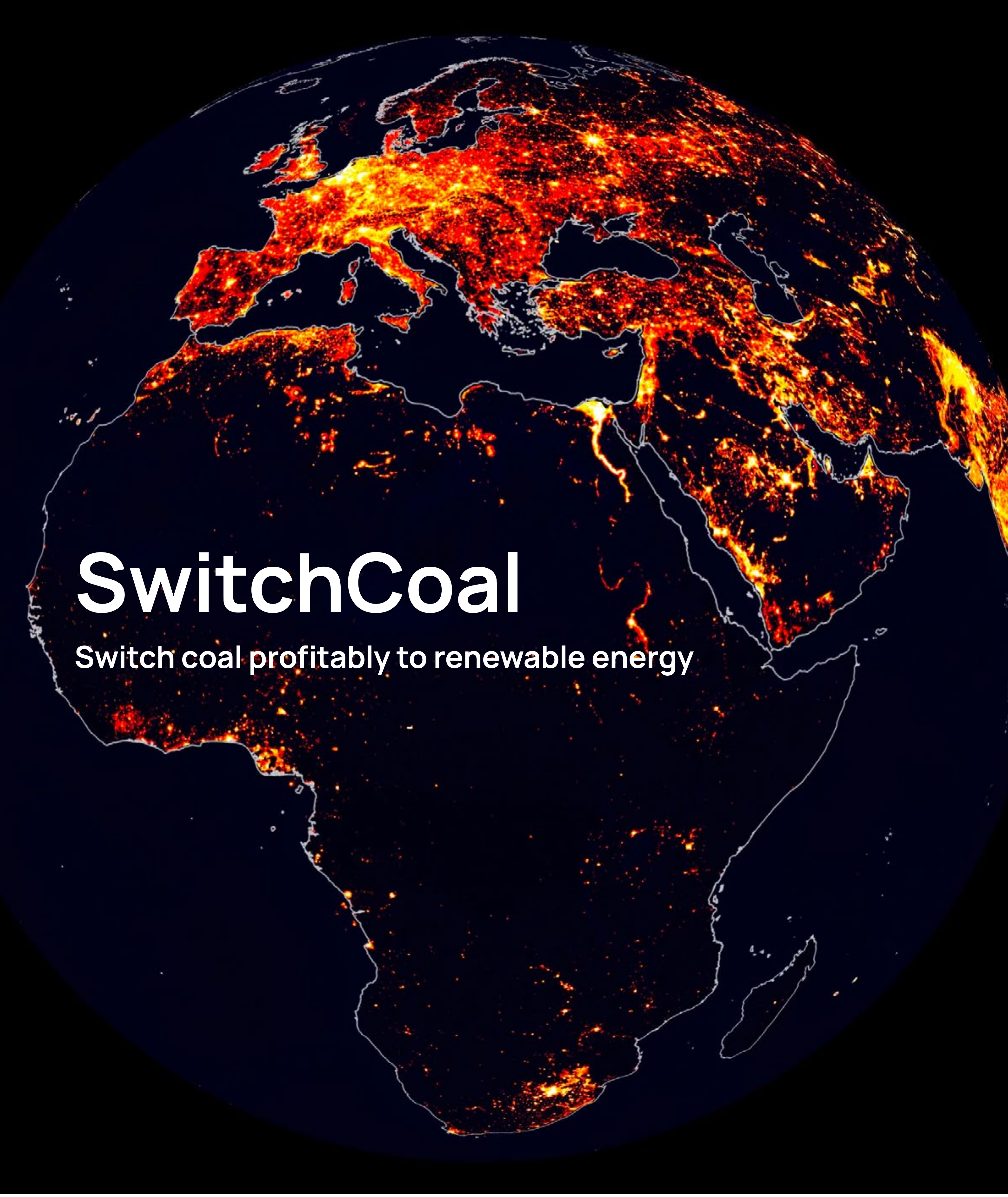

SwitchCoal

Switch coal profitably to renewable energy

SwitchCoal

Climate solution study by www.switchcoal.org

Imprint

SwitchCoal. Switch coal profitably to renewable energy

SwitchCoal is an initiative of ZETT Zero Emission Think Tank and Goodfuture from Berlin, Germany

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Title picture
The Open-source Data Inventory for Anthropogenic CO2 (A.K.A. ODIAC) is a global high-resolution (1x1km) emission data product for fossil fuel carbon dioxide (CO2) emission.
Source: NASA's Scientific Visualization Studio

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Executive Summary

Installing and operating wind and solar farms, together with large-scale batteries in some cases, is already cheaper than the operating costs of many existing coal-fired power plants, see red arrows in Figure 1. This has been assessed by trustworthy sources on purely economic grounds, such as Bloomberg NEF, the International Energy Agency (IEA), and the International Renewable Energy Agency (IRENA).[1-3]

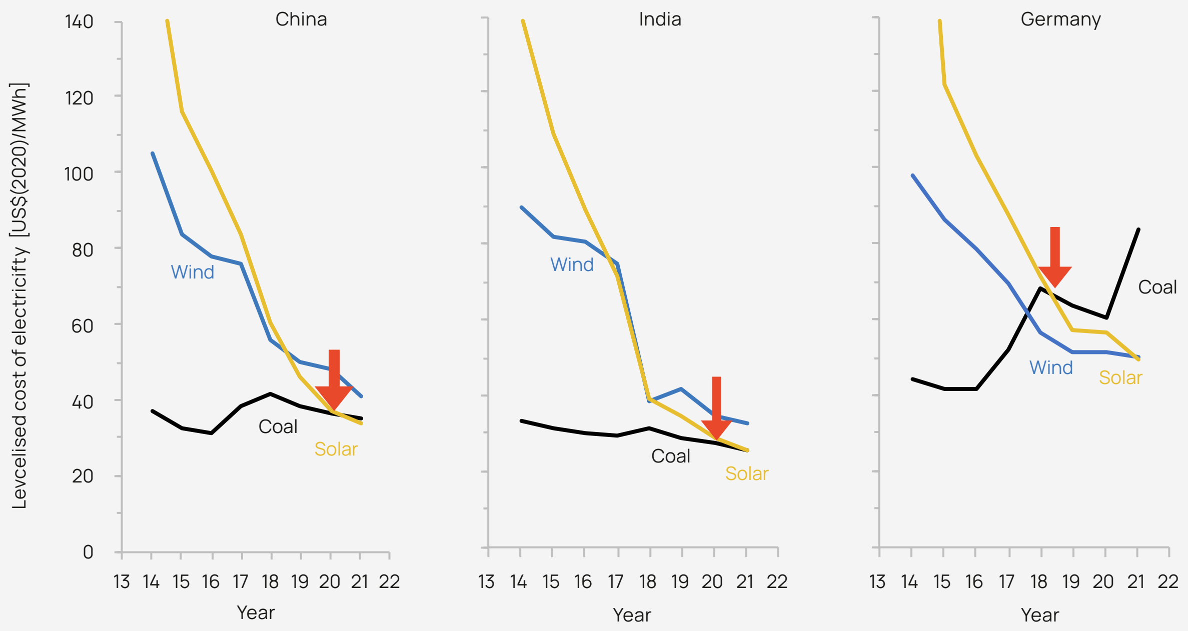
This implies that investments in replacing such coal-fired power plants with wind-solar-battery systems does not only offer the regular investment returns of a stand-alone renewable energy project, but also generates **additional profits** through lower operational costs, if compared to existing coal plants.

We assessed the approximately 2500 coal-fired power plant sites in operation and in construction worldwide and come to the following conclusions:

- **Approximately 90% of the world's coal-fired power plants** can profitably be switched to wind-solar-battery systems with equal energy amount
- **Billions in additional profits** can be achieved by the local (coal) power companies over the lifetime of the wind-solar-battery systems in many cases, shortening amortization times. See adjacent Figure.
- **10 Gigatons of CO_2 emissions** can be reduced prior to 2030[4], because the existing grid connection of the coal plants is used, shortening planning times.

Cost development of coal-fired and renewable power from 2013–2021

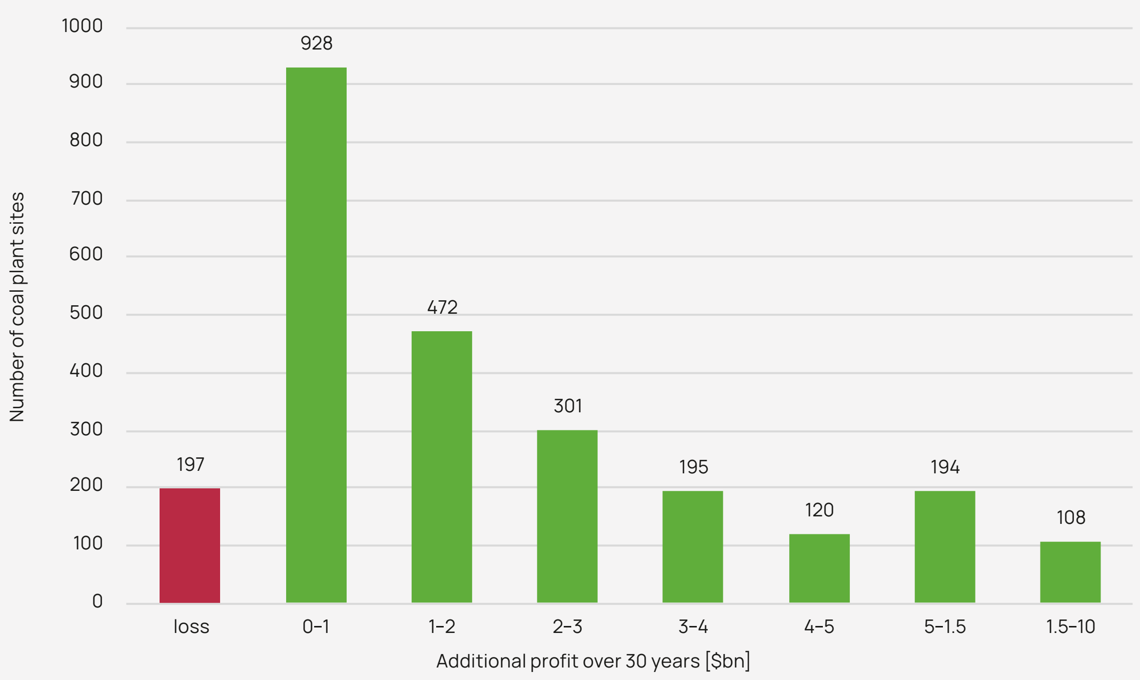
Figure 1



Source: Bloomberg NEF, 2021

After switching from coal to renewables and batteries, additional profits can be gained due to lower operating cost of renewables

Figure 2



Source: SwitchCoal, 2023

- **The employees of the coal plants** can continue to be employed after short retraining, while they assemble and install the solar modules locally and elsewhere.

To practically support delegates at COP28 and political stakeholders with these solutions, we present the results on a country-by-country basis as COP28 guide.

