How the Energy Trilemma can provide Learning Points between Countries – the Case for Nuclear

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> *We can ignore reality,*
> *but we cannot ignore the consequences*
> *of ignoring reality.* – Ayn Rand –

Introduction

After two decades in pursuit of a sustainable energy system, there are still many unresolved questions. For one, a clear definition of what constitutes a sustainable energy system is lacking. The European Commission sets the target of reducing GreenHouse Gas (GHG) emissions to 80 % – 95 % below 1990 levels by 2050 in 2009 (European Commission 2018), and the power sector is expected to contribute significantly. Thus, Emblemsvåg (2022) suggests defining a low-carbon electricity grid as a grid where the life-cycle emissions are 100 gram CO_2-eq./kWh in an electric grid.

The low carbon electricity grid concept is a consequence of UN's Sustainable Development Goals (SDG) 7, i.e., "Ensure access to affordable, reliable, sustainable and modern energy for all" (UN DESA 2015). While 'modern' can be difficult to define, affordable, reliable and sustainable are clearer. Another way of phrasing the same key variables is through the Energy Trilemma, which also address SDG 7 (Marti and Puertas 2022). The Energy Trilemma is the continuation of the SD concept and developed by World Energy Council (WEC and Oliver Wyman 2021), see **Figure 1**.

Some consider the energy trilemma concept to be the foundation for the sustainable development of the energy sector (Tomei and Gent 2015). The concept has been encapsulated in an index, as well, see **Figure 2**. The World Energy Trilemma Index (WETI) comprises of the dimensions energy security, energy equity, environmental sustainability and country context (Šprajc et al. 2019).

The goal of WETI is to provide insights into a country's relative energy performance with regards to the three dimensions. Thus, the Index highlights a country's challenges in balancing the Energy Trilemma and opportunities for improvements in meeting energy goals now and in the future (WEC and Oliver Wyman 2021). However, there are significant methodological issues concerning the

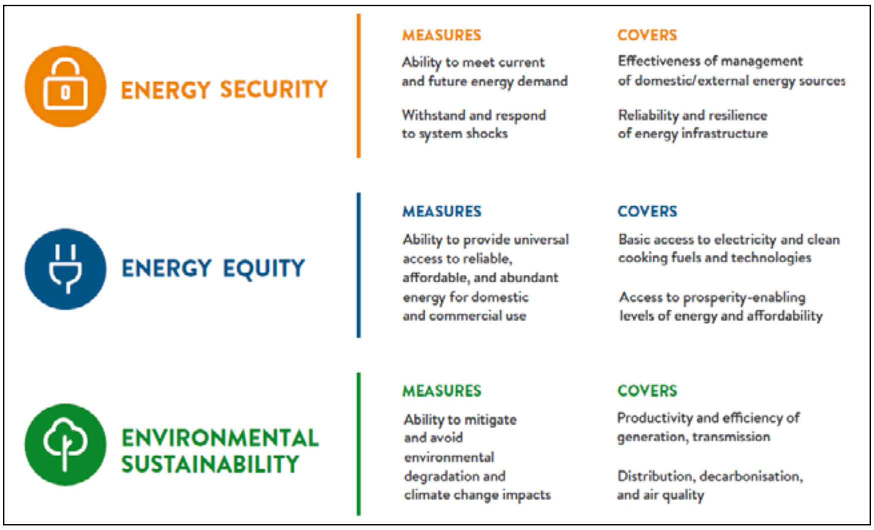
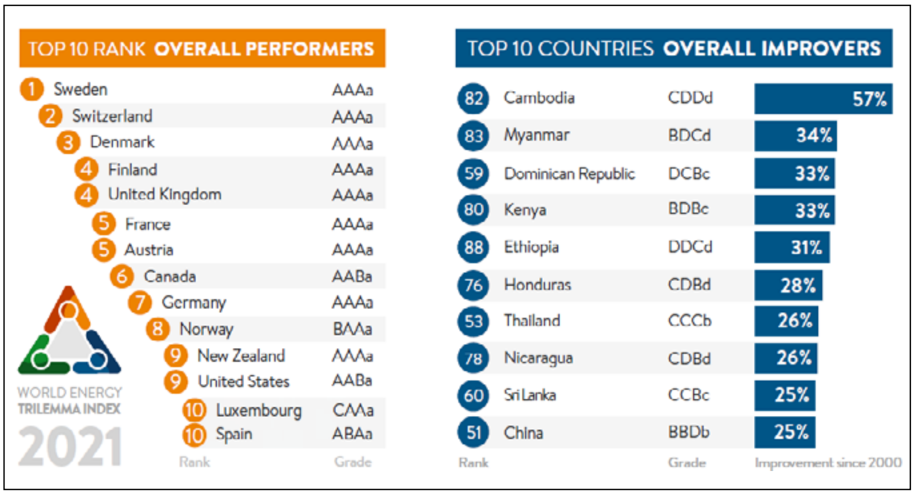


Fig. 1
The World Energy Trilemma Index (WETI).
Source: WEC and Oliver Wyman (2021)



TOP 10 RANK **OVERALL PERFORMERS**

Rank		Grade
1	Sweden	AAAa
2	Switzerland	AAAa
3	Denmark	AAAa
4	Finland	AAAa
4	United Kingdom	AAAa
5	France	AAAa
5	Austria	AAAa
6	Canada	AABa
7	Germany	AAAa
8	Norway	BAAa
9	New Zealand	AAAa
9	United States	AABa
10	Luxembourg	CAAa
10	Spain	ABAa

TOP 10 COUNTRIES **OVERALL IMPROVERS**

Rank		Grade	Improvement since 2000
82	Cambodia	CDDd	57%
83	Myanmar	BDCd	34%
59	Dominican Republic	DCBc	33%
80	Kenya	BDBc	33%
88	Ethiopia	DDCd	31%
76	Honduras	CDBd	28%
53	Thailand	CCCb	26%
78	Nicaragua	CDBd	26%
60	Sri Lanka	CCBc	25%
51	China	BBDb	25%

Fig. 2
Top performers and top improvers.
Source: WEC and Oliver Wyman (2021)

WETI (Šprajc et al. 2019). The results from Wu and Sansavini (2021), in contrast, demonstrate that the trade-offs between the trilemma objectives are nonlinear, and that economic- and sustainability objectives are not always conflicting upon which the authors argue that optimizing all trilemma objectives simultaneously can yield highly efficient solutions. Yet, Resniova and Ponomarenko (2021) argue that the issues of assessing national energy sustainability have not yet been resolved.

The purpose of this paper is not to venture into this debate, but to merely point out a few simple facts using the Energy Trilemma concept and not the WETI itself. The literature seems to agree that the concept is overall sound, but that the issues lie in measuring it numerically though the WETI. We propose using a comparative approach whereby we identify two grids that have chosen two different paths in solving their Energy Trilemma, and therefrom distill learning points for others. The research question we propose is therefore 'which two grids can be chosen as opposing cases to the Energy Trilemma and what can be learned from them?'

The paper starts by discussing our approach in the next section, before presenting our two cases respectively. We will distill the learning points before closing the paper following a critical review of our approach.

Our approach

The WETI has been gradually refined since its introduction and now ranks 127 countries (WEC and Oliver Wyman 2021). In **Figure 2**, we see the top performers and the bottom performers in 2021.

However, we find that synchronous grids are more important than countries because grid stability and synchronization is closely tied, which in the end also translates into costs. For example, the Danish grid relies heavily in grid stability services from Sweden and Germany. Germany has in turn also import from a number of other grids, but it is sufficiently independent to constitute a unit of analysis. Hence, the first criterium we deploy is that the unit if analysis – a grid – must be sufficiently independent to realistically be in control of its performance. In our analysis, we therefore study how production volumes [TWh/yr] have changed over the years.

