



# A critical review of global decarbonization scenarios: what do they tell us about feasibility?

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Dozens of scenarios are published each year outlining paths to a low carbon global energy system. To provide insight into the relative feasibility of these global decarbonization scenarios, we examine 17 scenarios constructed using a diverse range of techniques and introduce a set of empirical benchmarks that can be applied to compare and assess the pace of energy system transformation entailed by each scenario. In particular, we quantify the implied rate of change in energy and carbon intensity and low-carbon technology deployment rates for each scenario and benchmark each against historical experience and industry projections, where available. In addition, we examine how each study addresses the key technical, economic, and societal factors that may constrain the pace of low-carbon energy transformation. We find that all of the scenarios envision historically unprecedented improvements in energy intensity, while normalized low-carbon capacity deployment rates are broadly consistent with historical experience. Three scenarios that constrain the available portfolio of low-carbon options by excluding some technologies (nuclear and carbon capture and storage) *a priori* are outliers, requiring much faster low-carbon capacity deployment and energy intensity improvements. Finally, all of the studies present comparatively little detail on strategies to decarbonize the industrial and transportation sectors, and most give superficial treatment to relevant constraints on energy system transformations. To be reliable guides for policymaking, scenarios such as these need to be supplemented by more detailed analyses realistically addressing the key constraints on energy system transformation. © 2014 John Wiley & Sons, Ltd.

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## INTRODUCTION

A variety of recent studies conclude that avoiding extreme climate change outcomes may require near-total decarbonization of the world's energy system during this century, with 50–90% reductions

in energy-related CO<sub>2</sub> emissions required by 2050.<sup>1–8</sup> Projected economic and population growth means that by mid-century, the global energy system must deliver roughly twice as much energy as today, while simultaneously achieving very deep reductions in CO<sub>2</sub> emissions.<sup>9–11</sup> This is an unprecedented undertaking.

A number of organizations and researchers have published prospective scenarios for 21st century low-carbon energy system transformations designed to stabilize atmospheric concentrations of CO<sub>2</sub> or projected global temperature increases at acceptable levels. This study reviews 17 such decarbonization scenarios drawn from 11 studies in 12 publications. These studies are selected so as to include diverse examples of four different general approaches to

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developing low-carbon energy scenarios, including: top-down scenario-based back-casting<sup>12–16</sup>; top-down integrated assessment modeling<sup>17–19</sup>; bottom-up energy systems modeling<sup>20,21</sup>; and bottom-up techno-economic assessments.<sup>22,23</sup>

Prior studies have conducted detailed inter-model comparisons of dozens of scenarios produced by various integrated assessment models (IAMs) of the energy–climate–economic system.<sup>7,8,18,24</sup> These studies help the modeling community compare and calibrate different IAM formulations, illuminate for policy makers the points of agreement and divergence between these models, and identify the impact of different model assumptions or formulations on key results. Our purpose here is complementary and different. First, we assess a set of scenarios constructed using a diverse range of methods, including IAMs but also several other influential studies constructed using different methods (i.e., scenario-based backcasting, bottom-up studies, etc.). Second, we focus on what these studies usefully tell us about the *feasibility* of various decarbonization strategies. The benchmarking methods introduced herein and the results of this scenario comparison can both helpfully inform policy makers and provide useful historical, empirical comparators for the scenario building and modeling community.

‘Feasibility’ can of course be interpreted or defined in a number of ways (see, e.g., pp. 8 and 13 in chapter 6 of Ref 7). For example, physical constraints, such as limits on the concentration of atmospheric CO<sub>2</sub> consistent with certain mean average temperature stabilization targets or limits on natural resource availability, may render some scenarios physically impossible and thus infeasible. Beyond these hard physical constraints, however, policy makers must contend with additional feasibility considerations, including the rate of physical transformation of energy systems (e.g., infrastructure turnover and deployment), economic implications, social acceptance of the technologies underpinning decarbonization efforts, political feasibility, and interactions with other societal objectives. While judging a particular scenario ‘feasible’ or ‘infeasible’ is ultimately a subjective interpretation, our aim here is to quantify and illuminate several key metrics that can assist policy makers and others in assessing the feasibility of various decarbonization strategies.

To this end, we introduce a set of empirical benchmarks that can be applied to compare and assess the pace of energy system transformation (explicitly or implicitly) entailed by the results of any global decarbonization scenario. Importantly, these metrics are agnostic as to the underlying model formulations or

methods. In particular, the bulk of this study is devoted to quantifying the implied rate of change in energy and carbon intensity and low-carbon technology deployment rates for each scenario and benchmarking each against historical experience and industry projections, where available. In addition, we examine how each study addresses the key technical, economic, and societal factors that may constrain the pace of low-carbon energy transformation.

## A CRITICAL REVIEW OF GLOBAL DECARBONIZATION SCENARIOS

This study reviews 11 studies proposing a range of global decarbonization scenarios intended to stabilize atmospheric CO<sub>2</sub> levels or global temperature rise to acceptable levels, implying 50–90% reductions in global CO<sub>2</sub> emissions by mid-century.

While there is no generally accepted typology of decarbonization scenarios,<sup>25</sup> we classify these studies as examples of four general approaches to developing low-carbon energy scenarios.

1. *Top-down, scenario-based back-casting* methods<sup>12–16</sup> begin by selecting a proposed target for final decarbonization and generally preselect a portfolio of eligible low-carbon technologies. These studies then construct a scenario of energy system transformation that complies with the final decarbonization target.
2. *Top-down integrated assessment modeling* approaches utilize integrated models of the climate and economic systems of varying detail.<sup>8,17–19</sup> These studies establish a normative decarbonization constraint and use the model to develop a cost-effective portfolio of technologies to comply with that constraint, or they use the model to perform a cost-benefit analysis to determine the economically efficient evolution of global energy technologies and CO<sub>2</sub> emissions. By constraining the portfolio of available technologies, IAMs can also be used to explore the feasibility of alternative technology pathways and the sensitivity of model results to the availability of specific technologies.<sup>26</sup>
3. *Bottom-up energy systems modeling* approaches use relatively detailed representations of the energy system to construct scenarios capable of achieving normative decarbonization goals.<sup>20,21</sup> These models are generally very data-intensive and allow consideration of technical constraints in the energy systems as well as some degree of economic assessment.

**TABLE 1** | Global Decarbonization Studies Reviewed: Targets, Approaches & Results

Study	Scenario	Scenario Construction Approach/Scenario		CO <sub>2</sub> Target	TPED	C/GDP Rate	E/GDP Rate	Technology Options		Notes
		Purpose	Considered							
Greenpeace/European Renewable Energy Council [EREC] (2010) <sup>12</sup>	'Greenpeace/ EREC'—Advanced Energy [R]evolution scenario	Top-down scenario-based back-casting/Explore energy supply and end-use transformations to achieve 80% renewable energy share in primary energy supply	4.3 Gt in 2050 (80% below 1990 levels)	14.8 TW-yr in 2050	-8%/yr	-3.4%/yr	Nuclear and CCS excluded/Renewables at 80% of share by 2050, fossil at 20% Current coal plant lifetimes reduced			
Jacobson and Delucchi (2011) <sup>13</sup> ; Delucchi and Jacobson (2011) <sup>14</sup>	'Jacobson & Delucchi'—100% Wind, Water, Solar (WWS) scenario	Top-down scenario-based back-casting/Explore options to provide 100% of global energy needs exclusively with wind, water, and solar energy	0 Gt in 2050	N/A (End-use energy specified)	> -15%/yr	-3.6%/yr (Change in end-use energy)	Wind, hydro-electric, ocean, and solar PV and solar thermal only Nuclear, fossil and biomass excluded in electricity, transport and industry 95% of LDV fleet electric by 2050	Conflicting language in papers regarding target for 100% WWS (2030 or 2050). This paper assumes 2050 target is intended		
Worldwatch (2009) <sup>15</sup>	'Worldwatch'—Renewable Revolution scenario	Top-down scenario-based back-casting/Explore energy supply and end-use transformations	13.8 Gt in 2030 (34% below 1990)	15.6 TW-yr in 2030	-6.8%/yr	-3.4%/yr	CCS and new nuclear capacity excluded 50% of LDV fleet electric by 2030			
Brook (2012) <sup>16</sup>	'Brook'	Top-down scenario-based back-casting/Explore energy supply transformations assuming significant nuclear role	3.1 Gt in 2060	31.7 TW-yr in 2060	-7.7%/yr	-1.9%/yr	All options considered	Scenario sees growth in all nonfossil sources and CCS, but places emphasis on nuclear fission, which provides 52% of TPED in 2060		
U.S. Climate Change Science Program [CCSP] (2007) <sup>17</sup>	'CCSP IGSM'—CCSP MERGE'—CCSP MiniCAM'	Top-down integrated assessment modeling/Open-ended exploration of energy supply transformation	16 Gt in 2050 (450 ppm target)	15.9 TW-yr in 2050	-4.7%/yr	-3.3%/yr—3.6%/yr—3.0%/yr	All options considered			
Clark et al (2009)—22nd Energy Modeling Forum (EMF22) <sup>18</sup>	'EMF22 ETSAP-TIAM'—EMF22 ETSAP-TIAM 450, No, Full	Top-down integrated assessment modeling/Open-ended exploration of energy supply transformation	0.4 GT in 2050	30 TW-yr in 2050	-14.4%/yr	-1.7%/yr	All options considered	450 ppm CO <sub>2</sub> target, assuming no overshoot of target and full international participation		
—	'EMF22 MiniCAM'—EMF22 MiniCAM Base 450 No Full	Top-down integrated assessment modeling/Open-ended exploration of energy supply transformation	4 GT in 2050	21.1 TW-yr in 2050	-8.2%/yr	-2.6%/yr	All options considered	450 ppm CO <sub>2</sub> target, assuming no overshoot of target and full international participation		