Delegates are encouraged to "Act - Borrow - Cash in":

1. **Act: pledge additional coal plant retirements** for their Nationally Determined Contributions (NDCs) for the Global Stock Taking process,
2. **Borrow: find financing for investments** at COP28 to switch from coal to renewables,
3. **Cash in: catalyze the local implementation** at home with billion $ additional profits.

Note:Historically countries have used prospective additional profits to lower electricity rates or boost investment returns.

SwitchCoal's "low-hanging fruit" is indeed more than a highly profitable way to reduce greenhouse gas emissions before 2030: It may be the last chance to control a favorable climate for us humans,[5-7] as global climate tipping points are predicted if 1.5° Celsius is exceeded.[8]

The study is a blueprint for a pragmatic approach that is profitable and feasible. Therefore, instead of "act on climate", like the UN has done so far, it is far more engaging to adopt "act on climate and make profits".

Main results by country

The table below shows COP28 delegates the number of coal-fired power plant sites in their country that can be profitably switched to a wind-solar-battery system, with billions of dollars in additional profit (see green numbers) due to the lower operating costs of renewables.

These profits are calculated over the 30-year service life of the renewable system with a battery replacement after 15 years. The table also shows the annual CO_2 emissions saved, the expected investment and the return on investment.

Key SwitchCoal study results on country level, using physics-based optimization model (see Appendix)

Table 1

	Number of coal plants	**Annual CO_2 emissions**	**Investments**	**Regular profits**	**Additional profits**
	profitably switchable	saved by switching	in wind-solar-battery farm	at 5–6% IRR, approx., not compounded	from switching, over 30 years
Country	**profitable / all**	**Mt / yr**	**US$bn**	**US$bn**	**US$bn**
Argentina	2 / 2	3.2	1.2	2.5	**2.3**
Australia	16 / 19	98.6	43.8	87.7	**60.8**
Bangladesh	7 / 7	34.6	16.8	33.6	**15.0**
Bosn and Herz	0 / 5	0.0	0.0	0.0	**0.0**
Botswana	2 / 2	3.6	1.6	3.3	**2.8**
Brazil	7 / 7	15.7	7.2	14.4	**9.1**
Brunei	1 / 1	1.2	0.5	1.1	**0.8**
Bulgaria	10 / 10	28.3	15.2	30.4	**77.4**
Cambodia	5 / 5	8.0	4.0	8.1	**3.0**
Canada	10 / 10	17.2	10.0	20.0	**13.4**
Chile	8 / 8	22.6	10.7	21.4	**13.5**
China	1162 / 1187	5261.1	2671.0	5341.9	**2826.7**
Colombia	5 / 5	8.8	4.4	8.9	**5.3**
Croatia	1 / 1	1.2	0.7	1.4	**4.1**
Czech Rep	25 / 25	43.6	21.8	43.7	**123.1**
Denmark	4 / 4	8.0	4.0	8.0	**27.6**
Dominican Rep	3 / 3	5.2	2.1	4.2	**3.8**

	Number of coal plants	**Annual CO_2 emissions**	**Investments**	**Regular profits**	**Additional profits**
	profitably switchable	saved by switching	in wind-solar-battery farm	at 5–6% IRR, approx., not compounded	from switching, over 30 years
Country	**profitable / all**	**Mt / yr**	**US$bn**	**US$bn**	**US$bn**
Finland	7 / 7	8.0	5.1	10.2	**25.3**
France	6 / 6	13.1	7.2	14.5	**41.7**
Germany	58 / 58	204.7	106.3	212.6	**616.5**
Greece	4 / 4	15.0	7.5	15.1	**42.4**
Guadeloupe	1 / 1	0.4	0.2	0.3	**0.3**
Guatemala	12 / 12	5.7	2.5	5.1	**4.0**
Honduras	1 / 1	0.6	0.3	0.6	**0.2**
Hong Kong	2 / 2	32.0	18.0	35.9	**17.0**
Hungary	2 / 2	5.8	3.2	6.4	**15.5**
India	274 / 291	1133.0	548.5	1097.0	**146.0**
Indonesia	88 / 99	264.3	126.2	252.4	**43.9**
Iran	1 / 1	2.8	1.0	2.1	**1.9**
Ireland	1 / 1	5.1	2.4	4.8	**17.8**
Israel	2 / 2	21.9	10.9	21.8	**12.9**
Italy	6 / 6	29.8	19.3	38.5	**97.9**
Japan	90 / 90	258.7	136.7	273.5	**105.3**
Kazakhstan	20 / 21	68.4	30.4	60.8	**39.8**
Kosovo	0 / 2	0.0	0.0	0.0	**0.0**
Kyrgyzstan	1 / 1	4.6	1.6	3.2	**2.8**
Laos	0 / 1	0.0	0.0	0.0	**0.0**
Madagascar	1 / 1	0.6	0.3	0.5	**0.3**
Malaysia	7 / 8	55.2	32.0	64.1	**35.1**
Mauritius	3 / 3	1.0	0.4	0.8	**0.6**
Mexico	3 / 3	27.4	13.0	26.0	**21.1**
Mongolia	5 / 5	5.7	2.1	4.1	**3.6**
Montenegro	0 / 1	0.0	0.0	0.0	**0.0**
Morocco	4 / 4	19.8	8.9	17.8	**12.3**

	Number of coal plants	Annual CO_2 emissions	Investments	Regular profits	Additional profits
	profitably switchable	saved by switching	in wind-solar-battery farm	at 5–6% IRR, approx., not compounded	from switching, over 30 years
Country	**profitable / all**	**Mt / yr**	**US$bn**	**US$bn**	**US$bn**
Myanmar	3 / 3	0.9	0.4	0.8	**0.5**
Namibia	1 / 1	0.8	0.3	0.7	**0.7**
Netherlands	4 / 4	16.5	9.8	19.5	**53.8**
New Zealand	1 / 1	3.0	1.1	2.3	**1.6**
Nigeria	3 / 3	1.7	0.8	1.6	**0.7**
North Korea	4 / 7	7.3	3.3	6.6	**3.1**
N. Macedonia	0 / 2	0.0	0.0	0.0	**0.0**
Pakistan	12 / 16	26.0	11.7	23.4	**16.7**
Panama	1 / 1	1.4	0.9	1.7	**0.7**
Philippines	24 / 26	58.5	27.1	54.2	**33.8**
Poland	43 / 43	157.6	87.4	174.8	**490.6**
Romania	8 / 8	17.2	9.5	18.9	**46.0**
Russia	0 / 73	0.0	0.0	0.0	**0.0**
Senegal	2 / 2	0.8	0.3	0.7	**0.5**
Serbia	0 / 4	0.0	0.0	0.0	**0.0**
Slovakia	4 / 4	4.5	2.6	5.1	**13.2**
Slovenia	2 / 2	5.2	2.7	5.3	**14.2**
South Africa	16 / 16	221.4	99.0	198.0	**174.7**
South Korea	25 / 25	180.3	91.4	182.8	**86.5**
Spain	6 / 6	11.9	7.2	14.4	**37.7**
Sri Lanka	1 / 1	4.3	1.8	3.6	**2.5**
Taiwan	20 / 20	90.9	48.0	95.9	**44.6**
Tajikistan	1 / 1	1.8	0.8	1.5	**0.8**
Thailand	9 / 10	16.9	9.0	18.1	**8.6**
Türkiye	10 / 34	35.2	19.9	39.8	**13.0**
Ukraine	14 / 14	55.6	21.7	43.5	**13.2**
United Kingdom	3 / 3	21.2	10.0	20.0	**8.8**

	Number of coal plants	Annual CO_2 emissions	Investments	Regular profits	Additional profits
	profitably switchable	saved by switching	in wind-solar-battery farm	at 5–6% IRR, approx., not compounded	from switching, over 30 years
Country	**profitable / all**	**Mt / yr**	**US$bn**	**US$bn**	**US$bn**
United States	202 / 216	1004.7	475.1	950.1	**553.7**
Uzbekistan	0 / 2	0.0	0.0	0.0	**0.0**
Vietnam	27 / 28	131.2	70.6	141.2	**49.7**
Zambia	2 / 2	1.5	0.6	1.2	**1.0**
Zimbabwe	3 / 3	10.2	4.6	9.3	**8.2**
Global (sum)	**2318 / 2515**	**9833**	**4917**	**9834**	**6172**

These values can be used by delegates at COP28 to
(1) **pledge** additional coal plant retirements
(2) **find investments** at COP28 to switch from coal to renewables
(3) **use billions of dollars in profits** to catalyze the local implementation at home

Study approach

This study determines the solar radiation and wind speeds in the vicinity of around 2500 coal-fired power plant sites that are in operation or under construction worldwide. Based on this data, the study estimates the cost of solar and wind electricity near by these locations. Furthermore, it proposes for each location the optimal mix of solar, wind and battery capacities to be installed to replace the coal power supply as close as possible over each day and the seasons. Finally, it estimates the total amount of capital investments required, the total operating costs of the combined wind-solar-battery plant compared to the coal plant, and the resulting additional profits or losses.

A physical and an economic model have been developed.

- Using the physical model, we calculate the required size of the wind, solar, and battery components so that enough renewable electricity can be reliably generated near the same location of each coal plant.
- Using the economic model, we assess the investments in the renewable system. To estimate the additional profits due to the lower operating costs compared to coal power, we use data from 2021, assuming that last year's price increase is temporary.

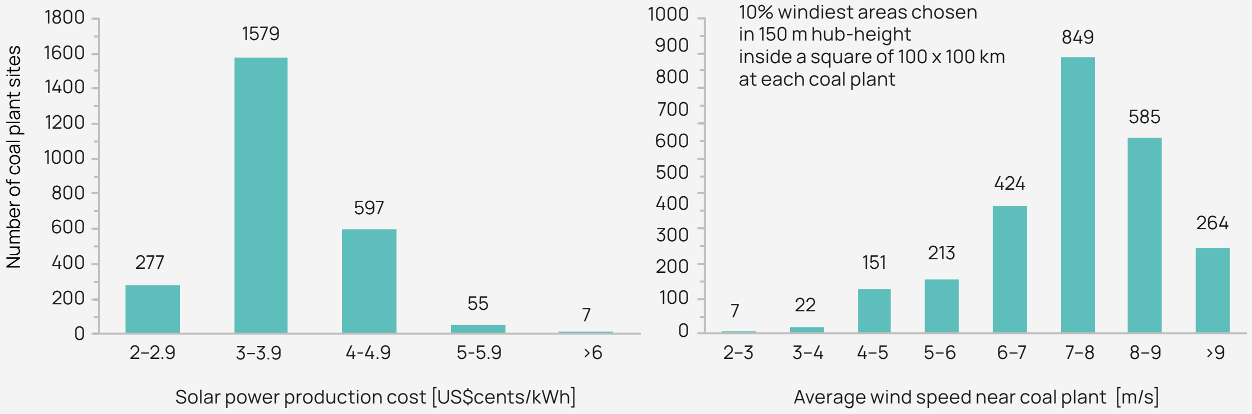
Sunshine and wind

The greater the amount of sunshine over the year, the cheaper solar electricity is. On top of this, there are of course variations we can find among countries, such as tax rates.[2] We found that most coal plant sites are in sunny places, where solar energy is cheap (about 3–4 US$cents per kWh of electricity), see Figure 3.