Another criterium we use is that only OECD countries that have stayed within their respective Loss of Load Expectations (LOLE) measures are included. A LOLE value of 0.1 days/year, or 2.4 hours per year based on the target of one outage-day every 10 years is the typical target in the US (Kahn 2004). From the LOLE requirements we can already exclude California and Texas because both grids have experienced either rolling blackouts or outright grid collapse. Both are due to renewables, although the report by ASCE Texas (2021) concerning the Texas blackout is the clearest: "ASCE Texas Section identified two primary and related problems:

1) a failure to support reliable dispatchable power generation, and
2) the negative impact from sources of intermittent electric power generation".

Just a few weeks earlier, the entire ENTSO came minutes also close to collapse on 8th of January 2021 (Starn et al. 2021), but lady Fortuna intervened. Indeed, with the current policies (excluding the part of the current energy crisis related to the war in Ukraine), Europe is on the road to a major grid collapse, according to Saurugg (2021). To our surprise, much of the literature we have reviewed is actually neglecting the grid stability issues altogether. They seem to assume that it will just be fixed since it is not discussed. From a scientific point of view, this is an untenable approach.

The third criterium we use is that the grid must have a relatively high degree of fossil energy at the start. This criterium therefore effectively exclude Hydroelectric power (Hydro) countries such as Sweden and Norway and Nuclear countries such as France. The fourth criterium is derived from the fact that we study only OECD countries to simplify the metrics. By doing that we end up with two key metrics; climate gas emissions [kg CO_2 equivalent/MWh] and costs [EUR/MWh]. Costs are captured by using prices and price volatility as proxy. The price volatility is a good indication of system costs. Hence, all of our variables – production volume, emissions, prices and price volatility – are highly numerical unlike some of the criteria in the WETI. In our estimation, this simplifies the analyses as well as makes them more robust as long as we discuss countries on a similar development, i.e., all are OECD countries.

When it comes to the cases, the first case was chosen due to its high focus on the energy transition and large investments committed – Germany. Since Germany has achieved almost exactly what the United States achieved, but at greater expense (Smil 2020), some American states must therefore have done comparably well. The US is therefore of interest to study as done later on.

Germany

Germany embarked on its Energiewende (energy transition) more than 20 years ago. Smil (2020) sums it well up when he writes that “In 2000, Germany had an installed capacity of 121 gigawatts and it generated 577 terawatt-hours, which is 54 percent as much as it theoretically could have done (that is, 54 percent was its capacity factor). In 2019, the country produced just 5 percent more (607 TWh), but its installed capacity was 80 percent higher (218.1 GW) because it now had two generating systems”. Depending on the baseline, we get different figures. Compared to the year with the maximum production in the period (651.4 TWh in 2017), the production in 2019 was 7 % lower. 2020 was even lower, but since it is a COVID-19 year we should be careful interpreting it too much.

The impact on electricity prices is staggering, as shown in **Figure 3**. For the end-users we see more than 230 % increase in price! The price volatility is also very high. Even if we include the entire Euro area, the price volatility measured by semester intervals is 9.1 %[1] for minor consumers such as households. As we see from **Table 1**, this is worse than 90 % of US states.

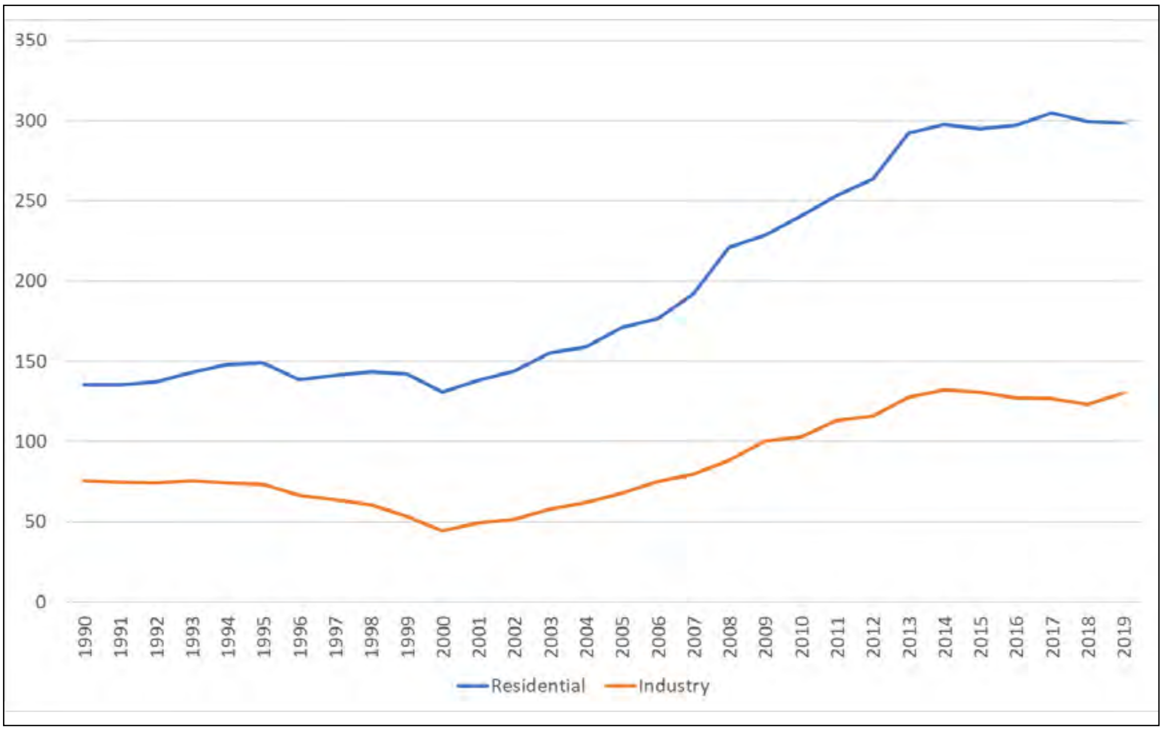


Fig. 3
Composition of electricity prices [EUR/MWh] in Germany.
Source: Calculated by the authors using data from https://ec.europa.eu/eurostat/web/energy/data/database

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[1] Calculated using information from EuroStat

The costs are also very large. Indeed, in the 2021 report, the "The Federal Audit Office [in Germany] sees the danger that the energy transition in this form will endanger Germany as a business location and overwhelm the financial strength of electricity-consuming companies and private households" (Bundesrechnungshof 2021), as translated by Wetzel (2021). The federal auditors in Germany are seriously questioning the transition arguing that the results are highly disproportionate to the results (Dohmen et al. 2019). In fact, if the results of Emblemsvåg (2021) from Ireland are transferable to Germany, which we believe they are, Germany will never obtain a sustainable energy system unless some major, unforeseeable innovations in storage take place. This is very unlikely, not just due to the costs but also the sheer scale as Shaner et al. (2018) show in the case for USA.

The results in terms of the shares of the different energy sources in the German grid are shown in **Figure 4**. Clearly, there is a long way to go before the emission targets are met.

The actual reductions from 2001 through 2020 in climate gas emissions are 46 %[2] in relation to electricity production, resulting in a carbon intensity of 314 kg CO_2-equivalent/MWh yearend 2020. With the COVID-19 issues of 2020, a more representative year is 2019 where the carbon intensity is 346 kg CO_2-equivalent/MWh which implies that the reduction in emissions from electricity production from 2001 through 2019 is 37.5 %. The distance from the 100 kg CO_2-equivalent/MWh target is large.