TABLE 1 | Continued

Study	Scenario	Scenario Construction Approach/Scenario		CO <sub>2</sub> Target	TPED	C/GDP Rate	E/GDP Rate	Technology Options		Notes
		Purpose	Modeling					Considered	Excluded	
Global Energy Assessment [GEA] (2012) <sup>19</sup>	'GEA Efficiency'—geala_450_atr_nonuc	Top-down integrated assessment modeling/Explore energy supply and end-use transformations excluding nuclear	7.8 Gt in 2060 (450 ppm target)	17.9 TW-yr in 2060	-5.6%/yr	-2.4%/yr	New nuclear excluded and existing nuclear retired at end of useful life/Advanced transportation' options: electrification focus with ~50% electrification by 2060, biofuels at ~20%	Results reported for IMAGE model runs		
-	'GEA Mix'—geama_450_btr_full	Top-down integrated assessment/Explore energy supply and end-use transformations with diverse mix of decarbonization options	7.1 in 2060 (450 ppm target)	23.3 TW-yr in 2060	-5.8%/yr (	-1.9%/yr	All supply options considered/Basic transportation' options: biofuels, fossil synguels, and compressed gas/biogas focus with ~20% electrification by 2060	Results reported for IMAGE model runs		
-	'GEA Supply'—geaha_450_atr_full	Top-down integrated assessment modeling/Explore energy supply and end-use transformations with limited energy intensity rate	7.9 Gt in 2060 (450 ppm target)	27.2 TW-yr in 2060	-5.6%/yr	-1.6%/yr	All supply options considered/Advanced transportation' options: electrification focus with ~50% electrification by 2060, biofuels at ~20%	Results reported for IMAGE model runs		
International Energy Agency [IEA] (2010a) <sup>20</sup>	'WEO 450'—World Energy Outlook 450 ppm stabilization scenario	Bottom-up energy systems modeling/Open-ended exploration of energy supply transformation	21.7 Gt in 2035 (450 ppm target)	19.8 TW-yr in 2035	-4.4%/yr	-2.5%/yr	All options considered	Uses IEA's World Energy Model		
International Energy Agency [IEA] (2010b) <sup>21</sup>	'IEA Blue Map'—Energy Technology Perspectives Blue Map scenario	Bottom-up energy systems modeling/Open-ended exploration of energy supply transformation	14 Gt in 2050 (50% below 2005 levels)	20.8 TW-yr in 2050	-5.0%/yr	-2.6%/yr	All options considered	Uses IEA's World Energy Model		
World Wildlife Fund [WWF] (2007) <sup>22</sup>	'WWF'—World Wildlife Fund Vision for 2050	Bottom-up technical or techno-economic assessment/Explore energy supply and end-use transformations	11.7 Gt in 2050 (60% below 2006 levels)	23.0 TW-yr in 2050	-5.5%/yr	-2.4%/yr	All options considered at outset, but technologies excluded from scenario based on cost/benefit and technical potential analysis/Nuclear phased out/Large-scale hydrogen infrastructure planned	Technical feasibility assessment, using proprietary model		

**TABLE 1** | Continued

Study	Scenario	Scenario Construction Approach/Scenario		CO <sub>2</sub> Target	TPED	C/GDP Rate	E/GDP Rate	Technology Options		Notes
		Purpose	Method					Considered	Not Considered	
McKinsey (2009) <sup>23</sup>	'McKinsey A'—Maximum growth of renewables and nuclear	Bottom-up technical or techno-economic assessment/Explore energy supply transformations with rapid growth of nuclear and renewables	techno-economic assessment/Explore energy supply transformations with rapid growth of nuclear and renewables	21.9 Gt in 2030	N/A	-4.6%/yr	Not reported	All options considered	Assumes nuclear and renewables built to maximum potential in each market	Techno-economic assessment of abatement potential across all economic sectors
-	'McKinsey B'—50% growth of renewables and nuclear	Bottom-up technical or techno-economic assessment/Explore energy supply transformations with limited growth of nuclear and renewables	techno-economic assessment/Explore energy supply transformations with limited growth of nuclear and renewables	21.9 Gt in 2030	N/A	-4.6%/yr	Not reported	All options considered	Growth of renewables and nuclear limited to 50% of that in McKinsey A scenario	Techno-economic assessment of abatement potential across all economic sectors

4. *Bottom-up technical or techno-economic assessments* start with comparative rankings of various decarbonization technologies and/or opportunities.<sup>22,23</sup> Technologies can be ranked on abatement cost alone (e.g., McKinsey), or on some other set of criteria, which may not include costs at all (e.g., WWF). Highly ranked technologies are then deployed to develop the decarbonization scenario.

Note that this taxonomy distinguishes scenarios based on the *method* of scenario construction, rather than the *purpose* for which that scenario is constructed. Irrespective of method, scenarios can be constructed for a variety of purposes, including, identifying the least-cost pathway to accomplish a specific CO<sub>2</sub> stabilization target, exploring the technical feasibility or economic cost of certain pathways, describing the expected results of policies, or exploring the sensitivity of scenario results to specific key assumptions. Where possible, we therefore also note the intent for which the scenarios were constructed (see Table 1).

While important differences exist between the methodological approach, level of detail, and motivating objective of each approach to constructing decarbonization scenarios, these key distinctions are often lost outside of the relevant research communities. This is particularly true when such studies enter into public discourse and policy making debates, where only the headline conclusions receive the bulk of attention. Furthermore, within each category of scenario methods, we find a range of resulting energy system transformation rates and treatments of constraints to change. When it comes to feasibility, we find that the choice of scenario construction method itself is much less important than the specific scenario assumptions.

As such, this study conducts a cross-comparison of decarbonization scenarios selected to include notable examples from of each of these four scenario construction approaches and to span a range of decarbonization strategies—i.e., studies employing a diversity of technology portfolios, different degrees of emphasis on energy efficiency improvements versus supply decarbonization and so on. To facilitate this cross-comparison, this study uses a set of metrics that are agnostic to the underlying scenario construction methods and are selected to aim focus at the pace of energy system transformation envisioned by selected studies and the varying treatment of key constraints on such transformation therein.

Table 1 lists the decarbonization studies and scenarios reviewed by this study, along with their classification based on the taxonomy described above. This table also lists each scenario's CO<sub>2</sub> emissions

target, assumptions about energy demand growth and energy and carbon intensity improvement rates, and the low-carbon technologies considered by the scenario.