In addition, the windier it is, the cheaper the electricity from wind. Interestingly, most coal plants are also in areas with sufficient wind to

For the majority of coal plant sites, solar electricity costs are cheap (4 US$cents/kWh) and average wind speed is sufficiently high (6 m/s or higher)

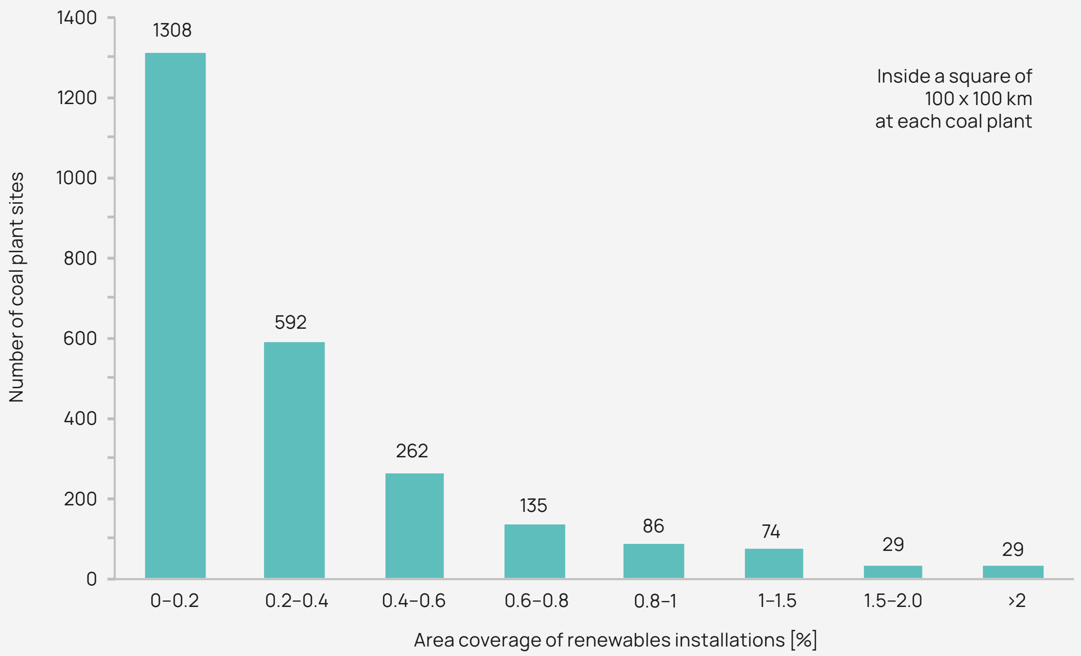
Figure 3



Source: SwitchCoal, 2023

For the majority of coal plant sites, less than 0.2% of the surrounding 100x100km area would be covered by the new solar, wind and battery installations

Figure 4



Source: SwitchCoal, 2023

warrant wind power at competitive energy prices (6–9 m/s average wind speed). However, the resulting electricity costs from wind farms depend on the local conditions, such as accessibility for transporting the blades, which must be considered on a case-by-case basis.[2]

Local surroundings

In our study, we generally choose the position of the solar and wind farms within a square of 100 by 100 km around existing coal plant sites. In this way, the new power sources can be fed into the existing grid at the location of the coal plant. This minimizes interconnection planning, which takes several years in many countries. It also avoids costly and lengthy network upgrades.

The choice of a 100 x 100 km square also considers the possible local variations in wind speed. Coal-fired power plants are often located in valleys, while good wind conditions prevail on hills and ridges. We have therefore selected the 10% windiest areas within this square. This approach also allows for flexibility when areas close to the plant cannot be used for solar or wind farms like built-up areas, nature reserves, water bodies, etc. In half of all the existing coal plant sites, solar, wind and battery power installations would cover less than 0.2% of the surrounding area of 100 x 100 km, see Fig. 4.

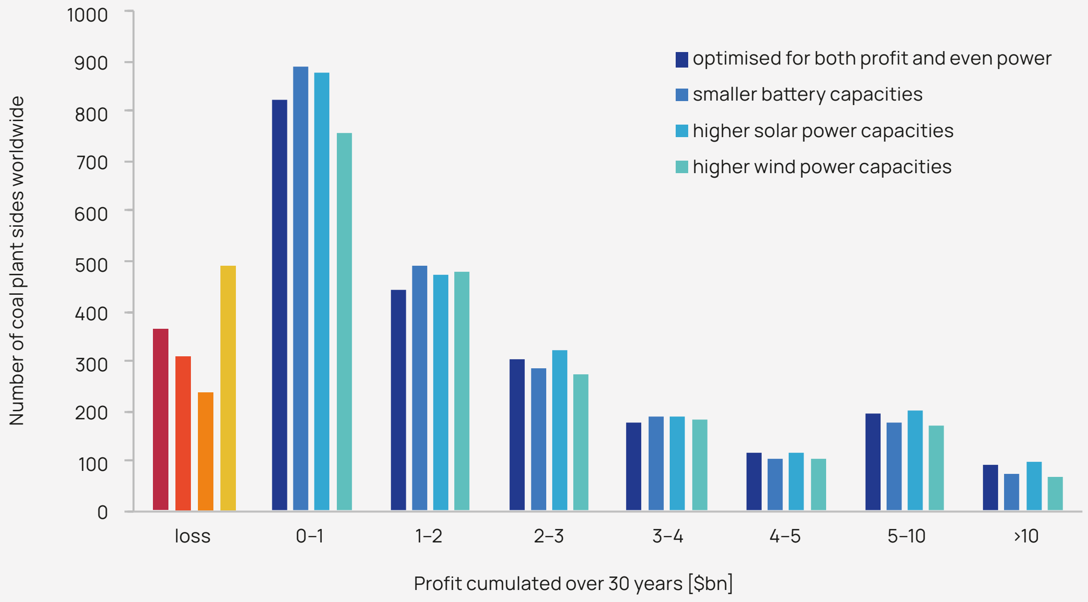
Sensitivity analysis of additional profits

On top of the regular project return on investment for the wind-, solar- and battery installations, including full return of capital and some 5–6% Internal Rate of Return (IRR), which are included in the power prices, additional profits arise from the much lower operating costs of renewable energies compared to coal.

Among other factors, these additional profits depend on the coal plant's operating costs as well

Robustness of the economic model, in terms of sensitivity to different ratios of installed solar, wind and battery capacities. The optimum is calculated for both profits and for evenly distributed power over the seasons.

Figure 5



Source: SwitchCoal, 2023

as on the ratio between installed solar-, wind- and battery capacities. This ratio determines how evenly renewable electricity generation is distributed throughout the year.[9] For the operating costs of coal plants, we use regional averages given by the International Energy Agency (IEA).[3] It is important to note that the studied variations of wind-solar-battery capacities have no significant impact on the distribution of calculated additional profits across global coal power plants. In other words, the economic model is robust, see Figure 5.

Of course, the exact additional profits need to be investigated in more detailed local assessments depending on local conditions. The robustness shown in Figure 5 is strengthened by the fact that we chose conservative estimates for fossil fuel prices, by using low coal power cost data from 2021, prior to the price spikes in 2022.

It might be surprising that the additional profits are not substantially influenced by the amount of batteries, but large-scale batteries have become much cheaper. Our aim is to match the output of the renewable energy plant as closely as possible to the existing coal-fired power plant over the whole year so that CO$_2$ emissions are truly avoided and not transferred to other types of fossil-fueled power plants that would have to compensate for lacking power. To match daily variations, we choose 8 hours of battery power per day – 4 hours in the evening when the sun goes down and 4 hours in the early morning when people get up before the sun rises. In summary, the physical and economic models are based on technologically and economically sound boundaries.

Amortization times

The resulting amortization times of the initial investments by the reduction of operating costs is

5–6 years at most sites in Spain, Poland and other European countries, and for example 15 years at many sites in India.

The very short amortization rates in Europe are due to the EU Emission Trading System (EU ETS) and the annually increasing prices per ton of CO_2 emission. Overall, an amortization period of 10 to 15 years is short and makes the switch from coal to renewables economically attractive.

Employment

Also the social perspective of switching from coal to renewable energy can be made positive, as employees of the coal plants can continue to be employed at least for some time. Planning and installing solar power takes about two years. After short retraining, plant employees can assemble the solar modules in local assembly lines and install them. This gives time for a smooth transition of employment and local economic structures.

The same can be done for the employees in coal mines. Generally renewable energies are a strong job generator, creating one million new employments just in 2022.[2]

CO_2 emissions

The investigated 2500 operating coal plant sites emitted approximately 11 Gt of CO_2 in 2021.[4] With about 90% of the coal plants switched profitably to renewable plants, nearly 10 Gt of CO_2 can be avoided per annum. This is about one quarter of all global CO_2 emissions.[4] Please note that this amount of CO_2 emissions can only be avoided if the renewables and battery capacities are installed in such a way that the output of the renewables matches the output of the coal plant throughout the day and the year. Otherwise, other (fossil) power plants will make up for the missing output. We therefore try to match the renewable power as closely as possible to the coal-fired power by choosing batteries and an optimal ratio of solar and wind farms.

Background

At the world climate summit COP28 in the United Arabic Emirates (UAE), countries are expected to communicate the status of their carbon emission reductions since the Paris agreement, called the Global Stock Take.

COP28 president Dr. Sultan Al Jaber has recently stated that at COP28 “we are going after the Gigatons” with a goal to “reduce 22 Gigatons by 2030”.