Before we venture to study the US states, it should be noted that we sometimes hear that the reason for the costs in Germany is the cost of paving the way for renewable energy globally as an early adopter. This argument holds some realism, but not on the scale the supporters claim. This can be proven by investigating the Intellectual Property Rights (IPR) and their origin. If Germany was the trailblazer some claim, we would expect them to hold a dominating portion of the IPR, but they do not. Sure, Madvar et al. (2019) find that Germany is the leading country with 19,071 published patents by end of 2018, but this constitutes less than 30 % of the total. The US is the second country with the highest published patent with 12,486 patents following by Denmark and China with 7,717 and 7,307 published patents, respectively.

The best American states

Using data from the US EIA we identify which states have the highest improvements in emissions, the lowest changes in retail prices, and the smallest volatility in the grid as measured by the standard deviation of the electricity prices over the last year. Furthermore, we also studied whether or not the states reduced their overall electricity production, and hence became more dependent on others in the

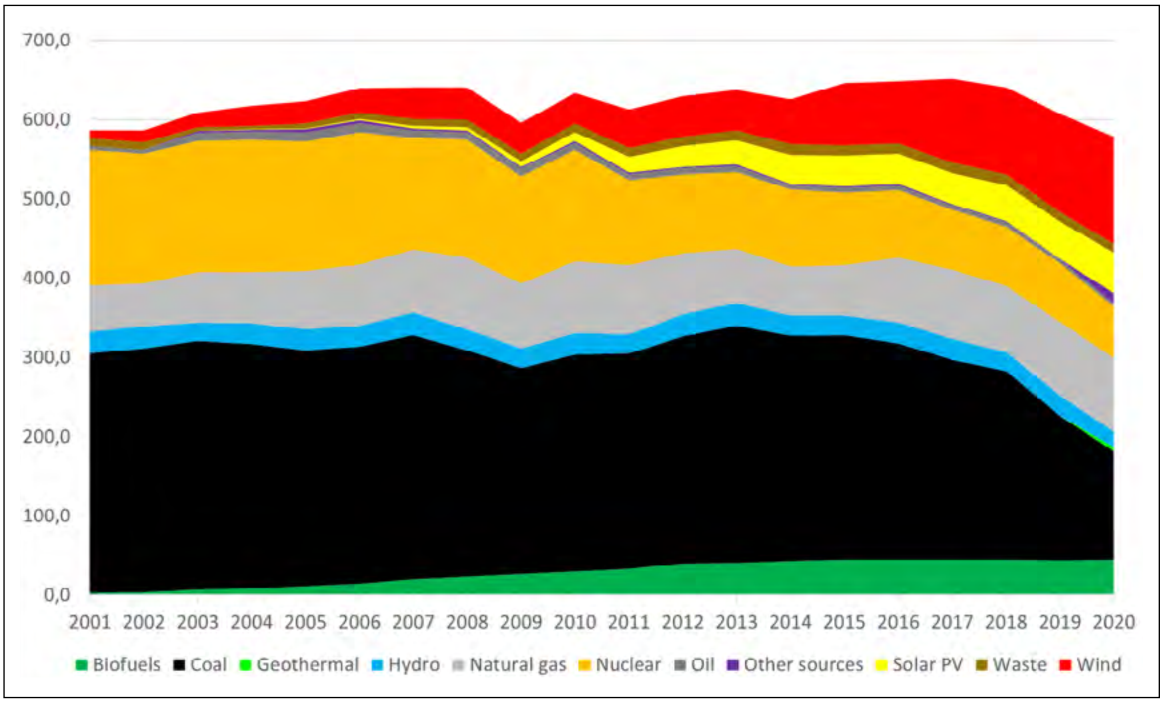

Fig. 4
The German Grid Mix Trend. Calculated by the authors using data from EIA and Statista.

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[2] According to https://www.statista.com/statistics/1290224/carbon-intensity-power-sector-germany/

Percentiles	Electricity Change	Emission Change	Price Change	Price volatility
0 %	– 61 %	– 98 %	10 %	0,8 %
10 %	– 23 %	– 62 %	36 %	2,1 %
20 %	– 13 %	– 44 %	46 %	2,7 %
33 %	**1 %**	**– 37 %**	**50 %**	**3,3 %**
40 %	3 %	– 34 %	55 %	3,5 %
50 %	9 %	– 31 %	62 %	4,0 %
60 %	16 %	– 26 %	65 %	4,6 %
67 %	**21 %**	**– 18 %**	**66 %**	**5,1 %**
80 %	27 %	– 9 %	76 %	5,9 %
90 %	41 %	5 %	86 %	8,2 %
100 %	**140 %**	**1651 %**	**116 %**	**25,0 %**

Tab. 1
The Percentiles of the 50 US States.

same grid area. This is important because the overall US electricity production increased by 9 % in the period.

In **Table 1**, we see the percentiles of the 50 states in the analysis according to these four dimensions. To sort the states, we use 1) a simple ABC classification to handle the production volume and emission changes, 2) a 'Large', 'Medium' and 'Small' denotation for the price changes and 3) a 'High', 'Medium' and 'Low' denotation for the price volatility. The percentiles we use for the classifications are the 33 % and the 67 % percentiles in bold. We see that Germany is performing poorer than the average American state on all four parameters – electricity volume, emission change, price change and price volatility. In terms of price, Germany has more than twice the price increase compared to the worst performing US state.

By sorting the 50 states like this, we obtain the results in **Table 2**. The ideal case is AAA (increase in volume and major reduction in emissions), low price volatility and small price change. Note that AAA here is not the same as AAA in the WETI. Nevertheless, no state has achieved Low Low AAA.

However, there are 17 A (significant emission cuts, i.e., more than 37 %) states out of which 4 are AAA states (production increased by more than 21 %), 3 are AA states (production increased by 1 % – 21 %) and 10 are A states (production fell or was barely maintained), see **Table 3**. These 17 A states constitute 36 % of the entire US electricity production in 2001 and 33 % in 2021, and they are responsible for 55 % of the US emissions cuts. In total, the US has cut its overall emissions by 30 %, which is in the same magnitude as Germany – but at a fraction of the costs, as Smil (2020) notes.

When interpreting these results, we must also take into account the overall grid performance of the grid system these states are located in. For example, if the grid system a state is located in, is running a shortage of electricity production, being a state in the same grid that also runs a shortage is potentially risky whereas a state that has a production increase in the same grid can offer an opportunity to sell surplus electricity. Hence, interpreting the results is not straightforward – states must be seen in context to the grid they are located in. These best performing states are shown in **Table 5**.

Price change	Price volatility	Emissions			Production
		CCC	**BBB**	**AAA**	**Triple**
Large	High	1	0	0	1
	Medium	1	1	0	2
	Low	1	0	1	2
Medium	High	0	0	0	0
	Medium	2	0	0	2
	Low	3	0	0	3
Small	High	2	1	1	4
	Medium	0	0	2	2
	Low	0	1	0	1
		CC	**BB**	**AA**	**Double**
Large	High	0	1	1	2
	Medium	0	1	0	1
	Low	0	2	0	2
Medium	High	2	1	0	3
	Medium	1	0	0	1
	Low	0	0	1	1
Small	High	1	2	1	4
	Medium	0	1	0	1
	Low	0	1	0	1
		C	**B**	**A**	**Single**
Large	High	0	0	1	1
	Medium	0	3	2	5
	Low	1	1	1	3
Medium	High	1	0	0	1
	Medium	0	0	0	0
	Low	0	0	3	3
Small	High	0	0	1	1
	Medium	0	0	2	2
	Low	1	0	0	1
		C - group	**B - group**	**A - group**	**Total**
Large	High	1	1	2	4
	Medium	1	5	2	8
	Low	2	3	2	7
Medium	High	3	1	0	4
	Medium	3	0	0	3
	Low	3	0	4	7
Small	High	3	3	3	9
	Medium	0	1	4	5
	Low	1	2	0	3
		17	**16**	**17**	**50**

Tab. 2
The sorting of the 50 US States.