Notably, all of the studies reviewed primarily focus on the transformation of the electricity sector, even though CO<sub>2</sub> emissions from electricity and heat generation accounted for only 41% of all energy-related emissions in 2010.<sup>27</sup> Transportation and industrial emissions added together account for another 42% of energy-related emissions, essentially equal to electricity and heat generation, but as we will see, most of these studies provide much less consideration of decarbonization options for these sectors. This likely reflects a general consensus in the climate mitigation literature that the near-complete decarbonization of electricity generation along with electrification of other sectors (e.g., heat and transport) will play an integral role in reducing global energy-related CO<sub>2</sub> emissions, particularly through the first half of the century.<sup>7,28</sup>

The remainder of this section compares key metrics for energy system transformation for each study on a consistent basis, whenever sufficient detail has been provided to allow for valid comparisons to be made. Because of this limitation, not every study is included in each comparison. For uniformity and to allow comparison across studies, we convert and

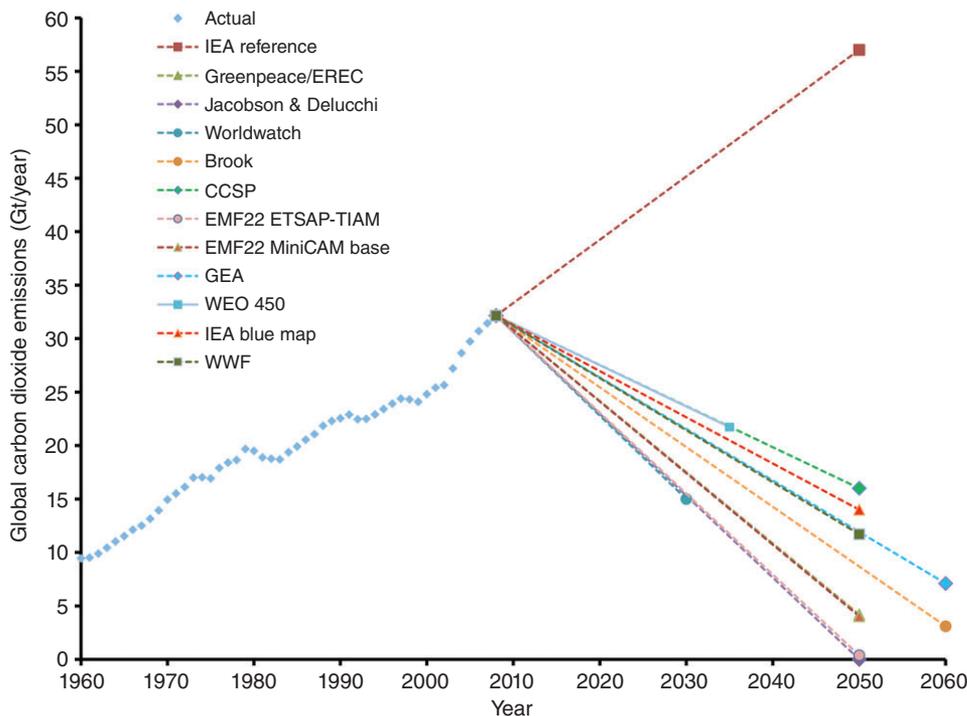
present all energy quantities in terawatt-years (TW-yr) and power quantities in terawatts (TW) or gigawatts (GW). Carbon emissions are presented consistently in gigatonnes of carbon dioxide (Gt CO<sub>2</sub>).

### CO<sub>2</sub> EMISSIONS TARGETS

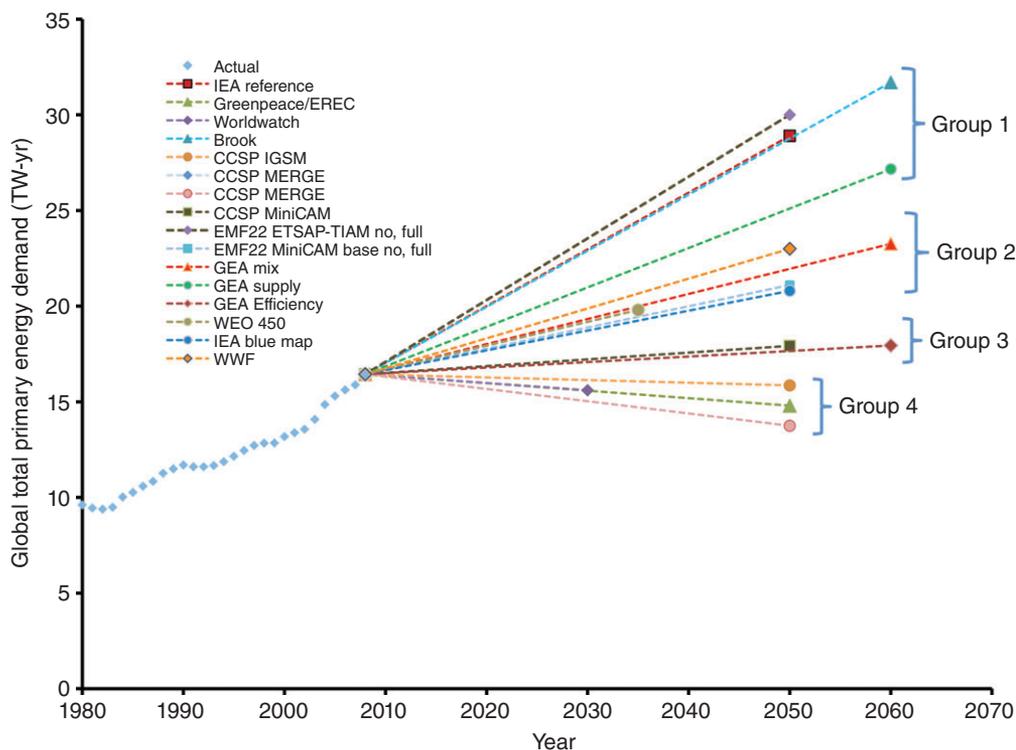
While business-as-usual (BAU) projections see global CO<sub>2</sub> emissions reaching 57 Gt/year by 2050,<sup>21</sup> the surveyed studies all propose strategies for deep decarbonization, on the order of 50–90% below current levels by 2050 (see Table 1 and Figure 1).

As expected given the nature of global decarbonization scenarios, meeting even the least demanding of the emissions targets (i.e., the WEO 450 or the CCSP targets) would represent a significant departure from the historical trajectory of carbon emissions, which have increased by 2.4%/year for the period 1965–2009.<sup>27</sup> The implied reductions in carbon intensity (CO<sub>2</sub> emitted per unit of GDP) range from 4–5%/year (WEO 450, CCSP, WWF) to over 10%/year (Jacobson & Delucchi, EMF22 ETSAP-TIAM). For comparison, global carbon intensity was reduced by 0.9%/year from 1990 to 2005, despite significant policy efforts in some countries.<sup>29</sup>

The CO<sub>2</sub> targets in these studies are met by implementing two strategies: (1) reduction in total primary energy demand (TPED) and (2) reduction



**FIGURE 1** | CO<sub>2</sub> emissions targets of the global climate stabilization studies reviewed (see Table 1 for key to sources). Dashed lines are for clarity and do not imply emissions trajectories.



**FIGURE 2** | Projected total primary energy demand for the climate stabilization scenarios reviewed (see Table 1 for key to sources). Dashed lines are for clarity and do not imply energy trajectories.

in the carbon intensity of energy supply. In the following sections, we assess the rates of energy system transformation associated with each of these strategies.