Coal-fired power plants are the easiest way to reduce carbon emissions and account for a staggering 11 gigatons of carbon emissions.[4]

Renewable energy has seen great cost reductions over the past decade and reaching an economic tipping point in 2017 (Germany) and 2019 (India and China) with now being even cheaper than running existing coal plants, according to Bloomberg.[1]

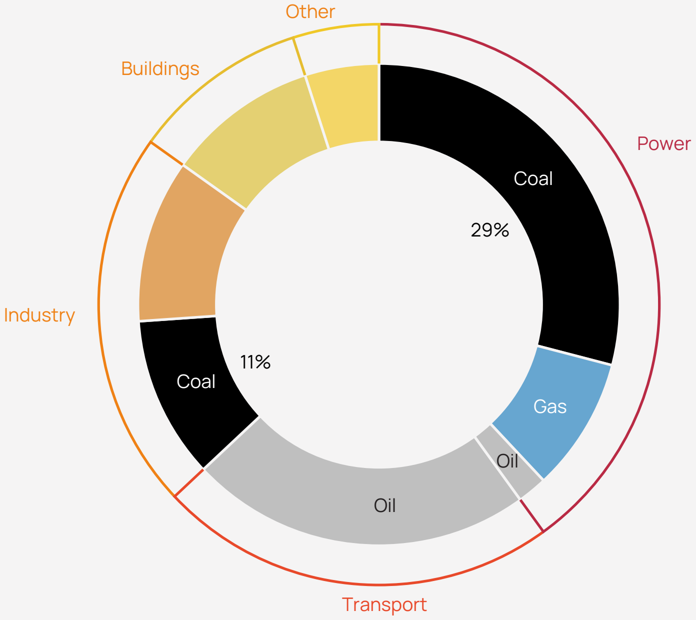
A comprehensive study of 145 countries accounting for 99.6% of the world's emissions has recently shown that it takes US$62tn for the global economy to transition to renewable energy systems, including 8 hours of battery power, with a payback time of only 5 years on purely economic grounds.[10]

Therefore, we have evaluated whether the world’s 2500 coal plant sites can be profitably switched to wind-solar-battery systems, including 8 hours of battery power, replacing coal plants on-site, on purely economic grounds.

Carbonbrief has published data on the world’s coal plants that are larger than 30 MW.[11] The

Global emissions by sector. 29% comes from coal-fired power plants, another 11% from industrial use of coal[1,4]

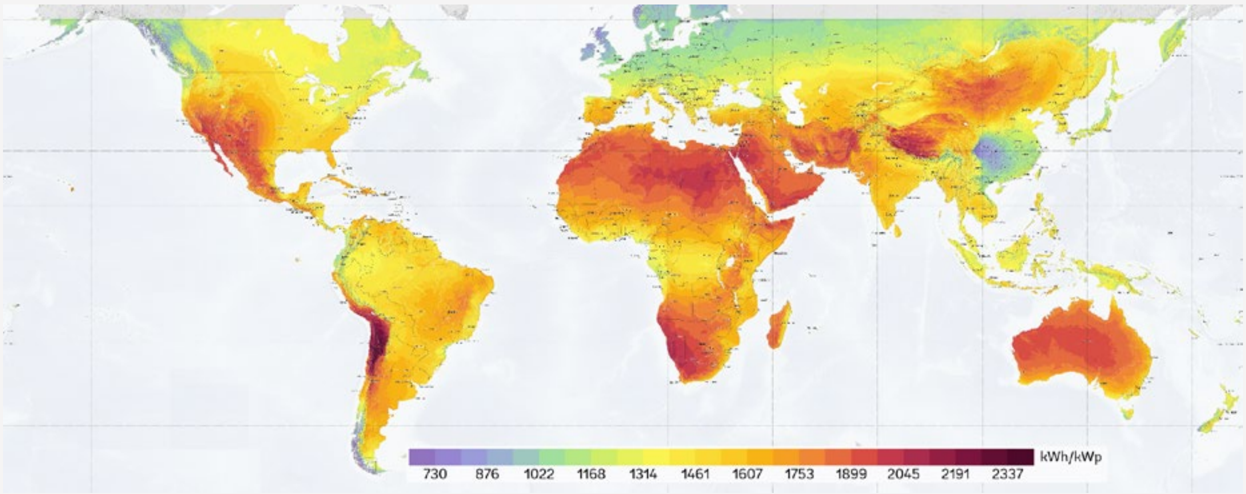
Figure 6



Source: International Energy Agency[3]

World Bank's global solar atlas.[12] In all regions colored light green, yellow, orange or red, solar energy is produced at 4 US$cents per kWh or less

Figure 7



Source: World Bank[12]

study uses these data, in conjunction with the World Bank's global solar[12] and global wind[13] atlas to evaluate the renewable resources at each coal plant site.

Economics for wind and solar energy production at the coal plant sites were calculated based on economic data from the International Energy Agency (IEA).[3]

2500 coal plant sites cause 30% of global emissions

According to the IEA, coal-fired power plants (coal plants) are responsible for 29% of the energy related global greenhouse gas emissions, as depicted in Figure 6.[3]

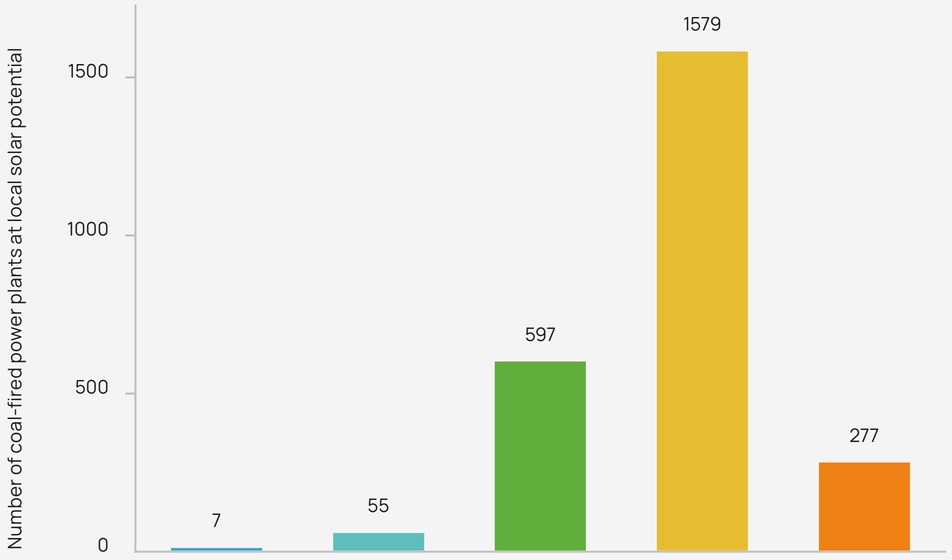
Solar potential at the 2500 coal plant sites

The World Bank has published a global solar atlas[12] for yearly photovoltaic power yields, shown in Figure 7.

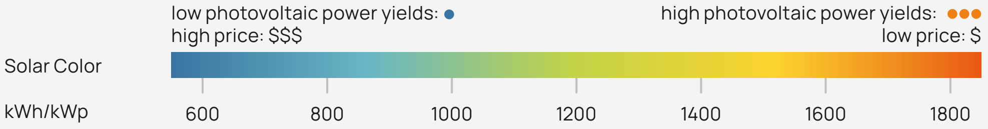
To assess the solar potential, an algorithm was developed to automatically extract the solar resources from the world solar atlas at each coal plant site.

The results depicted below show that about 74% of the coal plants have a solar potential with an annual production of more than 1233 kWh for each kWp installed (light green in the map), which is equivalent to solar energy production costs of 4 cents or less per kilowatt-hour (US$ct/kWh)

World Bank's global solar atlas.[12] Solar potential at the world`s 2500 coal plant sites (annual kWh/kWp). About three quarters of sites produce solar energy at 4 US$cents or less



% of plants	0.3%	2.2%	23.7%	62.8%	11.0%
Price [Cent/kWh]	> 6¢	≤ 6¢	≤ 5¢	≤ 4¢	≤ 3¢
Harvest [kWh/kWp]	‹821	822–986	987–1232	1233–1645	from 1645



Source: SwitchCoal, 2023, using data from World Bank[12]

Calculations of the solar potential at the coal plant sites

We developed an algorithm to automatically extract the "specific photovoltaic power output", which is kWh of electric power produced per kWp of installed solar panels over an average year (kWh/kWp), from the World Bank's global solar atlas[12] within an area spanning 100 km x 100 km around a coal plant.

The area needed for a large 500 MW solar farm is about 2.3 km x 2.3 km (500 hectars = 1.235 acres). Because not all the terrain might be suitable for solar, a larger 100 km x 100 km area was chosen. Note: The solar irradiation is quite uniform in such an area.

The solar potential,[12] which is kWh of electric power produced per kWp of installed solar panels over an average year. It varies only slightly within 100 km² in most geographies

Figure 9

Source: SwitchCoal, 2023

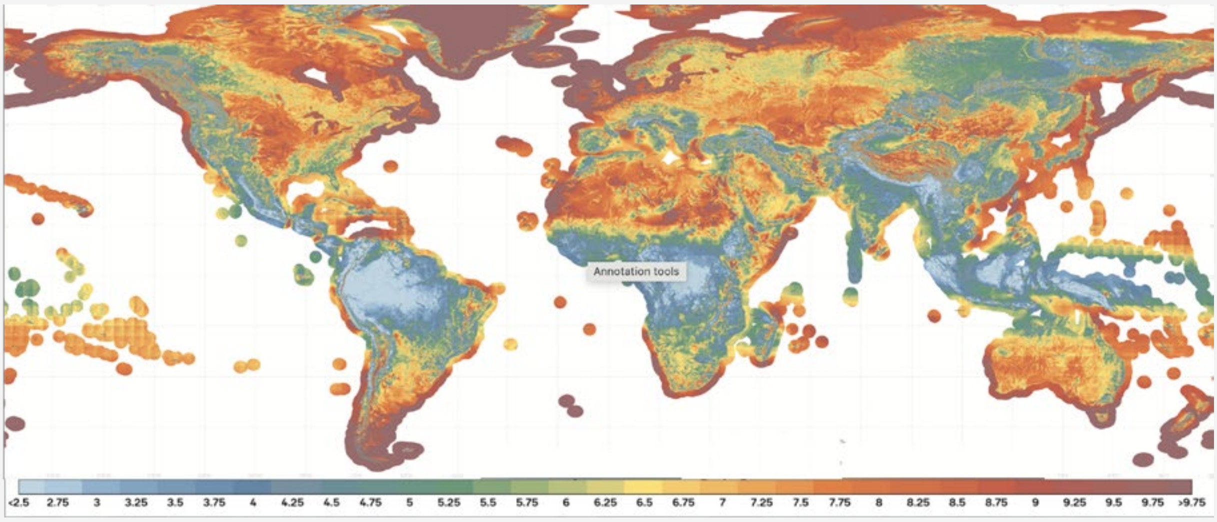
Wind potential at the 2500 coal plant sites

To assess the wind potential, we developed an algorithm to automatically extract the wind resources from the World Bank's global wind atlas[13] at each coal plant site.

The results depicted in Figure 10 show that 73% of the coal plant sites have a wind potential that exceeds an average windspeed of 7 m/s (orange in the map). This is equivalent to wind energy production costs of about 4 cents or less per kilowatt-hour (ct/kWh) in many countries (a main exception is the EU with 5.13 US$ct/kWh).