State	Energy source	2001		2021		Change	Change %	Classification
Alabama	Natural gas	9.6	8 %	53,8	38 %	44,2	460 %	Large High AA
	Nuclear	30.4	24 %	46,0	32 %	15,7	52 %	
	Coal	72.2	58 %	26,9	19 %	– 45,3	– 63 %	
	Hydro	8.4	7 %	12,5	9 %	4,2	50 %	
California	Natural gas	112.0	60 %	3,0	52 %	– 1,2	– 14 %	Large High A
	Solar PV utility	0.5	0 %	0,0	18 %	– 0,4	6209 %	
	Nuclear	33.2	18 %	0,0	9 %	0,0	– 50 %	
	Wind	3.5	2 %	0,0	8 %	– 0,2	347 %	
	Hydro	25.5	14 %	96,5	8 %	– 15,4	– 43 %	
Delaware	Natural gas	1.6	23 %	34,3	86 %	33,7	120 %	Medium Low A
	Coal	3.7	49 %	16,5	7 %	– 16,7	– 92 %	
	Petro. liquids	1.7	25 %	15,6	0 %	12,1	– 100 %	
Indiana	Coal	116.1	95 %	14,6	58 %	– 11,0	– 53 %	Large Medium A
	Natural gas	2.3	2 %	5,8	30 %	0,4	1098 %	
	Wind	0.0	0 %	1,4	8 %	0,3	0 %	
Kansas	Wind	0.0	0 %	0,6	45 %	0,4	63965 %	Large Low AAA
	Coal	31.8	71 %	0,3	34 %	– 1,9	– 39 %	
	Nuclear	10.3	23 %	0,1	15 %	– 0,9	– 17 %	
	Natural gas	2.0	4 %	0,0	5 %	– 2,1	48 %	
Maine	Hydro	2.6	14 %	– 0,3	28 %	0,0	12 %	Small Medium A
	Natural gas	10.0	51 %	3,5	25 %	1,9	– 73 %	
	Wind	0.0	0 %	0,3	24 %	– 3,1	0 %	
	Biomass	3.8	20 %	0,1	20 %	0,0	– 43 %	
	Petro. liquids	2.1	11 %	0,1	0 %	0,1	– 99 %	
Maryland	Nuclear	13.7	28 %	0,1	38 %	0,1	10 %	Large Medium A
	Natural gas	1.8	4 %	0,0	37 %	– 1,7	738 %	
	Coal	28.4	58 %	0,0	15 %	0,0	– 79 %	
	Hydro	1.1	2 %	0,0	5 %	0,0	80 %	
Massachusetts	Natural gas	11.7	30 %	54,5	80 %	– 61,5	27 %	Medium Low A
	Solar PV utility	0.0	0 %	27,9	9 %	25,6	0 %	
	Other	0.8	2 %	7,9	5 %	7,9	22 %	
Nevada	Natural gas	11.5	35 %	2,2	69 %	– 0,8	127 %	Small High AA
	Solar PV utility	0.0	0 %	0,5	18 %	0,5	0 %	
	Coal	17.7	54 %	0,5	7 %	0,3	– 84 %	
	Hydro	2.5	8 %	0,2	5 %	– 0,4	– 22 %	
New Hampshire	Nuclear	8.7	58 %	0,1	57 %	– 0,2	13 %	Medium Low AA
	Natural gas	0.1	1 %	0,0	26 %	– 0,2	3684 %	
	Hydro	1.0	7 %	25,6	7 %	25,6	18 %	
	Biomass	1.0	7 %	19,4	6 %	– 12,4	0 %	
	Coal	3.7	25 %	8,6	2 %	– 1,8	– 92 %	
New York	Natural gas	38.7	27 %	2,9	46 %	0,9	47 %	Small High A
	Nuclear	40.4	28 %	0,1	25 %	0,1	– 23 %	
	Hydro	23.1	16 %	0,0	22 %	– 0,6	21 %	
	Petro. liquids	16.5	11 %	0,0	1 %	0,0	– 94 %	
	Coal	23.4	16 %	3,0	0 %	0,3	– 100 %	
Ohio	Natural gas	0.9	1 %	2,7	44 %	– 7,3	5767 %	Small Medium A
	Coal	124.2	87 %	2,5	37 %	2,5	– 63 %	
	Nuclear	15.5	11 %	2,2	14 %	– 1,6	13 %	
Oklahoma	Wind	0.0	0 %	0,3	41 %	– 0,1	0 %	Small High AAA
	Natural gas	17.9	32 %	0,1	41 %	– 0,5	83 %	
	Coal	34.6	63 %	0,0	14 %	– 2,1	– 68 %	
Pennsylvania	Natural gas	3.0	2 %	15,0	53 %	1,3	4093 %	Small Medium AAA
	Nuclear	73.7	38 %	14,7	31 %	13,0	3 %	
	Coal	111.9	57 %	5,8	12 %	– 22,5	– 74 %	
Tennessee	Nuclear	28.6	30 %	2,1	44 %	0,9	24 %	Large Low A
	Coal	59.7	62 %	0,7	23 %	0,7	– 69 %	
	Natural gas	0.5	0 %	0,5	18 %	0,5	3079 %	
	Hydro	6.9	7 %	0,4	16 %	0,0	85 %	
Vermont	Hydro	0.8	16 %	0,4	50 %	0,1	22 %	Medium Low A
	Biomass	0.4	7 %	0,1	25 %	– 2,9	45 %	
	Wind	0.0	0 %	0,0	16 %	– 0,4	2982 %	
	Solar PV utility	0.0	0 %	14,9	9 %	3,2	0 %	
	Nuclear	4.2	76 %	1,8	0 %	1,8	– 100 %	
Virginia	Natural gas	4.2	6 %	0,9	60 %	0,2	1190 %	Small Medium AAA
	Nuclear	25.8	35 %	0,8	31 %	0,1	11 %	
	Coal	37.8	51 %	0,4	3 %	– 0,9	– 92 %	

Tab. 3
Changes in A-States energy generation [TWh] and classification.

In the grand picture we see that the secret behind the US performance compared to Germany is predominantly the usage of gas and nuclear. However, some states experience far more price volatility than other states that have performed better. Indeed, there are only two states that score very well on emission cuts and avoid price volatility and other problems – New Hampshire and Tennessee. Both have expanded their nuclear base while using natural gas for balancing. The advantage of combining nuclear and gas compared to natural gas and renewables is that when gas is balancing nuclear it has far less consumption of natural gas than when natural gas is used in conjunction with renewables.