## TOTAL PRIMARY ENERGY DEMAND, ENERGY INTENSITY, AND HISTORICAL BENCHMARKS

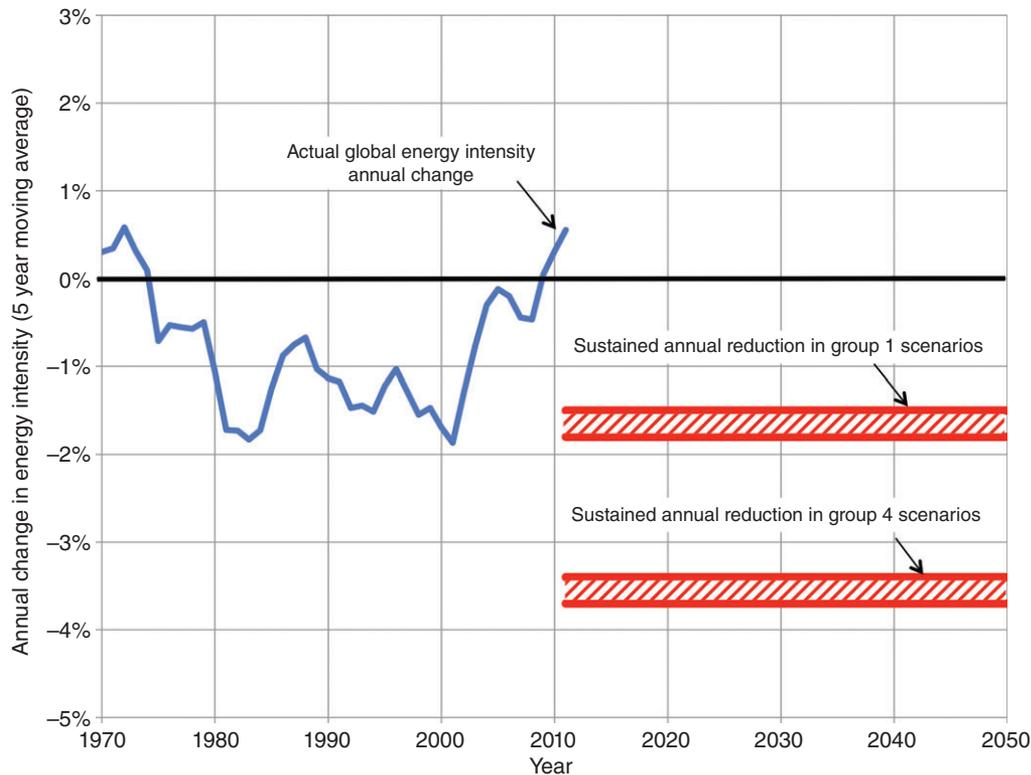
Global TPED stood at 16.4 TW-yr in 2010 with fossil fuels supplying more than 80% of demand.<sup>30</sup> On average, TPED grew 2.6% annually over the 44 years from 1965 to 2009; as the global population doubled over this period, TPED tripled.<sup>30,29</sup>

Reference, or BAU, scenarios, project TPED will grow more slowly, roughly doubling over the next 40 years<sup>21</sup> with an annual growth of approximately 1.4%. Non-OECD countries are responsible for roughly 90% of the projected growth, with China and India alone accounting for more than half of the increase in energy use.<sup>30</sup>

Figure 2 illustrates the projected TPED assumptions in each of the scenarios, together with the IEA Reference BAU scenario<sup>30</sup> for comparison. Most scenarios assume demand reduction strategies will significantly reduce the growth of TPED over the next 20–40 years. TPED projections depend on both the

growth in *demand* for energy services and in changes in the energy *intensity* of the global economy (i.e., improvements in energy productivity or efficiency). Many studies assume reductions in TPED in the range of 30–40% relative to BAU scenarios, thereby requiring much greater annual rates of improvement in energy intensity than have been experienced in the last 40 years.

As Figure 2 illustrates, projected TPED varies widely across the scenarios, which fall roughly into four groupings. The first group (Brook, EMF22 ETSAP-TIAM and IEA reference scenario) projects continued growth in TPED at roughly recent rates. The second group (IEA WEO 450 and Blue Map, GEA Supply and Mix, WWF, and EMF22 MiniCAM Base scenarios) projects more modest growth (~1.2% annually), leading to a roughly 30% reduction relative to the reference case by 2050. The third group (GEA Efficiency and CCSP MiniCam) sees TPED remaining roughly flat through 2050, increasing by only 10–15% from 2010 levels. Finally, the fourth group (Greenpeace/EREC, Worldwatch, and CCSP MERGE and IGSM scenarios) envisions absolute declines in global TPED through 2050. Jacobson & Delucchi also envision absolute declines in energy consumption to 2030, but present projections of end-use energy rather than total primary energy.



**FIGURE 3** | Global trends in energy intensity, past, and projected (sources: Refs 31, 32, and the various studies reviewed herein).

Figure 3 illustrates the implied ranges of rates of improvements in energy intensity (TW-yr/\$GDP) for ‘Group 1’ studies projecting sustained BAU growth rates in energy demand and ‘Group 4’ studies projecting absolute declines in global TPED, and compares these rates to historical annual changes in global energy intensity, which declined by 0.8%/year on average over the last 40 years.

Even the ‘Group 1’ scenarios require sustained improvements in energy intensity of  $-1.5$  to  $-1.8\%$ /year, matching the highest annual rates seen over the last 40 years. Furthermore, the ‘Group 4’ scenarios require sustained declines in energy intensity of  $-3.4$  to  $-3.7\%$ /year, roughly double the most rapid rates observed over the past 40 years. These rates fall far outside the range of historical experience and also significantly exceed the fastest sustained rates of energy intensity decline observed in any individual OECD nation from 1971 to 2006.<sup>33</sup>

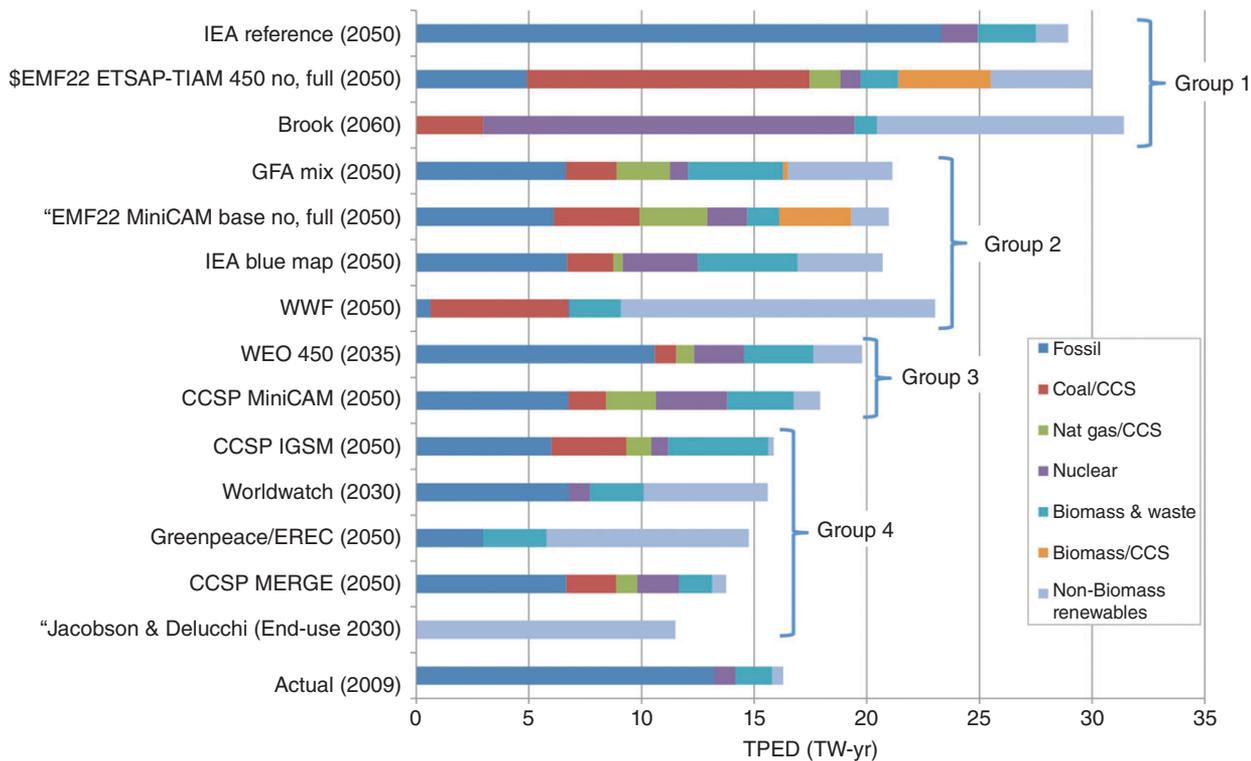
## DECARBONIZATION OF ENERGY SUPPLY, LOW-CARBON TECHNOLOGY DEPLOYMENT, AND HISTORICAL BENCHMARKS

Figure 4 presents the breakdown of projected TPED by major categories of supply. It illustrates the very