The World Bank's global wind atlas.[13] Most of the regions colored orange, red or purple have a sufficiently high average wind speed to produce wind energy for US$4 cents per kWh or less

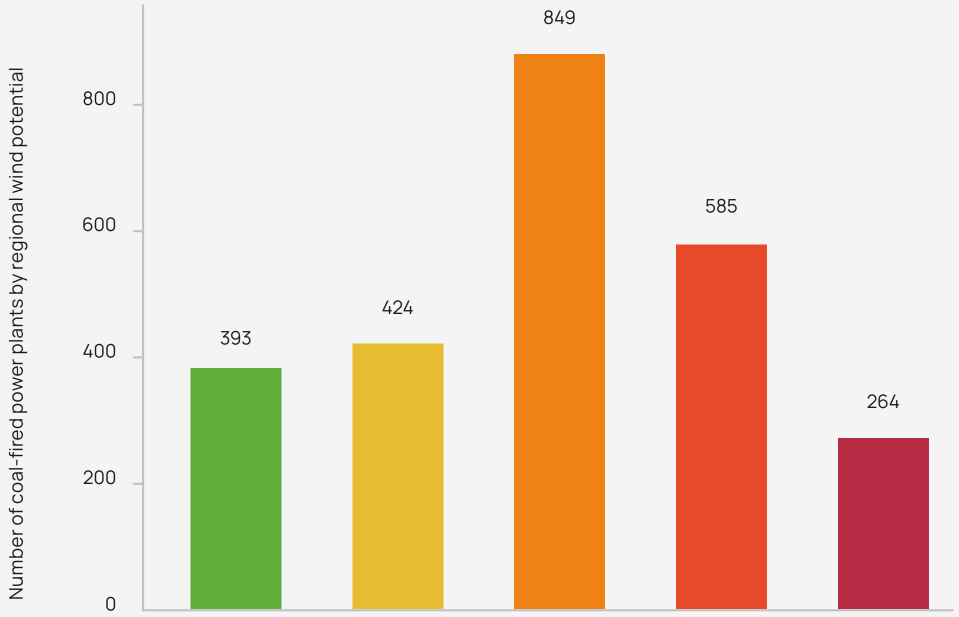
Figure 10



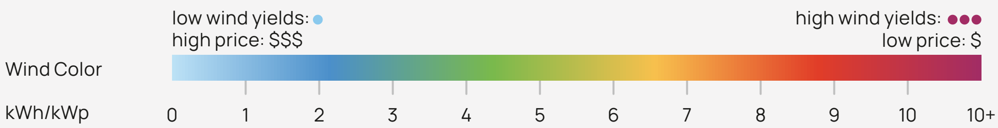
Source: World Bank[13]

Wind potential at the world's 2500 coal plant sites (annual kWh/kWp).
About 68% of sites with 7m/s or more produce wind energy at 4 cents or less.
The derivation of the cost (ct/kWh) is described in the section
"Wind and Solar Energy production costs" below

Figure 11



% of plants	15.6%	16.9%	33.8%	23.3%	10.5%
Price for US: [Cent/kWh]	> 5.28¢	≤ 5.28¢	≤ 4.27¢	≤ 3.74¢	≤ 3.44¢
Price for EU: [Cent/kWh]	> 6.24¢	≤ 6.24¢	≤ 5.13¢	≤ 4.53¢	≤ 4.2¢
Price for China: [Cent/kWh]	> 4.69¢	≤ 4.69¢	≤ 3.94¢	≤ 3.54¢	≤ 3.32¢
Price for India: [Cent/kWh]	> 4.72¢	≤ 4.72¢	≤ 3.84¢	≤ 3.38¢	≤ 3.12¢
Price for RoW: [Cent/kWh]	> 5.02¢	≤ 5.02¢	≤ 4.07¢	≤ 3.57¢	≤ 3.29¢
10% windiest area [m/s]	< 6	≥ 6	≥ 7	≥ 8	≥ 9



Source: SwitchCoal, 2023, using data from World Bank[13]

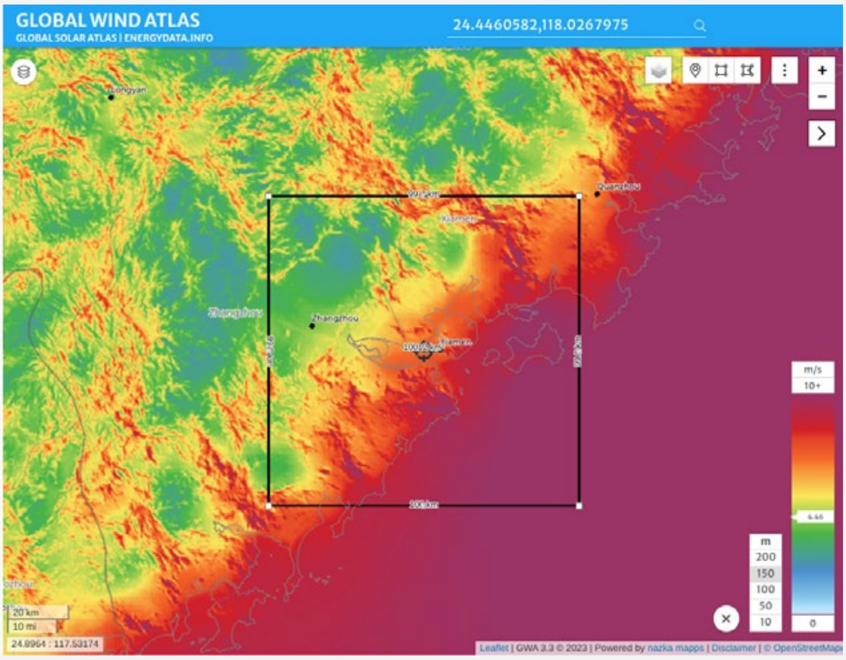
Calculations of the wind potential at the coal plant sites

An algorithm was developed to automatically extract the average wind speed (m/s) from the World Bank's global wind atlas[13] of the best 10% area within a 100 km x 100 km area around the coal plant, see Figure 12.

The area needed for a large 500 MW wind farm is calculated as follows:
Wind turbine rated capacity: 6.8 MW
No. of wind turbines needed: 500 MW / 6.8 MW = 74
Diameter (D) of wind turbine rotor: 175m
Spacing between wind turbines: 3D x 10D (525 m x 1750 m)

An area of 100 x 100 km around a coal plant in the World Bank's global wind atlas

Figure 12



Source: World Bank[13] and SwitchCoal, 2023

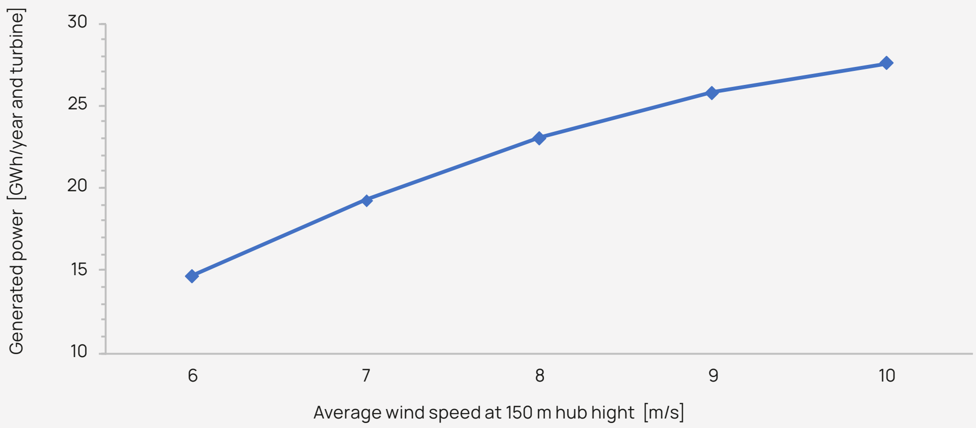
Note: This spacing assumes strong average wind speeds exceeding 8 m/s from a predominant wind direction. For lower wind speeds, a less spreadout 3D x 5D spacing may be sufficient.
Area needed for 74 wind turbines: 10.5 km x 6.5 km
Wind speeds were assessed at 150 m hub height for wind turbines. Current developments with up to 199 m hub heights were not considered.

For the calculation of wind energy production from average wind speeds, a Raleigh distribution is used, averaging out local wind profile variations to estimate the wind energy production:

For the calculation of wind energy production from average wind speeds, a Raleigh distribution is used, averaging out local wind profile variations to estimate the wind energy production:

Example of wind energy production estimating using a Rayleigh distribution

Figure 13



Source: SwitchCoal, 2023

Optimization of the wind-to-solar ratio

In order to optimize the wind-to-solar ratio economically, the capital and operational expenditures (CAPEX and OPEX) for the installation and energy production for wind-solar-battery systems were assessed and compared to the operational costs (OPEX) of existing coal plants. The questions were a) how many coal plants can be profitably replaced with wind-solar-battery systems, and b) how profitable would it be to replace each of the world's 2500 coal plants?

Wind and Solar Energy production costs

Production costs were estimated based on 2021 economic data from the World Energy Outlook[3] from the International Energy Agency (IEA).[14]

A simplified unleveraged financial model was used to calculate internal rates of returns (IRR) as deducted from the IEA economic data. Keeping these returns constant, production costs for wind and solar energy were calculated for the local wind and solar resources at each coal plant site. The results were already shown above in Figures 8 and 11.

Conclusions are:

- 68% of the coal plant sites with wind speeds of 7 m/s (orange in the wind map) or more, produce wind energy at 4 cents or less in many countries.
- 74% of the coal plant sites with solar resources of 1233 kWh/kWp (light green in the solar map) produce solar energy at 4 cents or less in most countries.

Economic input data of wind energy

The IEA provides economic data[3] for four geographic regions: the US, EU, India and China. Especially for wind farms, investment costs reflect many more parameters than for relatively simple solar farm constructions. For example, upgrading roads for the transport of long and heavy loads often adds to the investment costs.

For the purpose of our study, these IEA data were used, and a 5th region was defined as "Rest of World" averaging out the somewhat similar economic parameters between the US, China and India. EU data were excluded because of high renewable energy installation costs, but also because of high operating costs (OPEX) for coal plants in the EU, both of which are not representative for countries outside the EU.

The IEA furthermore provides economic data for 2021, with often much lower cost estimates for 2030 and beyond. Despite the study scope focused on short term installations from 2024–2030, we used only the rather conservative 2021 data to estimate wind energy production costs for each of the five regions.

Economic input data of solar energy

The IEA provides economic data[3] for 2021 for four geographic regions: The US, EU, India and China. However, solar utility construction is relatively simple. The CAPEX consists mainly of solar panels, a racking system, inverters, electrical items, dirt roads and planning costs. With global markets for all items, there is no technical reason for higher costs, except for labor and political reasons like permission costs, trade barriers and so on.
The IEA furthermore forecasts lower CAPEX costs for 2030, possibly reflecting such global market adjustments.

According to the IEA, international tenders often result in CAPEX costs of $0,65 cents/Wp or less, for which reason a CAPEX of $0.65 ct/Wp is assumed for all countries in the current study.

Operating costs are based on experiences in the US with 200 MW solar farms, where operating expenses (OPEX) were assumed to be 9% of the revenues. Larger solar farms tend to have lower costs. However, we do not assume any cost degression for the large solar projects in this study.