Some states also maintain a large share of Coal, which is clearly not a viable approach towards a low carbon grid. With these two states being identified

Grid	2001 [TWh]	2021 [TWh]	Change [TWh]		Price change	Price Std. Dev	2001 [MTonne]	2021 [MTonne]	Change	
East North Central	615	581	-33	-5,4 %	66 %	2 %	453	289	-163	-36 %
East South Central	370	362	-8	-2,2 %	84 %	3 %	292	184	-108	-37 %
Middle Atlantic	400	425	25	6,3 %	36 %	5 %	195	114	-81	-42 %
Mountain	317	366	49	15,3 %	51 %	5 %	237	193	-43	-18 %
New England	117	102	-15	-12,5 %	68 %	2 %	44	19	-24	-55 %
Pacific Contiguous	315	355	41	13,0 %	69 %	7 %	75	55	-19	-26 %
Pacific Noncontiguous	17	15	-2	-12,8 %	105 %	4 %	11	9	-2	-18 %
South Atlantic	728	806	78	10,7 %	53 %	3 %	467	312	-155	-33 %
West North Central	282	357	75	26,8 %	66 %	7 %	189	158	-31	-16 %
West South Central	563	722	160	28,3 %	31 %	12 %	106	82	-24	-22 %

Tab. 4
Grid summary – generation, prices and emissions. Authors calculations using data from US EIA.

State	Main strategy	Production	Emission cuts	Comments	Sustainability
Alabama	Natural gas and nuclear	13 %	-37 %	Growth, but must cut more fossil	Volatile, not sustainable
California	Natural gas and renewables	-1 %	-41 %	Rolling blackouts, but grid surplus	Volatile, not sustainable
Delaware	Natural gas and import	-41 %	-67 %	Depend on others and grid shortage	Not sustainable
Indiana	Natural gas and import	-23 %	-38 %	Depend on others and grid shortage	Not sustainable
Kansas	Wind	27 %	-44 %	Growth, coal for balancing, grid surplus	Not sustainable
Maine	Import	-45 %	-80 %	Depend on others	Avoidance
Maryland	Natural gas, nuclear and import	-19 %	-62 %	Grid shortage	Not sustainable
Massachusetts	Natural gas and import	-51 %	-72 %	Depend on others	Avoidance
Nevada	Solar PV and natural gas	16 %	-46 %	Growth, but need gas for balancing	Volatile, not sustainable
New Hampshire	**Natural gas and nuclear**	**16 %**	**-61 %**	**Surplus production can cut gas**	**Transition**
New York	Natural gas, hydro and import	-13 %	-62 %	Small grid surplus	Volatile, not sustainable
Ohio	Natural gas	-13 %	-46 %	Grid shortage	Not sustainable
Oklahoma	Wind and natural gas	46 %	-39 %	Small grid shortage	Volatile, not sustainable
Pennsylvania	Natural gas and nuclear	23 %	-37 %	Small grid surplus	May approach transition
Tennessee	**Nuclear, natural gas and hydro**	**-16 %**	**-59 %**	**Small grid shortage**	**Transition**
Vermont	Import	-61 %	-98 %	Depend on others, grid shortage	Not sustainable
Virginia	Natural gas and nuclear	23 %	-38 %	Grid surplus	May approach transition

Tab. 5
Shortlist of best performing US States.

as the overall best American states, the development of the share of their energy sources is shown in **Figure 5** and **Figure 6**.

None of the states have reached a low-carbon grid performance, but if they continue on their Nuclear path, they will reach the targets. When it comes to the Biomass of New Hampshire it depends on how it has been produced. If it is genuine biological waste mass, then it is a good contribution whereas if it is of the large-scale kind that leads to deforestation it is everything but sustainable (800 scientists 2018). Biomass is therefore a niche solution when it comes to sustainability and therefore ignored in this study. Contrast this with the two Wind states Oklahoma and Kansas, which both have increased their production and achieved emission reduction among the best third (AAA). Kansas maintains Coal but ends up with significant price increases although low price volatility while Oklahoma uses Gas with Wind and achieves lower price increases but more price volatility. None of them achieves more than 44 % emission cuts which is roughly on par with Germany. Hence, these states illustrate well the finding of Emblemsvåg (2021) that wind with fossil balancing results in a system that does not lead to a sustainable grid. On top of this, Wind received about 160 times more subsidies in 2018 than Nuclear compared to their output in the US (Bryce 2020).

The two other AAA states are Pennsylvania and Virginia. Both of them rely too much on fossil energy, but depending on future investment decisions they may approach a transition particularly if they invest in Nuclear and reduce their fossil dependencies without needing too much Gas for balancing.

Identifying learning points

When we compare the two cases there are some key differences. Two US states, New Hampshire

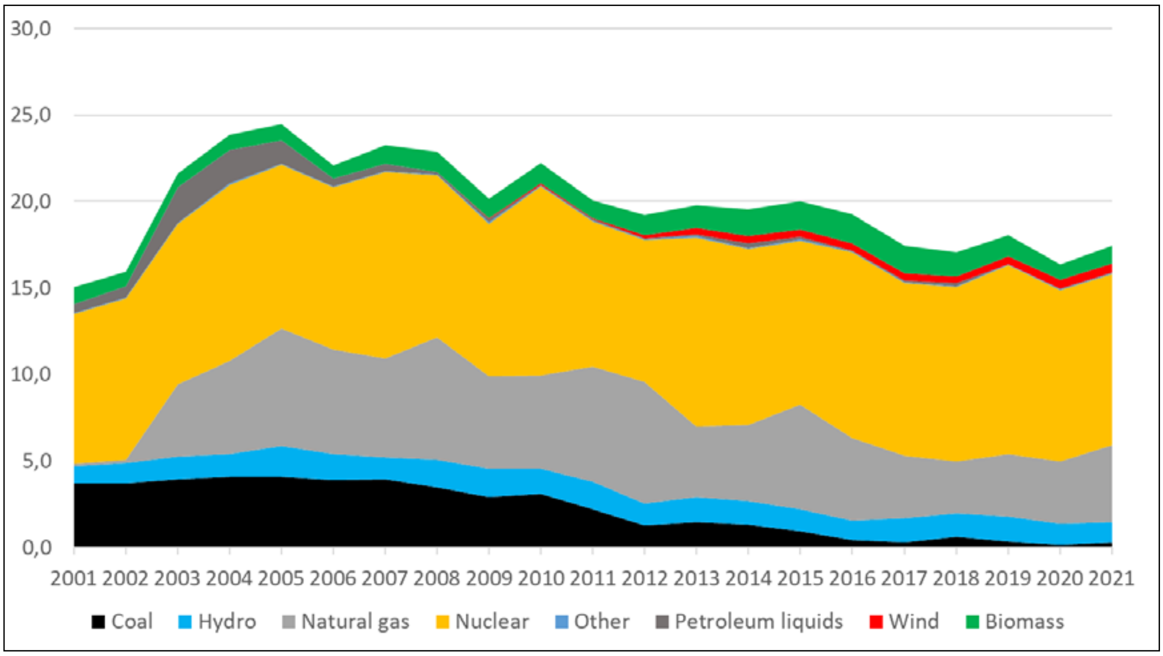

Fig. 5
The New Hampshire Grid Mix. Authors calculations using data from US EIA.