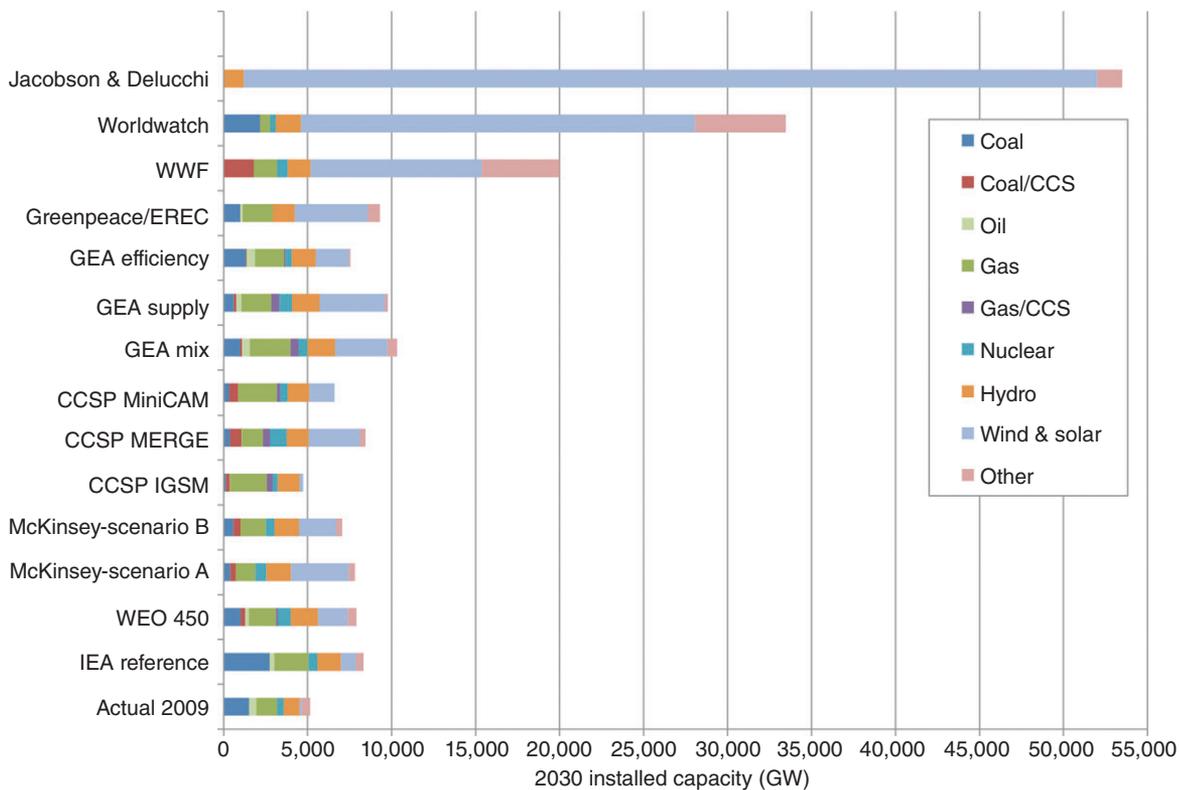
different approaches taken to meet the desired emissions reduction. ‘Group 4’ studies (e.g., Jacobson & Delucchi, Greenpeace/EREC, Worldwatch) adopt a strategy of very large rates of demand reduction combined with very heavy reliance on renewables and massive electrification, and they specifically exclude certain technologies from consideration. Others (e.g., EMF22, GEA, CCSP, WEO 450, IEA Blue Map) include a broad mix of all available options and less stringent demand reductions.

Figure 5 compares projected electricity generating capacity in each study for the year 2030. The actual mix of installed generating capacity for 2009 is provided for comparison.

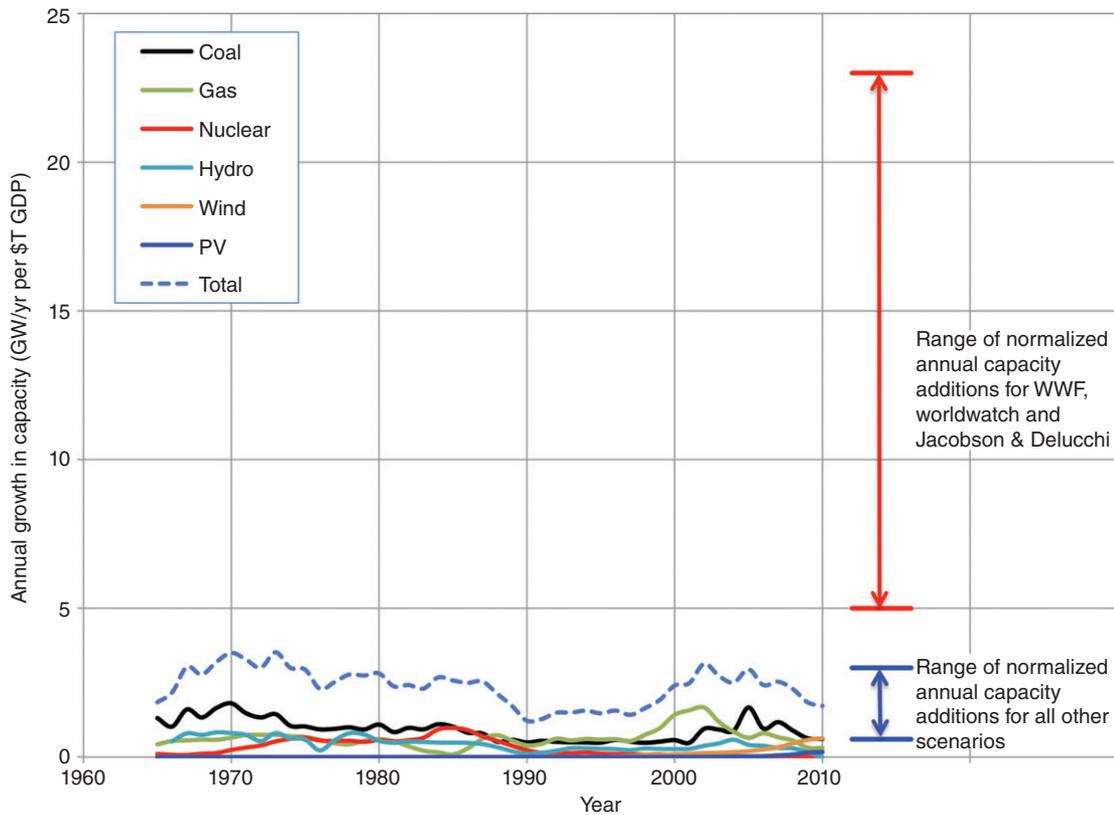
The studies all project a significant expansion of installed electrical generating capacity as well as major changes in the mix of generating sources, driven both by a shift to lower-carbon technologies and fuels and by increased electrification of the transportation, heat, and in some cases, industrial sectors. In general, the studies project an increase in electricity’s share of final demand from the current 17% to the 30–50% range, continuing a 20-year trend. Jacobson & Delucchi is outlier in this regard, as they exclude every option except wind, solar, hydro, and ocean energy; as a result, 100% of energy demand is supplied by electricity or electrolytic hydrogen in their scenario.



**FIGURE 4 |** Share of projected total primary energy demand for specified year by energy source (nonbiomass renewables includes hydro, wind, solar, and geothermal; see Table 1 for key sources).



**FIGURE 5 |** Projected installed power generation capacity in 2030, and current installed capacity in 2009 ('other' includes oil, biomass, geothermal, and ocean).