Unleveraged financial model of the wind farm

We developed a simple unleveraged financial model (FM) to calculate the internal rate of return (IRR) for the IEA base case economic data.[2]
The IRR was calculated over 30 years.

Example for the US:
Investment (CAPEX): 1380 $/kW
Average Capacity factor: 28%
Operating expenses (OPEX): $10/MWh
LCOE production costs: $45/MWh
The IRR was calculated, based on these input data, resulting in the base case internal rate of return.

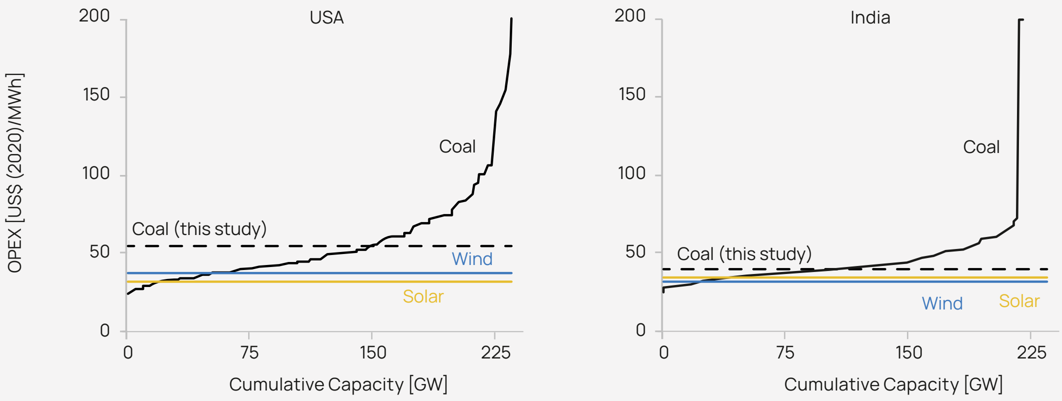
Single input parameter changes were used to calculate different capacity factors, based on different wind speeds, resulting in a variation of the output, i.e. LCOE production costs.
These input/output data pairs were used to develop a trendline which was used to calculate the production costs for each wind farm at each of the coal plant sites in a region.

OPEX costs for coal plants – examples

The graphics below show the US and India coal fleets with operating expenses (Renewable Energy Generation costs, IRENA 2020). According to the IEA, India's operating costs are on average 4 ct/kWh. According to Lazard, operating costs in the US are 5.2 ct/kWh.

Operating expenditure of coal plants in the US and in India. The dashed lines represent purchase agreements (PPAs) of solar and onshore wind[2]

Figure 14



Source: SwitchCoal, 2023

Coal plant operating costs (OPEX)

The operating expenses for coal plants were taken from the World Energy Outlook (IEA)[3] with adjustments and extrapolations for regions not covered, as listed below. Furthermore, adjustments were made for lignite plants (see below).

Operating expenses for existing coal plants.

India	4.0 ct/kWh	(a)
Indonesia	4.0 ct/kWh	(b)
China	5.5 ct/kWh	(c)
US	5.2 ct/kWh	(d)
EU	13.8 ct/kWh	(a)
Rest of world	5.2 ct/kWh	(d)

(a) IEA World Energy Outlook 2022, except lignite
(b) Assumed similar to India (a), except lignite
(c) IEA World Energy Outlook 2023, not 2022 because it is lower.
(d) Lazard 2023

Lignite power plants

Based on IEA data (World Energy Outlook 2022, p. 412), peat and lignite coal represent 5% of the overall coal production:

Mt	**2010**	**2021**
World coal production	**5235**	**5825**
Steam coal	4069	4560
Coking coal	866	1030
Peat and lignite	300	235

The Carbon Brief data on coal plants used in this study identify 264 lignite power plants. The following assumptions are made for the study:

OPEX

China	4.0 cents/kWh – reflecting carbon pricing
US	1.5 cents/kWh – reflecting clean air standards
EU	no corrections made because of high carbon pricing
Rest of world	1.0 cents/kWh – with no carbon pricing

Additionally, we found that half of all coal plants have a remaining lifetime shorter than 25 years, a quarter of plants shorter than 5 years. The depreciation time is usually much shorter than the plant life.

Please note: A minor number of coal plants also supplies heat to heating networks. Once the coal plant is converted to renewable energies, the heat can be generated by heat pumps (or other sources), which require around 10% more electricity. This is not considered in this study, as the heating market is different from the electricity market.

Wind-solar-battery system – optimization for wind and solar

With regards to the ratio of wind to solar energy, we chose two different approaches:

1. **A physics-based optimization model** for even power generation over the seasons.[9]
2. **An economic optimization model**, which seeks to install cheaper renewable power than is optimum in the first model.

The first approach can be seen in Germany with both renewables being complimentary, especially with winds at night with no sunlight. There is also a seasonal component in Germany, with much more wind in winter and much more sun in summer. In this case, the energy produced by a coal plant could be substituted with about 50% wind energy and about 50% solar energy, i.e. same amount of annual kWh produced. Germany runs separate auctions for wind and solar energy, to take advantage of both complementary renewable energy sources.

The second approach is to optimize for the cheapest renewable energy in a region. For example, in India, many coal plant sites only have marginal wind resources, but a high solar potential. In this case, a coal plant could be substituted by 90% solar energy and 10% wind energy (conceptually for the night / Note: The power grid usually provides backup power in power grids with renewables contributing less than 50% of the energy, with no need for batteries). This is probably the most common reality in the world, the cheapest renewable energy wins.

In the second approach (cheapest renewable energy), the wind-solar-battery system was optimized as follows:

1. A pricing coefficient Photovoltaics (PV)/Wind energy was calculated for each coal plant site
   ‹ 1: reflects solar energy being cheaper
   › 1: reflects wind energy being cheaper
   1: reflects same pricing for both, wind and solar
2. If the pricing coefficient is between 0.9 – 1.1, wind and solar energy were both taken into consideration on a 1:1 energy basis
3. If the pricing coefficient is ‹0.9
   Solar energy was added in for 90% of the energy, wind energy was taken for 10%.
4. If the pricing coefficient is ›1.1
   Wind energy was added in for 90% of the energy, solar energy was taken for 10%

With respect to the existing coal plants at 2500 sites, the average capacity factor is 53% according to Carbon Brief,[11] i.e. they are only running at half their capacity. For the purpose of this study, the energy produced by each coal plant was derived from the carbon emission data and has been completely replaced with wind and solar energy in the study.

Note: base load is becoming less relevant due to larger energy grids, storage capacities and the fact that wind and solar energy often balance each other well in higher latitudes.

Wind-solar-battery system – optimization of batteries

While wind and solar energy provide cheap renewable energy, batteries can fill in the gaps. The question is how much. The study distinguishes 3 scenarios.

The first scenario is a standard “load following” scenario which reflects historic power markets whereby load simply follows demand, which requires large amounts of batteries to back up renewables, with up to 100% of the system peak capacity.

An example is the power market in California. 4h batteries are used to discharge for 4h in the late afternoon, typically from 5–9pm, when the sun goes down and people go home for cooking and power use. Similarly, power is also needed in the morning before the sun raises. Therefore, this study assumes 8h of battery backup.

The amount of battery backup in this study was reduced to 50%, because of significant flexible loads coming on in the future with EVs and heat pumps, and because of a renewable energy penetration in most countries of much less than 100%.

The second scenario is a "flexible use" scenario, reflecting future power market designs with high renewable penetration whereby a "renewable pricing signal" indicates the abundance of cheap renewable energy ("green light"), or its scarcity ("red light"), functioning like a traffic light. 80% of the future energy consumption is expected to be flexible (EVs, heat pumps, smart fridges, laptops, etc.). Studies have shown that the amount of backup power is greatly reduced in such a future electricity market design, to only about 10% of the installed peak capacity for "flexible use" markets.[15] Therefore, the study assumes a 10% battery backup in this case.

A third scenario reflects "zero batteries". Countries with low overall renewable energy installations may not need to back up renewables with batteries at all.

All three scenarios were calculated, to determine the number of coal plants that can profitably be switched to wind-solar-battery systems. The results are depicted below.

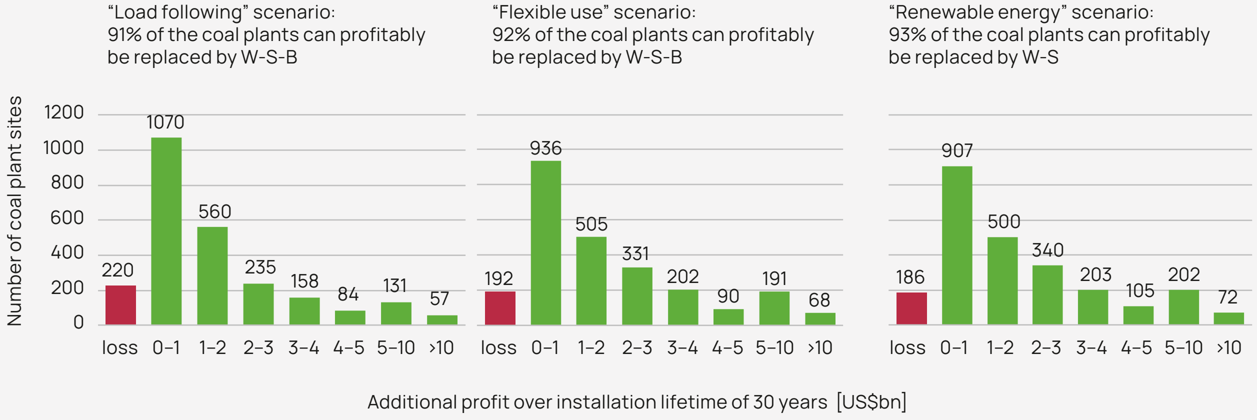
The observation that all three scenarios hardly differ in the results underpins the robustness and validity of our approach. In summary, the battery size (50% or 10% or 0% of the system peak capacity) does only marginally affect the number of coal plants that can be profitably switched to wind-solar-battery systems.

The results of the 1st approach, the physics-based optimization model, are listed below the executive summary (table 1 on pages 6 to 9). The detailed physical-economic model will be published in a scientific journal.

The results of the 2nd approach, the economically optimized for cheapest wind-so-

About 90% of the coal plants can be profitably switched to wind-solar-battery systems regardless of the battery capacities installed

Figure 15



Source: SwitchCoal, 2023

Battery cost assumption

The battery system is charged twice per day: during the day for the 4 hours in the evening, and by wind energy during the night for the 4 hours in the morning before sunrise. If less than 10% wind are installed optimally, the batteries are charged during the day for a whole of 8 hours. Investment costs into utility scale batteries are assumed to be $285/kWh for a 4-hour battery, according to the IEA (2021 data). Battery costs are assumed to decline to $185/kWh by 2030, however, such future cost degressions have not been considered in the study. With manufacturers warranties from 10 – 20 years, a 15-year lifespan was assumed for the battery.