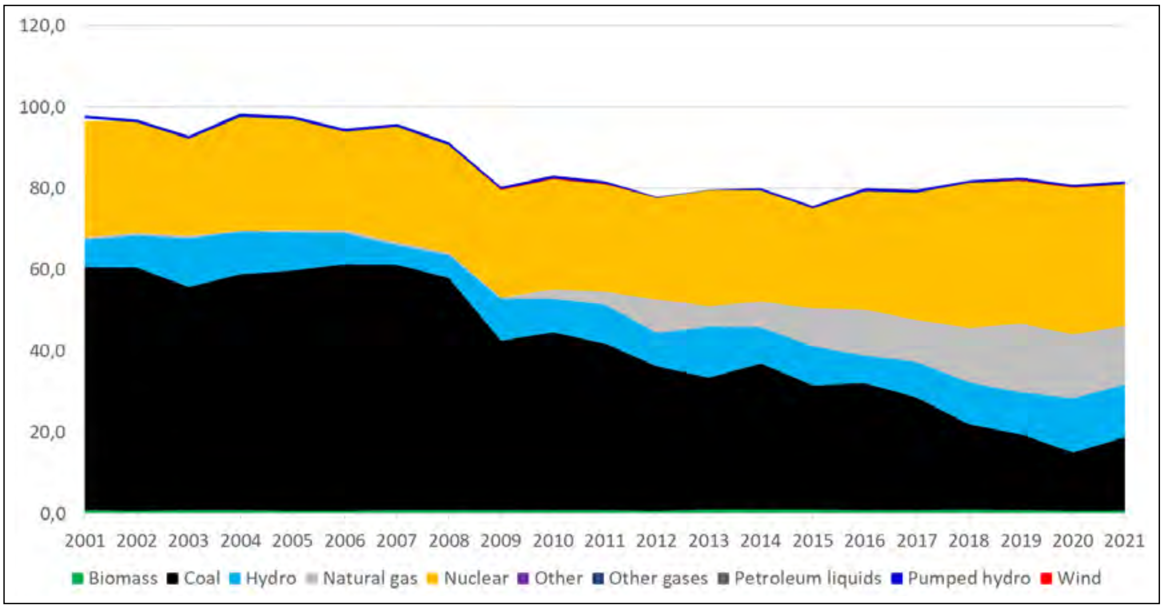

Fig. 6
The Tennessee Grid Mix. Authors calculations using data from US EIA.

and Tennessee, have decarbonized very well by expanding Nuclear. Tennessee could be compared with Germany, with similar percentage of Nuclear in their mix (30 % in Tennessee vs 29 % in Germany) in 2001, but with very different transition paths thereafter.

While Germany has systematically closed Nuclear, Tennessee has expanded. Germany has systematically expanded intermittent Wind and Solar Photovoltaic (PV), where public utility in Tennessee have been much more careful with renewables with only 3 % in 2021 (TVA 2022). In the longer term, "using effective planning and technologies available today, we have a plan to achieve 70 % reduction in carbon emissions by 2030 and a path to 80 % by 2035. We aspire to achieve net zero carbon emissions by 2050", according to Tennessee Valley Authority (TVA) Chief Sustainability Officer Rebecca Tolene.

Concerning generation volumes, the volumes have been going down for both entities over the 20-year period but slightly more in Tennessee although New Hampshire is still a net exporter. This decreasing generation in Tennessee can well be supported by import from neighboring Alabama, where TVA also operates Nuclear resources.

A way to augment the existing Hydro and Nuclear, Solar Photovoltaic (PV) can be deployed, which is a part of the plans of TVA (2022). The advantage of Solar PV over Wind is that it requires far less rapid ramping than Wind due to the higher predictability. The numbers are even better for New Hampshire, so it is no doubt that the Nuclear transition is faster and cheaper than the Wind- and Solar PV transition. Indeed, in terms of emissions, Germany has achieved about 60 % of the results that New Hampshire and Tennessee have achieved, but prices in Tennessee are about 1/3 of the rates paid in Germany.

Our results support the results presented by Cao et al. (2016). They investigated the 10 years of various countries with substantial scaling and the effects on decarbonization without any other parameters considered. Their key results are shown in **Figure** 7, and they show unequivocally that decarbonization is fastest using Nuclear.

It should be noted that the Solar PV and Wind of **Figure 7** ignore the balancing needs, which in 26 OCED countries is most commonly gas (Verdolini et al. 2018). That means that the emission reductions achieved by the renewables in **Figure 7** are also far smaller per added capacity. Indeed, Emblemsvåg (2021) estimates that for wind it is roughly 15 % –20 % compared to Gas only.

Our findings are also in tune with the Energy Return On Investment (EROI) concept. The EROI of a power plant is the ratio of the usable energy the plant returns during its lifetime to all the invested energy needed to make this usable energy (Weißbach et al. 2013). The strength of this concept is that it is not influenced by particular economic circumstances such as subsidies, market conditions and the like.

Moreover, in a proper EROI calculation it is crucial to use the exergy numbers (energy = exergy + anergy). Exergy is the component of the energy that actually produce a useful output (Ayres et al. 1998) whereas anergy is waste due to entropy. For electricity, the energy and exergy values are identical since electricity does not carry any entropy (Wall 2003) under the assumption that electrical energy is used for electrical end-uses. If electrical energy is used for creating thermal energy, there are major losses. The exergy efficiency (the ratio of output exergy to input exergy) for an electric heater is about 5 % and for the heat pump it is about 15 % (Wall 2011). In fact, up to 97 % of the input exergy is wasted in transformation to output exergy (Ayres and Narkus-Kramer 1976). The EROI is basically the exergy (useful energy) divided by the total life-cycle energy (useful and wasted) used to produce that exergy.

This shows how important it is to understand primary energy, energy carriers and energy end usage when performing energy accounting, but even reputed statistical organizations make many basic mistakes concerning primary energy, energy and exergy (Giampietro and Sorman 2012). A part of the problem is that defining energy is very difficult and

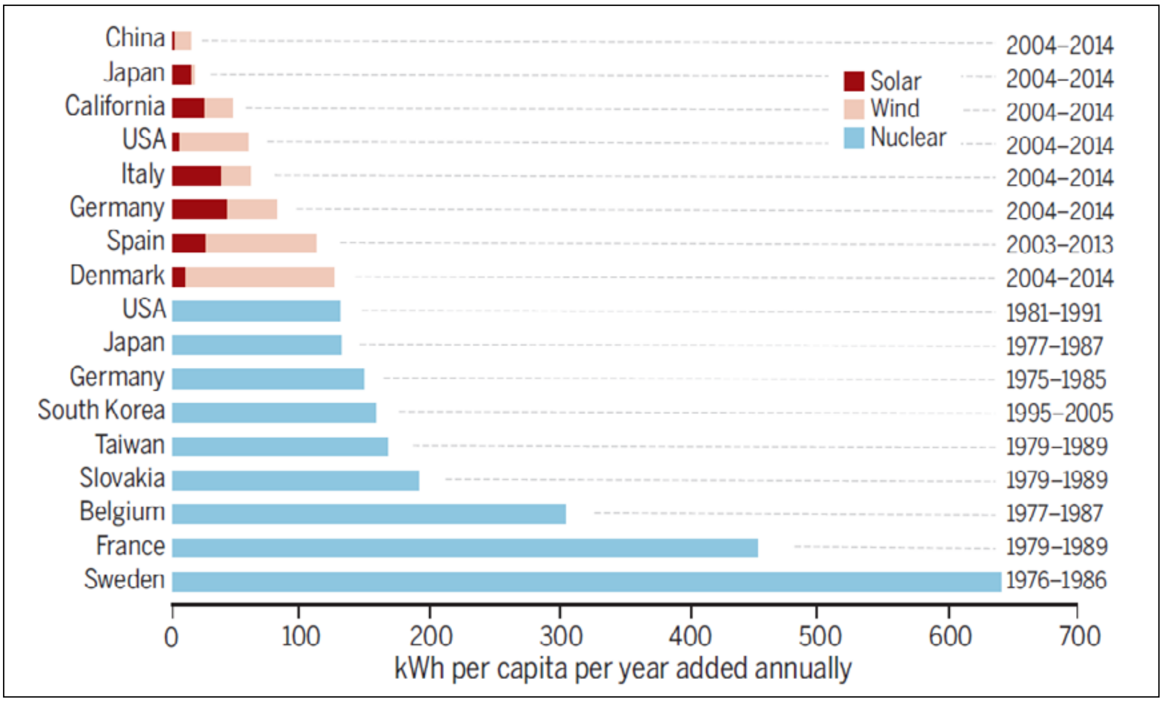

Fig. 7
Average annual increase of carbon-free electricity per capita during decade of peak scale-up. Source: Cao et al. (2016).

context dependent (Feynman et al. 1963). Another part of the problem is that most energy statistics try to squeeze incomparable numbers into one comparable number, which is only possible if one uses a predefined protocol. The protocol adopted by BP and the US Energy Information Agency (EIA) are logically defensible, but the International Energy Agency and EuroStat "represents a systemic violation of thermodynamics knowledge" (Giampietro and Sorman 2012).