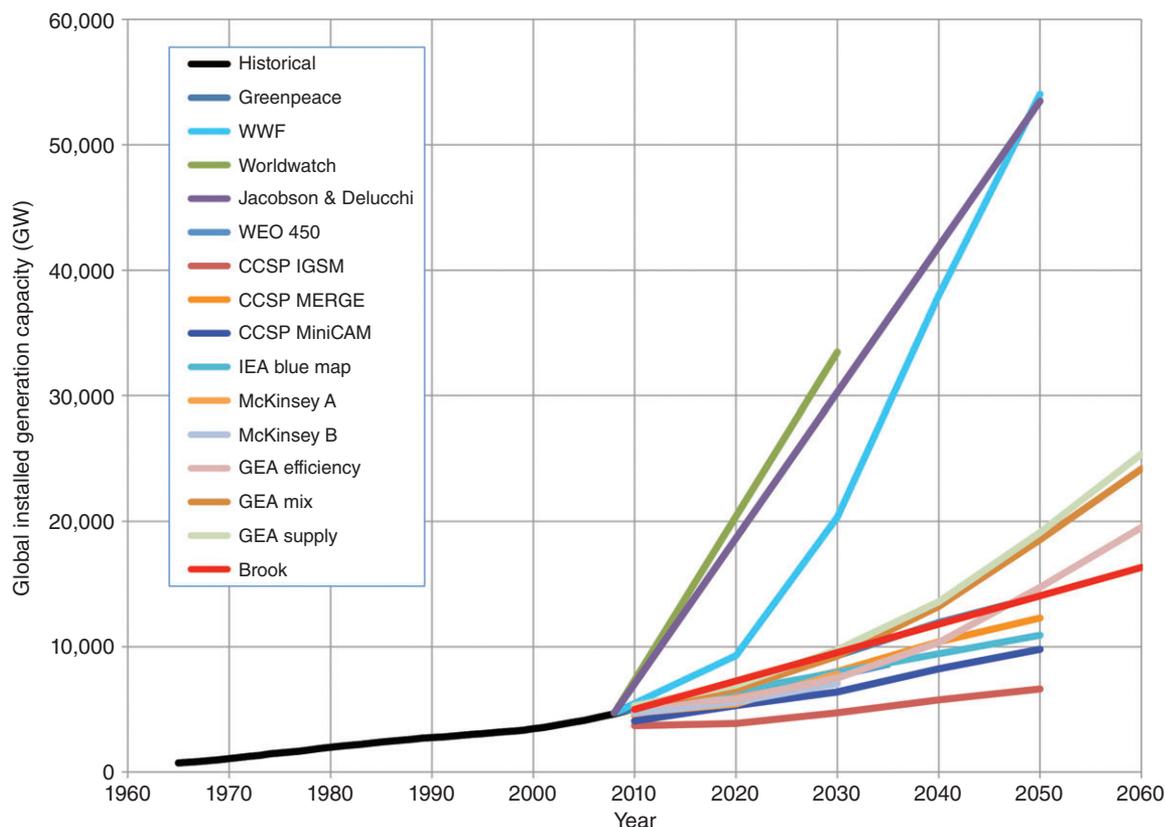


**FIGURE 6** | Worldwide normalized capacity addition rates of total power system capacity and key power generation technologies since 1965 (sources: Refs 30, 29, 34–37) and ranges of normalized capacity additions for scenarios reviewed. All capacity addition rates normalized by constant dollar global GDP.

The feasibility of the rates of new generating capacity additions implied can, in part, be assessed by benchmarking against historical experience.<sup>a</sup> Figure 6 presents normalized annual capacity addition rates for total power system capacity as well as individual power generation technologies since 1965.<sup>30,29,34–37</sup> Capacity addition rates are smoothed as a 3-year rolling average and normalized by global GDP (in constant dollars) in each year, so as to account for the growth of the overall global economy.<sup>b</sup> Total global capacity increased from ~725 to ~5330 GW from 1965 to 2011, and grew at an annual rate of between 2 and 6% over this period. Normalized capacity additions of individual energy sources was typically less than 1.5 GW/year/\$T of GDP while the total global capacity grew at between 1.5 and 3.5 GW/year/\$T of GDP (Individual technology ranges were: coal 0.6–1.6 GW/year/\$T of GDP, gas 0.2–1.6, nuclear 0–1.0, hydro 0.1–0.8, wind 0–0.6 and solar PV 0–0.2).

Figure 7 shows total global installed generation capacity as a function of time, both historical from 1965 to 2010 and projected in the various scenarios.

As Figures 6 and 7 illustrate, most studies call for expansion of global generation capacity at rates consistent with historical experience,<sup>c</sup> envisioning a roughly 50–100% cumulative increase in world electric generating capacity by 2030 (an increase of approximately 3000–5000 GW or a normalized rate of 0.6–3.0 GW/year/\$T of GDP). Three scenarios (Worldwatch, Jacobson & Delucchi, and WWF) that call for large percentages of wind and solar power and exclude key baseload technologies [e.g., nuclear and/or coal and gas with carbon capture and storage (CCS)] are striking exceptions. These studies envision a 4- to 10-fold increase in world generating capacity, calling for 20,000–30,000 GW by 2030 and over 50,000 GW by 2050, a build-out approximately an order of magnitude greater than the remainder of the studies. These studies also envision a normalized build-out of generating capacity in the range of 5–23 GW/year/\$T of GDP, or 1.4–15 times faster than historical experience. These unprecedented rates are a consequence of both the relatively low-capacity factors of wind and solar as well as increased demand due to the assumed widespread electrification of the economy.



**FIGURE 7 |** Historical and projected total global installed power generation capacity (see Table 1 for key sources).

We now compare the requisite deployment rates of specific low-carbon electricity generation technologies in each scenario with historical experience and industry projections, where available. The studies generally provide projections by decade, and we assume a linear growth in capacity for each decade.

## Wind

Most studies assume annual deployments of wind turbines in the range 50–100 or 0.5–1 GW/year/\$T of GDP. While these rates are roughly double the rate of wind capacity additions from 2010 to 2012, they compare favorably to normalized rates of capacity addition for several other technologies (i.e., coal, gas, nuclear, or hydro). Global annual wind capacity additions more than doubled from 20.3 GW in 2007 to 44.8 GW in 2012, and the Global Wind Energy Council projects global wind deployment rates will increase to 70–120 GW/year by 2020 and 100–150 GW/year by 2030.<sup>38</sup>

Much more aggressive plans were presented by three studies. Jacobson & Delucchi envision approximately 500 GW/year to yield 19,000 GW in 2050. WWF assumes 200–500 GW/year to attain 7200 GW in 2030. Worldwatch projects more than 200

GW/year to yield 4800 GW in 2030. These three scenarios call for global wind deployment in the range 2–6 GW/year/\$T of GDP, every year for the next 35 years. Those rates are roughly 33–300% faster than has been demonstrated historically for any single technology. Indeed, at the middle and upper end of this range, wind capacity additions alone would exceed the historical normalized capacity addition rate for all technologies combined (see Figure 6).

## Solar

Only a few of the studies separately specify contributions from solar photovoltaics (PV) and solar thermal, so we combine both technologies here for ease of cross-comparison. Apart from Jacobson & Delucchi, WWF, and Worldwatch, the projected average rate of solar capacity additions range from 50 to 150 GW/year in the next decade and beyond (a normalized rate of 0.7–2 GW/year/\$T of GDP). This rate is as much as five times the historical high of roughly 31 GW in 2012<sup>39</sup> and would thus entail a continuation of the rapid growth rates recently experienced by the PV industry, as well as the establishment of a viable, multi-GW-scale global solar thermal industry. However, solar capacity additions at that rate would

be within the normalized range that has been historically demonstrated for more conventional power generation technologies (see Figure 6) and consistent with the more ambitious visions of the solar industry.<sup>40,41</sup>

However, both Jacobson & Delucchi and Worldwatch call for building an average of more than 700 GW/year of solar—reaching a total installed capacity of 30,000 GW in 2050 and 18,000 GW in 2030 respectively. WWF envisions over 300 GW/year after 2030 as capacity grows to more than 8000 GW in 2050. These three scenarios call for sustained normalized solar deployment in the range of 3–8 GW/year/\$T of GDP. As with the wind addition rates envisioned by these studies, this solar capacity addition rate would be higher than has been demonstrated for any single technology in global history, and on a sustained basis, would be more rapid than total global power generation capacity additions (see Figure 6).

### Hydroelectric

Projected additions of hydroelectric power are universally modest compared with those for wind and solar. The various scenarios envision an increase of roughly 300–600 GW in total capacity by 2030, an increase of roughly 30–60% over 2008 capacity. Normalized buildout rates are in the range 0.2–0.3 GW/year/\$T of GDP, consistent with historical hydropower capacity addition rates of 0.2–0.8 GW/year/\$T of GDP.<sup>30</sup>

### Geothermal

Geothermal's 2012 contribution to global capacity stood at approximately 11 GW with additions over the last 20 years less than 0.01 GW/year/\$T of GDP.<sup>35</sup> Most studies project capacities increasing to 30–200 GW by 2030, with deployment rates in the range 0.01–0.1 GW/year/\$T of GDP. In contrast, Jacobson & Delucchi, Worldwatch, and WWF project much larger increases in installed capacity: approximately 500 GW in 2050, 1000 GW in 2030, and 3000 GW in 2050, respectively, or 0.2–1.0 GW/year/\$T of GDP. Although these rates are modest compared to those for other technologies (see Figure 6), they are orders of magnitude greater than historical geothermal capacity addition rates. As another point of comparison, an MIT Energy Initiative study estimated that an aggressive development plan making use of enhanced geothermal techniques not yet demonstrated at commercial scale could potentially yield a cumulative installed capacity in the United States of 100 GW by 2050.<sup>42</sup> Worldwatch calls for adding this much geothermal capacity worldwide every 2 years between now and 2030.