Please note: Several car manufacturers have announced to introduce sodium salt batteries to the market, in up to every 4th of its battery cells at only $40/kWh. With common (sodium) salt costs in the $800 range per ton, compared to $40,000 – 80,000 for Lithium, costs may drop sharply in the future for such utility scale cheap sodium salt batteries. Such cost drops have not been considered in the study.

Please note: Batteries are the only storage technology considered in this study. There are other proven storage technologies such as pumped hydro, electricity-heat sector coupling, and others.

lar-battery systems, are listed in the table in the appendix (table 2 on pages 30 to 33). This approach reflects market realities with mostly low renewable energy penetration and the cheapest renewable energy prevailing.

This simple model yields similar results as our first approach. This shows that also the simple model is accurate enough to support our arguments.

Feasibility by 2030

We next evaluated the feasibility of the switch from coal power plants to renewables by 2030. Experience shows that planning large scale wind-solar-battery projects requires years, with the grid connection studies often taking up most of the time. Results show that planning times can be reduced to 2–3 years if the existing grid connection of the coal plant can be used.

Furthermore, we evaluated the global wind, solar manufacturing capabilities to see if the coal plants at the 2500 sites can be switched to renewables before 2030 given global manufacturing capacities. The results show that manufacturing capacities are already sufficiently large (and growing fast) to install the necessary wind and solar farms by 2030,

Annual global PV manufacturing capacity

2021	168 GW
2022	239 GW
2023	790 GW

Annual global wind turbine additions

2021	94 GW
2022	78 GW
2023	117 GW

Note: Doubling the wind power capacity is possible by switching from the current 3-4 MW class of wind turbines to the new 6-7 MW class, which is expected to happen.

SwitchCoal

Wind capacity needed:	1.5 TW
Solar PV capacity needed:	4.8 TW

Considering that production capacities for wind and solar energy grow, both are sufficient to replace all coal-fired power plants prior to 2030, with production capacities still available for other applications.

References

[1] Brian Eckhouse, “Solar and Wind Cheapest Sources of Power in Most of the World”, Bloomberg NEF (2020). https://www.bloomberg.com/news/articles/2020-10-19/wind-solar-are-cheapest-power-source-in-most-places-bnef-says#xj4y7vzkg

[2] IRENA, “Renewable power generation costs in 2021” IRENA (2022), e.g. pages 36 and 72. https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021

[3] IEA, “World Energy Outlook 2022” IEA (2022), showing data from 2021, e.g. page 469. https://www.iea.org/reports/world-energy-outlook-2021

[4] UNEP, “Emissions gap report 2023” (2023). https://www.unep.org/resources/emissions-gap-report-2023

[5] C. Xu, T. A. Kohler, T. M. Lenton, J.-C. Svenning, and M. Scheffer, “Future of the human climate niche” Proc. Natl. Acad. Sci., vol. 117, pp. 11350–11355 (2020). https://doi.org/10.1073/pnas.1910114117.

[6] S. Asseng, D. Spänkuch, I. M. Hernandez-Ochoa, and J. Laporta, “The upper temperature thresholds of life” Lancet Planet. Health, vol. 5, pp. e378–e385 (2021). https://doi.org/10.1016/S2542-5196(21)00079-6.

[7] C. Mora et al., “Global risk of deadly heat” Nat. Clim. Change, vol. 7, pp. 501–506 (2017). https://doi.org/10.1038/nclimate3322.

[8] T. M. Lenton et al., “Climate tipping points — too risky to bet against” Nature, vol. 575, no. 7784, pp. 592–595 (2019). DOI10.1038/d41586-019-03595-0.

[9] J. Kapica, F. A. Canales, and J. Jurasz, “Global atlas of solar and wind resources temporal complementarity” Energy Convers. Manag., vol. 246, p. 114692 (2021). https://doi.org/10.1016/j.enconman.2021.114692.

[10] M. Z. Jacobson et al., “Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries” Energy Environ. Sci., vol. 15, pp. 3343–3359 (2022). https://doi.org/10.1039/d2ee00722c.

[11] Global Energy Monitor, “Global Coal Plant Tracker”. https://globalenergymonitor.org/projects/global-coal-plant-tracker/

[12] World Bank, “Global Solar Atlas”. https://globalsolaratlas.info/map See acknowledgements

[13] World Bank, “Global Wind Atlas”. https://globalwindatlas.info/en See acknowledgements

[14] IEA, “Trends in PV Applications 2021” (2022). https://iea-pvps.org/trends_reports/trends-in-pv-applications-2021/

[15] D. Bogdanov et al., “Low-cost renewable electricity as the key driver of the global energy transition towards sustainability” Energy, vol. 227, p. 120467, (2021) . https://doi.org/10.1016/j.energy.2021.120467.

Appendix

Results of the physics-based optimization model

According to Carbon Brief[11], there are about 2500 coal plant sites in the world with capacity greater than 30 MW. The Carbon Brief's country specific values of plant total capacity, carbon emissions from these coal plants and their share in electricity-related emissions are given in these tables. Main question for replaycing coal power is the optimal ration of wind capacity to solar capacity. The seasonal weigthing of "Kapicia" values were normalized to derive the optimal mixture closed to the maximum yield of local renewables. The solar, wind and battery capacities, necessary for the switch, are the results from this model.[9] The results for the expected investment, the return on investment and the additional profits from the switch (over the 30-year service life of the renewable system with a battery replacement after 15 years) are shown in table 1 (on pages 6 to 9).

Table 2

Country	**Capacity**	**Number of coal plants**	**Annual CO_2 emissions**	**Share**	**Solar power capacity**	**Wind power capacity**	**Battery capacity**
	of all coal plants	profitably switchable	saved by switching	in electr.-related CO_2 emissions	required for switching	required for switching	Battery capacity
	GW	**profitable / all**	**Mt / y**	**%**	**GWp**	**GWp**	**GW**
Argentina	0.6	2 / 2	3.2	1.7	0.6	0.7	0.1
Australia	24.0	16 / 19	98.6	26.8	40.3	13.4	1.9
Bangladesh	8.6	7 / 7	34.6	32.4	19.1	3.2	0.6
Bos Herz	2.1	0 / 5	0.0	0.0	0.0	0.0	0.0
Botswana	0.7	2 / 2	3.6	51.4	1.9	0.2	0.1
Brazil	3.2	7 / 7	15.7	3.2	7.5	1.6	0.4
Brunei	0.2	1 / 1	1.2	16.6	0.8	0.0	0.0
Bulgaria	4.7	10 / 10	28.3	64.8	7.6	6.1	0.5
Cambodia	1.7	5 / 5	8.0	47.2	4.7	0.7	0.2
Canada	4.7	10 / 10	25.3	4.5	4.0	5.9	0.5
Chile	4.3	8 / 8	22.6	26.4	10.0	3.1	0.5
China	1208.4	1162 / 1187	5284.5	42.4	2546.6	770.0	107.4
Colombia	1.6	5 / 5	8.8	11.3	6.0	0.1	0.3
Croatia	0.2	1 / 1	1.2	6.7	0.4	0.2	0.0

Country	Capacity	Number of coal plants	Annual CO_2 emissions	Share	Solar power capacity	Wind power capacity	Battery capacity
	of all coal plants	profitably switchable	saved by switching	in electr.-related CO_2 emissions	required for switching	required for switching	Battery capacity
	GW	**profitable / all**	**Mt / y**	**%**	**GWp**	**GWp**	**GW**
Czech Rep	7.4	25 / 25	43.6	44.6	8.6	9.7	0.8
Denmark	1.6	4 / 4	8.0	29.3	0.8	2.1	0.2
Dominican R.	1.1	3 / 3	5.2	18.8	2.7	0.2	0.1
Finland	1.5	7 / 7	8.0	20.5	1.5	2.5	0.2
France	2.5	6 / 6	13.1	4.3	3.7	2.9	0.3
Germany	40.5	58 / 58	204.7	30.7	37.0	48.9	3.9
Greece	2.9	4 / 4	15.0	28.1	5.2	2.4	0.3
Guadeloupe	0.1	1 / 1	0.4	22.2	0.2	0.0	0.0
Guatemala	1.2	12 / 12	5.7	28.2	3.5	0.1	0.2
Honduras	0.1	1 / 1	0.6	6.2	0.3	0.1	0.0
Hong Kong	6.1	2 / 2	32.0	96.4	14.1	6.9	0.7
Hungary	0.9	2 / 2	5.8	11.4	1.4	1.4	0.1
India	266.3	274 / 291	1148.6	43.4	653.8	102.9	24.4
Indonesia	59.5	88 / 99	260.1	43.2	176.0	1.1	9.2
Iran	0.7	1 / 1	2.8	0.4	1.2	0.2	0.0
Ireland	0.9	1 / 1	5.1	14.6	0.6	1.2	0.1
Israel	4.3	2 / 2	21.9	36.8	8.8	4.1	0.5
Italy	6.2	6 / 6	29.8	9.3	11.1	7.1	0.6
Japan	55.4	90 / 90	258.7	23.9	109.6	51.5	5.1
Kazakhstan	13.1	20 / 21	68.4	32.4	14.4	16.8	1.4
Kosovo	1.3	0 / 2	0.0	n.a.	0.0	0.0	0.0
Kyrgyzstan	0.8	1 / 1	4.6	42.7	0.9	0.8	0.1
Laos	1.9	0 / 1	0.0	0.0	0.0	0.0	0.0
Madagascar	0.1	1 / 1	0.6	11.3	0.3	0.1	0.0
Malaysia	13.3	7 / 8	55.2	21.9	45.3	0.0	2.3
Mauritius	0.2	3 / 3	1.0	24.2	0.4	0.1	0.0
Mexico	5.4	3 / 3	27.4	6.5	14.9	2.0	0.9