Energy is an integral part of many Life-Cycle Assessments, but there are methodological issues and when calculating EROI typical mistakes include (Weißbach et al. 2013); 1) confusion between energy, exergy and primary energy whereby renewable output is weighted by 3 to make it comparable to thermal energy sources (as just discussed), 2) tweaking the lifetime of energy sources using too short for nuclear and too long for renewables, 3) including all outputs even when they are not needed and 4) outdated material databases or work flows. When Weißbach et al. (2013) correct for these used mistakes, they obtain the results in **Figure 8**. We see that nuclear has by far the highest EROI, which means from pure physics and thermodynamics nuclear will give far more useful energy per spent energy. In an energy transition, this should be a key criterion.

Note that the economic threshold is estimated by assessing the ratio between the GDP per total, primary energy consumption and the average electricity cost. For example, the US GDP was $ 15 trillion in 2011 while the unweighted end energy consumption was about 20 trillion kWh, resulting in an "energy value" of some 70 cent/kWh whereas the average electricity price was 10 cent/kWh (US EIA 2011). Hence, a ratio of 7. This will, of course, vary from countries to countries depending on development level (Weißbach et al. 2013). Measuring across OECD countries, as we have done in our study, is therefore advisable.

Our research shows that using significant shares of Nuclear in the transition has other benefits in addition to being most effective at reducing emissions; 1) Nuclear leads to higher system stability, as represented by lower price volatility in our study, and 2) overall increased production. Using Nuclear is therefore the most credible alternative identified in this study.

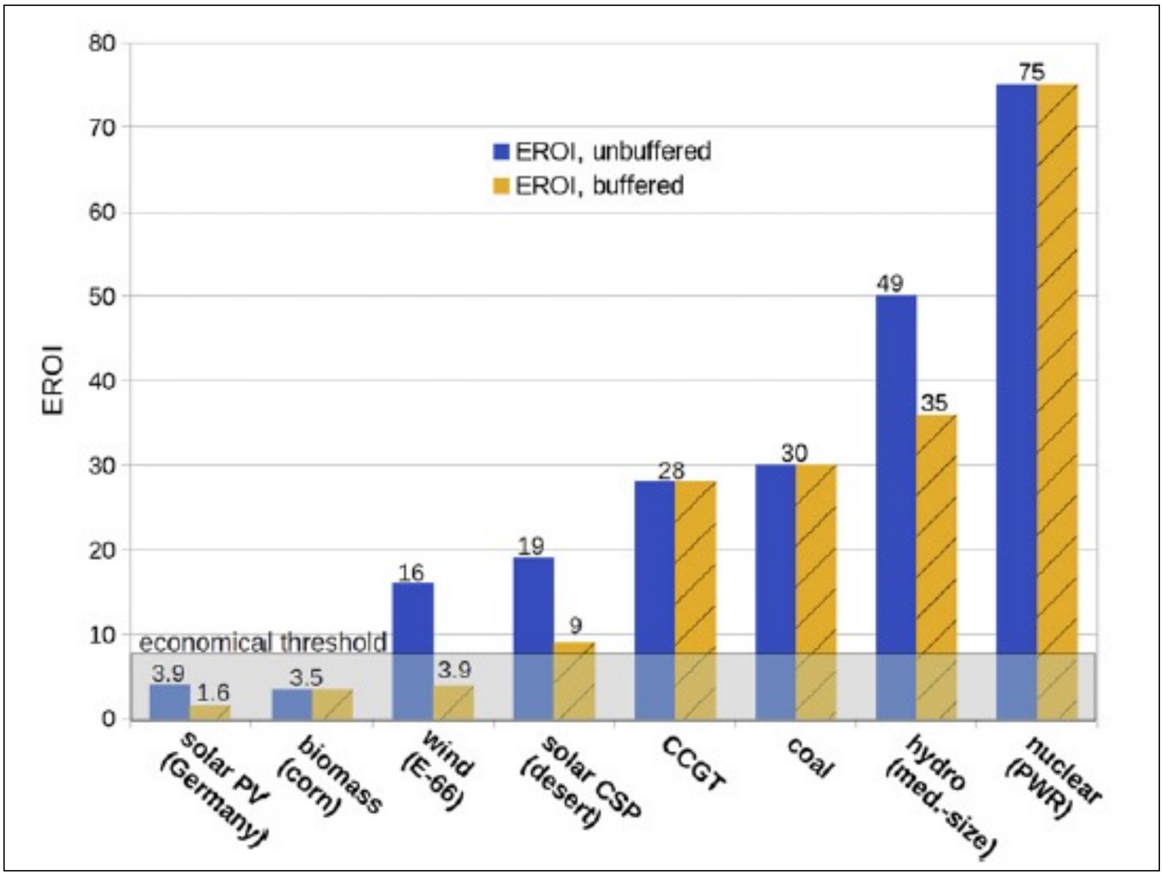

Fig. 8
EROI for various energy sources with relative error of 10 %. 'Unbuffered' implies that the energy is usable at all times as if it was stored which is an unrealistic assumption except for run of the river hydro and 'buffered' includes storage.
Source: Weißbach et al. (2013)

It should be noted that we see one other option available. Countries that have large shares of Hydro can use this approach to balance renewables provided strictly ties between Hydro and the renewables are enforced to ensure that they behave as one asset (Emblemsvåg 2022). As one asset, the marginal costs will rise substantially since more Wind means less Hydro and Hydro is dependent on reservoirs and precipitation. The cost implications are yet to be discussed, but the solution is technically possible as system stability is maintained.

Critical review of the study and future work

The purpose of the paper is not only to understand how fast decarbonization can progress, but also to overcome the limitations of using indices such as the WETI, as discussed earlier. However, all types of analyses have their shortcomings including ours. First, no two judicial entities (countries, states or other entity) will have the same historical path which implies that what works somewhere may not work everywhere particularly as grid stability concerns. Geography, grid bottlenecks and more have their impact. To limit this potential caveat, we limited our study to OECD countries since they have similar development level and therefore grid stability requirements.

Second, both New Hampshire and Tennessee are small grids in comparison to Germany. Germany has an average generation volume of 624 TWh in the period while New Hampshire has only 20 TWh (3 % of Germany) and Tennessee has 86 TWh (14 % of Germany). Thus, performing a transition is less demanding for these states, but their resources are also far smaller. Germany has an average GDP of 3315 billion USD in the period compared to 68 billion USD of New Hampshire (or 2 % of Germany) and 283 billion USD of Tennessee (or 9 % of Germany). This comparison ignores the Federal level in the US, but the German numbers also ignored the EU level. Hence, regarding basis for comparison, there can be no doubt that Germany is in a stronger position than New Hampshire and Tennessee even if we include the federal support these states receive.