### Ocean

Wave and tidal generators are not currently commercially viable and the installed base is essentially zero. Despite this, Jacobson & Delucchi's scenario assumes we can build 1000 GW of installed capacity by 2050, Worldwatch calls for roughly 300 GW by 2030, and Greenpeace/EREC envisions 200 GW by 2050. The other studies that specifically reference ocean power suggest much lower capacities in 2030, between 3 and 60 GW.

While the global resource potential of wave and tidal energy in locations likely to be developed for energy production exceeds 500 GW,<sup>13</sup> scaling up deployment of these immature technologies to tens of GW/year will require extensive design, development, testing, and evaluation, which can take many years. For reference, the first 1 GW of wind power was installed in California between 1981 and 1985,<sup>43</sup> and it took more than 25 years to reach a total global installed capacity of 100 GW.<sup>38</sup>

### Nuclear

With the exception of Brook, none of the studies reviewed here calls for an expansion of nuclear power comparable to those suggested for wind, solar, or geothermal. Greenpeace/EREC and Jacobson & Delucchi envision a complete phase-out of nuclear power worldwide, while the remainder of studies project 300–1000 GW of installed nuclear capacity in 2030. Current capacity stands at approximately 400 GW.<sup>30</sup> The required capacity additions in even the most ambitious scenarios are consistent with the 15–40 GW/year (or 0.2–0.6 GW/year/\$T of GDP) sustained rate of deployment that has been demonstrated by the nuclear industry historically (see Figure 6).

Brook presents a nuclear focused strategy, with a total projected nuclear capacity of approximately 5400 GW in 2060, equal to one third of the scenario's projected global generation capacity. Brook compares the required buildout to historical nuclear experience, scaling the French experience from 1977 to 1989 on the basis of capacity additions per year per unit of GDP and claims that his required build rate of ~135 GW/year is feasible. Over the course of the buildout, this would represent between 0.6 and 2 GW/year/\$T of GDP of capacity added per year, which is consistent with the deployment rate envisioned for solar in the bulk of scenarios and ranges from well below to slightly greater than the historical rates achieved for single technologies in the last 50 years.

### Carbon Capture and Storage

With the exceptions of Jacobson & Delucchi, Worldwatch, and Greenpeace/EREC, all the studies reviewed

envison CCS installed on 5–40% of global power generation capacity by 2050. Amongst the scenarios reviewed, WWF calls for the greatest CCS capacity, projecting roughly 1800 GW of coal power with CCS by 2030, most of which is added after 2020. This would require the addition of about 200 GW/year (or approximately 2 GW/year/\$T of GDP) of CCS capacity during the 2020s. Other studies project the addition of 10–50 GW/year, again with most capacity additions occurring after 2020 (a maximum of ~0.3 GW/year/\$T of GDP). Furthermore, WWF and the three CCSP scenarios project more than 50 GW of installed coal power with CCS by 2020.

In some of the studies that project out to 2050, CCS is implemented in energy-intensive industrial processes such as cement, iron and steel, pulp, paper, and chemicals, in addition to coal, gas, and biomass power generation. The WEO 450 scenario projects fossil and biomass energy with CCS will supply 9% of TPED in 2035. Among scenarios projecting out to 2050, the IEA Blue Map scenario projects CCS will meet 12% of TPED; the three GEA scenarios project 14–25%; the CCSP studies project 19–27%; and the WWF scenario projects 26%.

Over the long run, it can be argued that in terms of drilling and completing wells and installing compression and pipeline capacity, the CCS capacity additions that these decarbonization scenarios call for are close to the recent experience range of such activities in the global oil and gas industries.<sup>35</sup> The WWF study, which calls for the highest rate of CCS adoption is an exception. At the same time, however, others, notably Smil,<sup>44</sup> have pointed out that such comparisons only serve to highlight the enormity of the undertaking implied by the scale of CCS deployment envisioned in the bulk of scenarios.

## Biomass

While Jacobson & Delucchi exclude all combustion energy sources, renewable or otherwise, biomass and waste figure in the energy mix for all other surveyed scenarios, providing 10–28% of TPED (1.5–5.8 TW-yr) in 2030–2050. For reference, biomass and waste provided approximately 1.6 TW-yr or 10% of global TPED in 2008.<sup>30</sup> With the exception of Worldwatch (1–3 GW/year/\$T of GDP), the implied growth rate is consistent with historical energy technology deployment rates (0.5–1.5 GW/year/\$T of GDP).

In the case of biomass, however, the availability of arable land to produce biomass feedstocks may be a constraining factor. Estimates of the ultimate global bioenergy potential of the planet (including all land currently planted with food crops) range

from 7 to 11 TW-yr.<sup>45–47</sup> Biomass contributions to decarbonization scenarios, where clearly identified, range as follows: 2.8 (Greenpeace/EREC), 4.4 (CCSP IGSM and IEA Blue Map), 4.6 (EMF22 MiniCAM), and 5.8 TW-yr (EMF22 ETSAP-TIAM). The biomass energy targets envisaged in these studies would thus require 25–83% of the global bioenergy potential, with uncertain impacts on agriculture. It is also worth noting that these scenarios generally consider biomass resources to be carbon-free, ignoring the indirect carbon emissions associated with expanded land use for biomass.<sup>48–52</sup>

## TRANSPORTATION ENERGY

Transportation energy use was responsible for 22% of energy-related CO<sub>2</sub> emissions in 2010, and decarbonization of the transport sector will be critical to achieving climate stabilization objectives.<sup>27</sup> The surveyed studies overwhelmingly focus on electrification of transport, principally by means of electric vehicles and plug-in hybrid electric vehicles, as the best way to decarbonize the sector.

The overall range of projected light-duty vehicle (LDV) electrification across all reviewed studies is broad, however, from as low as 5% in 2035 in the WEO 450 scenario to 95% by 2050 in the case of Jacobson & Delucchi. Five studies (IEA Blue Map, Worldwatch, WWF, Greenpeace/EREC, and Jacobson & Delucchi) assume that more than half of all vehicles (including personal vehicles, rail, freight, air, and shipping) will be powered by electricity or hydrogen by 2050 or earlier.

In most cases, it appears that the percentage of vehicles electrified is specified rather than being based on any market-based fleet turnover analysis or assessment of the economic, technical, or policy conditions required to achieve this transformation. While in some cases this reflects the limitations of the underlying modeling or scenario construction methods, this is not a trivial omission given the technical and infrastructural challenges and relatively long time periods required for substantial vehicle turnover in vehicle fleets. Belzowski and McManus<sup>53</sup> estimate that 20–40 years would be required for alternative LDV powertrain technologies to increase their on-road penetration by 50 percentage points in the USA, approximately 30–40 years to reach an equivalent fleet penetration in Europe, and more than 44 years in China and India. The growth of diesel LDVs also provides a historical analogue. A significant fuel price differential, together with the inherent fuel efficiency advantage of diesel over gasoline engines led diesel LDV sales to reach 50–70% of new sales in many

**TABLE 2** | Treatment of Constraints on Energy System Transformation

	Technology Readiness	Economics	Integration Issues	Social & Non-Cost Barriers
IEA Reference	–	+	×	–
CCSP	–	+	×	–
EMF22	–	+	×	–
GEA	+	+	+	+
IEA WEO 450	–	+	–	–
IEA Blue Map	–	+	–	–
McKinsey	–	+	–	–
Worldwatch	×	×	–	–
WWF	×	×	–	–
Greenpeace/EREC	+	+	+	–
Jacobson & Delucchi	–	–	+	–
Brook	–	–	–	–

+, treated explicitly; –, some discussion; ×, omitted/ignored/minimal treatment.