Country	Capacity	Number of coal plants	Annual CO_2 emissions	Share	Solar power capacity	Wind power capacity	Battery capacity
	of all coal plants	profitably switchable	saved by switching	in electr.-related CO_2 emissions	required for switching	required for switching	Battery capacity
	GW	**profitable / all**	**Mt / y**	**%**	**GWp**	**GWp**	**GW**
Mongolia	1.0	5 / 5	5.7	22.8	1.7	0.7	0.1
Montenegro	0.2	0 / 1	0.0	n.a.	0.0	0.0	0.0
Morocco	4.3	4 / 4	19.8	26.9	8.4	2.6	0.4
Myanmar	0.2	3 / 3	0.9	2.2	0.5	0.1	0.0
Namibia	0.1	1 / 1	0.8	19.7	0.4	0.0	0.0
Netherlands	4.2	4 / 4	16.5	11.2	2.7	4.8	0.3
New Zealand	0.5	1 / 1	3.0	9.2	0.7	0.5	0.1
Nigeria	0.3	3 / 3	1.7	1.3	0.9	0.2	0.0
North Korea	3.3	4 / 7	7.3	11.7	3.1	1.0	0.1
N. Macedonia	0.8	0 / 2	0.0	0.0	0.0	0.0	0.0
Pakistan	8.4	12 / 16	26.0	11.8	15.1	0.8	0.9
Panama	0.3	1 / 1	1.4	11.2	1.2	0.0	0.1
Philippines	12.6	24 / 26	58.5	39.5	31.7	4.4	1.2
Poland	29.2	43 / 43	157.6	49.1	30.0	40.5	3.1
Romania	3.0	8 / 8	17.2	21.8	5.1	3.6	0.3
Russia	40.0	0 / 73	0.0	0.0	0.0	0.0	0.0
Senegal	0.2	2 / 2	0.8	6.7	0.4	0.0	0.0
Serbia	4.8	0 / 4	0.0	0.0	0.0	0.0	0.0
Slovakia	0.8	4 / 4	4.5	12.0	1.1	1.1	0.1
Slovenia	1.1	2 / 2	5.2	36.7	1.7	0.9	0.1
South Africa	45.2	16 / 16	221.4	50.8	119.6	13.9	4.6
South Korea	42.3	25 / 25	180.3	28.8	78.4	31.4	3.6
Spain	2.2	6 / 6	11.9	5.1	4.8	2.4	0.2
Sri Lanka	0.9	1 / 1	4.3	18.0	2.2	0.2	0.1
Taiwan	19.2	20 / 20	90.9	31.5	49.0	11.9	2.1
Tajikistan	0.4	1 / 1	1.8	17.8	0.6	0.3	0.0
Thailand	6.1	9 / 10	16.9	6.3	11.0	1.3	0.3

Country	**Capacity**	**Number of coal plants**	**Annual CO_2 emissions**	**Share**	**Solar power capacity**	**Wind power capacity**	**Battery capacity**
	of all coal plants	profitably switchable	saved by switching	in electr.-related CO_2 emissions	required for switching	required for switching	Battery capacity
	GW	**profitable / all**	**Mt / y**	**%**	**GWp**	**GWp**	**GW**
Türkiye	20.2	10 / 34	35.2	7.8	15.2	8.0	0.7
Ukraine	9.3	14 / 14	55.6	30	8.6	13.0	1.0
United Kingdom	4.1	3 / 3	21.2	6.3	2.9	4.8	0.4
USA	212.0	202 / 216	1,004.7	21.1	312.1	181.1	19.6
Uzbekistan	2.5	0 / 2	0.0	0.0	0.0	0.0	0.0
Vietnam	30.8	27 / 28	131.2	40.8	69.0	19.8	2.5
Zambia	0.3	2 / 2	1.5	21.4	0.8	0.0	0.1
Zimbabwe	1.9	3 / 3	10.2	83	6.1	0.2	0.4
Global	**2273**	**2318 / 2515**	**9876**	**29.4**	**4551**	**1420**	**206**

Sources: Carbon brief (2023), except the required solar and wind capacities.

Results of the economic optimization model

According to Carbon Brief[11], there are about 2500 coal plant sites in the world with capacity greater than 30 MW. The solar, wind and battery capacities, necessary for the switch, are the results from this study, using the economic optimization model, which seeks to install cheaper renewable power than is optimum for even power generation over the seasons. This model reflects the economic reality when the annual penetration of renewable energies in the electricity grid is below 50 %, where the fluctuations in renewable energies can be supplemented with the remaining fossil-fueled power plants. Above a renewable penetration of about 50%, sufficient energy storage must shift renewable power from day to night (mostly batteries). About 10% of renewable power must be shifted to periods of no sun and no wind only if renewable penetration exceeds about 80% (by hydro, pumped hydro, renewable gas, electricity-heat sector coupling, and other possibilities). A renewable penetration of 80% is usually not reached by switching coal plants alone.

Country	**Investment**	**Regular profits**	**Additional profits**	**Solar power capacity**	**Wind power capacity**	**Battery capacity**
	in wind-solar-battery farm	at 5–6% IRR, approx., not compounded	from switching, over 30 years	required for switching	required for switching	Battery capacity
	US$bn	**US$bn**	**US$bn**	**GWp**	**GWp**	**GW**
Argentina	1.2	2.5	**1.8**	1.2	0.5	0.2
Australia	43.7	87.4	**48.7**	49.9	8.8	5.5
Bangladesh	17.4	34.9	**13.1**	20.6	2.9	1.9
Bosn and Herz	0.0	0.0	**0.0**	0.0	0.0	0.0
Botswana	1.5	3.0	**2.1**	1.8	0.2	0.2
Brazil	7.2	14.5	**7.0**	8.1	1.7	0.9
Brunei	0.6	1.1	**0.6**	0.8	0.0	0.1
Bulgaria	15.1	30.1	**77.3**	18.0	1.9	1.6
Cambodia	4.2	8.5	**2.5**	5.1	0.7	0.4
Canada	11.1	22.2	**9.8**	8.0	7.5	1.4
Chile	9.9	19.7	**12.2**	11.5	1.7	1.3
China	2549.5	5099.0	**2074.5**	1950.6	1633.8	293.0
Colombia	4.2	8.4	**3.7**	4.6	1.1	0.5
Croatia	0.6	1.3	**3.3**	0.8	0.1	0.1
Czech Rep	24.8	49.7	**110.0**	19.3	12.0	2.4
Denmark	3.7	7.4	**21.5**	0.8	3.4	0.4
Dominican Rep	2.2	4.3	**3.0**	2.6	0.3	0.3
Finland	4.9	9.8	**19.5**	3.7	2.5	0.4

Country	**Investment**	**Regular profits**	**Additional profits**	**Solar power capacity**	**Wind power capacity**	**Battery capacity**
	in wind-solar-battery farm	at 5–6% IRR, approx., not compounded	from switching, over 30 years	required for switching	required for switching	Battery capacity
	US$bn	**US$bn**	**US$bn**	**GWp**	**GWp**	**GW**
France	7.1	14.2	**34.4**	5.9	3.1	0.7
Germany	111.3	222.5	**521.7**	69.4	66.9	11.3
Greece	7.5	15.0	**42.1**	8.8	1.0	0.8
Guadeloupe	0.2	0.3	**0.2**	0.2	0.0	0.0
Guatemala	2.5	5.0	**3.0**	2.9	0.4	0.3
Honduras	0.3	0.6	**0.2**	0.3	0.1	0.0
Hong Kong	16.4	32.9	**10.9**	12.3	11.1	1.8
Hungary	3.4	6.7	**15.2**	4.1	0.4	0.3
India	536.8	1073.6	**94.9**	628.7	121.6	62.8
Indonesia	117.7	235.5	**15.6**	151.1	7.6	13.2
Iran	1.2	2.3	**1.6**	1.4	0.2	0.2
Ireland	2.2	4.5	**13.8**	0.5	2.0	0.3
Israel	9.5	18.9	**11.9**	10.9	1.7	1.2
Italy	15.0	30.0	**83.7**	17.3	2.4	1.7
Japan	129.1	258.3	**76.2**	113.8	67.1	14.3
Kazakhstan	27.4	54.8	**27.1**	8.7	30.1	3.8
Kosovo	0.0	0.0	**0.0**	0.0	0.0	0.0
Kyrgyzstan	1.6	3.2	**2.3**	0.3	1.9	0.3
Laos	0.0	0.0	**0.0**	0.0	0.0	0.0
Madagascar	0.3	0.6	**0.3**	0.3	0.0	0.0
Malaysia	28.2	56.4	**21.0**	38.1	0.0	3.1
Mauritius	0.4	0.9	**0.5**	0.4	0.2	0.1
Mexico	11.9	23.8	**14.8**	14.9	0.8	1.5
Mongolia	2.4	4.8	**3.2**	2.9	0.3	0.3
Montenegro	0.0	0.0	**0.0**	0.0	0.0	0.0
Morocco	8.5	17.1	**10.7**	10.0	1.4	1.1
Myanmar	0.4	0.9	**0.4**	0.5	0.1	0.0
Namibia	0.3	0.6	**0.5**	0.4	0.0	0.0

Country	Investment	Regular profits	Additional profits	Solar power capacity	Wind power capacity	Battery capacity
	in wind-solar-battery farm	at 5–6% IRR, approx., not compounded	from switching, over 30 years	required for switching	required for switching	Battery capacity
	US$bn	US$bn	US$bn	GWp	GWp	GW
Netherlands	9.6	19.3	**41.1**	7.5	4.7	0.9
New Zealand	1.1	2.2	**1.3**	0.2	1.4	0.2
Nigeria	0.9	1.7	**0.6**	1.0	0.1	0.1
North Korea	3.6	7.2	**2.8**	4.2	0.7	0.4
N. Macedonia	0.0	0.0	**0.0**	0.0	0.0	0.0
Pakistan	11.8	23.5	**12.9**	13.7	2.1	1.4
Panama	0.7	1.4	**0.4**	0.5	0.5	0.1
Philippines	27.0	53.9	**25.2**	28.5	8.2	3.2
Poland	90.0	180.0	**396.4**	67.8	45.3	8.7
Romania	9.5	18.9	**46.3**	11.4	1.2	1.0
Russia	0.0	0.0	**0.0**	0.0	0.0	0.0
Senegal	0.3	0.7	**0.4**	0.4	0.1	0.0
Serbia	0.0	0.0	**0.0**	0.0	0.0	0.0
Slovakia	2.6	5.2	**11.7**	2.8	0.6	0.2
Slovenia	3.0	5.9	**13.7**	3.5	0.5	0.3
South Africa	92.1	184.1	**127.1**	107.2	14.5	12.3
South Korea	87.4	174.9	**67.1**	93.5	26.4	10.0
Spain	6.4	12.8	**32.1**	7.1	1.3	0.7
Sri Lanka	1.9	3.9	**2.1**	2.3	0.2	0.2
Taiwan	46.2	92.2	**31.2**	54.0	9.3	5.0
Tajikistan	0.8	1.7	**0.8**	1.0	0.1	0.1
Thailand	8.5	17.0	**6.4**	10.0	1.7	0.9
Türkiye	17.7	35.4	**12.9**	19.7	4.6	2.0
Ukraine	27.2	54.4	**8.9**	23.2	14.9	3.1
United Kingdom	9.4	18.8	**5.9**	2.1	8.4	1.2
United States	467.6	935.2	**419.5**	410.5	199.0	55.7
Uzbekistan	0.0	0.0	**0.0**	0.0	0.0	0.0
Vietnam	67.9	135.9	**36.1**	65.8	29.2	7.3

Country	Investment	Regular profits	Additional profits	Solar power capacity	Wind power capacity	Battery capacity
	in wind-solar-battery farm	at 5–6% IRR, approx., not compounded	from switching, over 30 years	required for switching	required for switching	Battery capacity
	US$bn	**US$bn**	**US$bn**	**GWp**	**GWp**	**GW**
Zambia	0.6	1.3	**0.8**	0.7	0.1	0.1
Zimbabwe	4.3	8.6	**5.7**	4.9	0.9	0.6
Global	**4742**	**9438**	**4726**	**4155**	**2376**	**545**

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