Third, Germany started not only earlier than these two states but also from an explicit desire to eliminate Nuclear from their grid, which actually supports our arguments. It shows that even by consciously trying to eliminate emissions from the German grid over longer period of time with a far greater resource base at their disposal, these two American states have for several years made greater strides towards a low-carbon grid. Hence, the explanation must be technological since politics and funding have been far more generous and in favor of Germany.

Fourth, the data availability in the US in generally better, which means that the granularity of the US is better. However, the differences we have uncovered are too large to be explained from different data accuracy.

Fifth, we have only investigated the electricity component of total energy consumption. As demonstrated by Smil (2022), after two decades of the green transition in Germany the share of fossil energy in primary energy supply has only declined from 84 % to 78 %. Combined with a globally underinvestment in fossil energy production, due to climate policies resulting in a 15 % increase in cost of capital subsequently leading to 40 % reduction in investments compared to long-term history across industries such as shipping, oil and gas, cement, steel (Goldman Sachs 2022), the result is major increases in energy costs. The reason is that renewable energy has not been able to replace this energy partly because renewable energy requires mainly gas power for balancing in 26 OECD countries (Verdolini et al. 2018) so that a growing base of renewables requires more gas.

In fact, Devlin et al. (2017) find that wind and gas are unlikely allies as does Emblemsvåg (2021). With a falling supply of gas and an increased demand for gas, the obvious result is higher prices. Hence, it is clear that the dependence on fossil energy must first be resolved before actually reducing the use of it to avoid major market problems as currently witnessed. Again, this supports the Nuclear case because Nuclear does not require balancing like renewables. However, decarbonizing 50 % of the primary energy of any country is a major undertaking also using Nuclear energy.

Finally, the material situation for renewables is impossible for a large-scale replacement of fossil energy as robustly proven by Michaux (2021). This will create even more difficult market situations for renewable energy by itself but even more so when seen in the context of item five above. Our analysis ignores this perspective, but it also plays to the advantage of the Nuclear case.

Concerning future work, overcoming these shortcomings is key and the best way to improve the robustness of our finding is to perform similar analyses for more countries in an effort to try to identify a case where our finding breaks down. Also, the primary energy aspect must be tackled, which is what ultimately just remove matters. In parallel, the WETI should be refined further and applied to these cases to investigate whether or not the same answers emerge.

Concluding remarks

We have analyzed some basic data from the US states and compared them to Germany, which is globally known for its commitment to a green transition. Yet, while the German rhetoric is clear and investments very large, the green transition is barely visible in the numbers when all factors are considered. Interestingly, two American states outperform Germany on all parameters used in the study without the rhetoric, with less funds, but with Nuclear and not renewables.

The only US States that use significant shares of renewables and has so far avoided serious problems are Oklahoma and Kansas. Yet, their performance is significantly poorer compared to New Hampshire and Tennessee. Overall, we therefore find that Tennessee and New Hampshire have struck the best compromise between the three dimensions of the Energy Trilemma. Although, no state has arrived at the target yet. In fact, no country has made any significant impact on decarbonizing the primary energy, which is ultimately what matters. Hence, there is a long way to go irrespectively of technology.

Our conclusion, as supported by other studies, is that Nuclear provides a faster transition, overall cheaper when all costs are included and with less negative impact on the electricity market (through price volatility). We therefore believe that future strategies of a green transition must open up for a serious deliberation around Nuclear in all countries committed to the climate goals, and an equally serious deliberation about the effectiveness of renewables. In the wise words of Daniel J. Boorstin;

The greatest obstacle to discovery is not ignorance –
it is the illusion of knowledge.

References

- 800 scientists (2018). Letter from Scientists to the EU Parliament regarding forest biomass. https://empowerplants.files.wordpress.com/2018/01/scientist-letter-on-eu-forest-biomass-796-signatories-as-of-january-16-2018.pdf.
- ASCE Texas (2021). Reliability and Resilience in the Balance: Building sustainable infrastructure for a reliable future. A vision beyond Winter Storms Uri and Viola. Austin, TX,Texas Section of the American Society of Civil Engineers (ASVE).
- Ayres, R.U. and M. Narkus-Kramer (1976). An Assessment of Methodologies for Estimating National Energy Efficiency.ASME Winter Annual Meeting, December 5-10:pp. No. 76-WA/TS-74 Conf Paper.
- Ayres, R.U., L.W. Ayres and K. Martin (1998). "Exergy, Waste Accounting, and Life-Cycle Analysis." Energy23(5):pp.355–363.
- Bryce, R. (2020). Why Is Solar Energy Getting 250 Times More In Federal Tax Credits Than Nuclear?Forbes. Jersey City, NJ. https://www.forbes.com/sites/robertbryce/2021/2012/2027/why-is-solar-energy-getting-2250-times-more-in-federal-tax-credits-than-nuclear.
- Bundesrechnungshof (2021). Bericht nach § 99 BHO zur Umsetzung der Energiewende im Hinblick auf die Versorgungssicherheit und Bezahlbarkeit bei Elektrizität (Report according to § 99 BHO on the implementation of the energy transition with regard to security of supply and affordability of electricity). Bonn,Bundesrechnungshof.
- Cao, J., A. Cohen, J. Hansen, R. Lester, P. Peterson and H. Xu (2016). "China-U.S. cooperation to advance nuclear power." Science353(6299).doi: 10.1126/science.aaf7131.
- Devlin, J., K. Li, P. Higgins and A. Foley (2017). "Gas generation and wind power: A review of unlikely allies in the United Kingdom and Ireland." Renewable and Sustainable Energy Reviews70:pp.757–768.
- Dohmen, F., A. Jung, S. Schultz and G. Traufetter (2019). German Failure on the Road to a Renewable Future.Der Spiegel.Hamburg. https://www.spiegel.de/international/germany/german-failure-on-the-road-to-a-renewable-future-a-1266586.html
- Emblemsvåg, J. (2021). "Wind is not sustainable when balanced by fossil energy." Applied Energy305.doi.org/10.1016/j.apenergy.2021.117748.
- Emblemsvåg, J. (2022). How to sustainably integrate wind.Proc. of the International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), 16-18 November 2022,Maldives,IEEE. Accepted for publication.
- European Commission (2018). A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. Brussels,The European Commission, The European Council, the European Economic and Social Committee of the Regions and European Investment Bank.
- Feynman, R.P., R.B. Leighton and M. Sands (1963). The Feynman Lectures on Physics, Vol. 1: Mainly Mechanics, Radiation, and Heat.Menlo Park, CA,Addison-Wesley Publishing Company.
- Giampietro, M. and A.H. Sorman (2012). "Are energy statistics useful for making energy scenarios?" Energy37:pp.5-17.
- Goldman Sachs (2022). "Why Oil Prices Are Surging but Investment is Drying Up." Briefings.https://www.goldmansachs.com/insights/pages/from-briefings-20-january-2022.html.
- Kahn, E. P. (2004). "Effective Load Carrying Capability of Wind Generation: Initial Results with Public Data." The Electricity Journal17(10):pp.85-95.
- Madvar, M.D., F. Ahmadi, R. Shirmohammadi and A. Aslani (2019). "Forecasting of wind energy technology domains based on the technology life cycle approach." Energy Reports5:pp.1236–1248.
- Marti, L. and R. Puertas (2022). "Sustainable energy development analysis: Energy Trilemma." Sustainable Technology and Entrepreneurship1.doi.org/10.1016/j.stae.2022.100007.

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