EU countries by 2005. Despite these economic and technical advantages and the maturity of the technology platform, the total LDV fleet diesel penetration only increased from 15 to 30% over a 10-year period (1995–2005).<sup>31</sup> The barriers to electric or hydrogen vehicle penetration are significantly larger than those facing diesel.<sup>54</sup>

## INDUSTRIAL ENERGY

Industrial fossil fuel use contributed 20% of global CO<sub>2</sub> emissions in 2008, with 52% of that fraction coming from combustion of coal, 26% from oil, and 22% from natural gas. Industrial coal use is concentrated in the cement industry and the iron and steel industry.<sup>27</sup>

In general, with the exception of the McKinsey report, the studies contain very limited to no discussion of industrial mitigation options. McKinsey identifies specific opportunities for the petroleum and gas, cement, iron and steel, and chemicals sectors. Several other studies (EMF22, IEA Blue Map, GEA, and WWF) see a role for CCS and propose additional, more conventional options but fail to provide a comprehensive assessment of emissions reduction potentials. The GEA scenarios, e.g., conceptually discuss and suggest improved energy efficiency and adoption of best available technologies (including greater combined heat and power use), optimization of material and energy flows through systems design, lifecycle product design and enhanced recycling, further electrification, and CCS as options for industrial decarbonization, but they provide no detailed discussion comparable to the scenario's treatment of

electricity or even transportation sector decarbonization. It is striking that relatively little planning has apparently occurred for the decarbonization of a sector responsible for one fifth of global emissions.

## KEY CONSTRAINTS ON ENERGY SYSTEM TRANSFORMATION

Table 2 provides a high-level summary of the treatment of key constraints on the transformation of the existing energy system amongst the scenarios reviewed herein. This section discusses the treatment of each of these key categories of constraint.

### Technological Readiness

Technological readiness—whether or not a given technology will, in fact, be commercially available at suitable performance levels within the study horizon—is a threshold constraint for any decarbonization scenario. The low-carbon technologies applied in these scenarios span a range of readiness. Nuclear energy, wind energy, solar PV, and geothermal are in wide commercial operation today and are readily scaleable. Other technologies, such as energy storage (excluding pumped hydro), electric, plug-in hybrid and fuel cell vehicles, ocean energy, and various smart grid technologies, are commercially available at demonstration or early commercial stages but require substantial maturation and face significant technical and cost hurdles to scale up.<sup>21</sup>

The key component technologies that make up the CCS option (industrial carbon dioxide capture, compression, pipeline transport, injection technology,

enhanced oil or gas recovery storage, and monitoring technologies) have been separately demonstrated commercially for decades<sup>55</sup> including through an integrated industrial coal gasification facility located in North Dakota utilizing CO<sub>2</sub> separation, compression, pipeline transport, and final sequestration and monitoring in the Weyburn oil field in Saskatchewan. However, CCS for power at commercial scale is still in its early days, with only two full commercial scale integrated CCS power plant projects in North America under construction as of 2014.<sup>55</sup>

In general, the degree of commercial readiness of these technologies, and the specific hurdles to be overcome for each low-carbon energy technology, are not well described in the studies examined (the IEA ETP<sup>21</sup> and the GEA<sup>19</sup> studies being notable exceptions). One implicit conclusion from the above discussion, although, is that deep energy system decarbonization is likely to require an ambitious, focused agenda of rapid innovation and improvement in every critical technology area, even those commercially available today, as well as substantial ‘demand pull’ efforts and policies to ensure early demonstration, industry maturation, scale-up, and ‘learning by doing’.<sup>21,19</sup>

## Economic Costs

The relative cost of goods, services, and public policies heavily influences the decisions of consumers and policymakers. The huge variance in the treatment of the costs of implementation of the various decarbonization studies—from detailed evaluations of capital and operating costs to no discussion at all—is therefore striking. Of particular interest is the incremental investment that would be required to meet aggressive carbon emissions targets by 2050. Where such additional costs are projected, they range from \$350 billion to several trillion per year, based on a wide range of assumptions.<sup>d</sup>

The IAM-based scenarios<sup>17–19</sup> consider economics by definition, but none report incremental investment costs in an obvious way. Five of the other studies provide incremental investment data that can be compared here. Greenpeace/EREC project the incremental cumulative investment to be \$7 trillion by 2030, or \$350 billion per year. The IEA WEO 450 Scenario estimates the additional cumulative spending to be \$18 trillion through 2035, or an average of \$720 billion per year. McKinsey estimates additional investment costs over the baseline of approximately \$650 billion per year in 2020 and \$950 billion per year in 2030. The IEA Blue Map scenario would require an incremental investment of \$46 trillion from 2010 to 2050, or \$1150 billion per year over the baseline

investment. In the *Energy Policy* papers,<sup>13,14</sup> Jacobson & Delucchi state that ‘energy costs will be similar to today’. However, in their *Scientific American* article,<sup>56</sup> they suggest that ‘overall construction cost for a WWS system [the authors’ wind, water, and solar 100% renewables scenario] might be on the order of \$100 trillion worldwide, over 20 years, not including transmission’. With the exception of the \$100 trillion case cited by Jacobson & Delucchi, the range of energy system incremental investment is approximately 20–50% over the baseline investment, or in the range of 1% of global GDP. Finally, as noted below, none of the studies seriously address the costs associated with integration of large amounts of variable generation.

## Integration into Energy Systems and Associated Infrastructural and Operational Challenges

Several scenarios depend heavily on intermittent power generation technologies, primarily wind, and solar PV. Their technical feasibility therefore also depends on their treatment of the various issues related to integration of such variable sources into power systems.<sup>57</sup>

In general, those studies that acknowledge the challenges associated with integrating large quantities of intermittent generation invoke the same set of options. Broadly these are ‘smart grid’ and demand response technologies for more dynamically balancing electricity supply and demand, high-voltage transmission expansion and larger geographic balancing areas, some kind of energy storage, and using excess generation to produce hydrogen as an intermediate fuel. Only one study (Worldwatch) explicitly makes reference to the potential need for increased amounts of flexible gas-fired capacity for load matching, and only one study (Jacobson & Delucchi) notes the importance of improved forecasting of variable power production.

The Jacobson & Delucchi papers provide by far the most detailed and comprehensive overview of related work that has been done in the areas of integration of dispersed variable resources, storage, demand response, and vehicle-to-grid (V2G) technologies. The remainder of the papers that address integration issues essentially do so conceptually, simply by referring to the need for one or more of the integration methods discussed above. In general, these scenarios do not include any detailed discussion of technology status, development timeframes, infrastructure investment costs, or requisite policy frameworks needed to prompt the development and large-scale deployment of these technologies.

All of these key supportive technologies have their own research, development, and demonstration gaps that must be addressed through a significant expansion of current activities.<sup>21</sup> The pace and cost of technology development and deployment for these supportive integration methods is therefore a critical determinant of the technical feasibility of any scenario relying heavily on intermittent electricity sources. To illustrate this point, proper system-wide accounting of the back-up generation and/or storage, additional transmission, and ancillary services needed to integrate large amount of intermittent generation could increase the total per MWh costs of these generation sources by twofold or more at high penetration levels.<sup>58–61</sup>

The transformation of transportation energy brings its own system integration challenges. For example, requirements for modifications or re-building of existing local electrical distribution systems for widespread vehicle charging and/or energy storage are uncertain.<sup>59</sup> Transitions to alternative liquid or gaseous fuels such as ethanol or hydrogen will require new production, storage, and distribution systems, with major infrastructure implications. According to NREL, the expansion of the retail infrastructure for alternative fuels may pose greater issues than fuel costs, resources, or production capacity.<sup>62</sup>

### Social Acceptability and Other Noncost Barriers

For the most part, the studies examined do not address social acceptability and noncost issues such as the availability of key materials, land use, convenience, labor, and governance constraints. However, these constraints may be as significant as technical and economic hurdles. Opposition to nuclear power is well known, but opposition to large-scale wind farms, on- and off-shore, as well as associated transmission, has surfaced as a serious issue in Germany, the USA, the UK, and other countries with large-scale wind energy deployment. Likewise, large solar thermal plants or centralized PV plants as well as run-of-the-river hydroelectric plants have been the subject of opposition and litigation in the USA and elsewhere. CCS has been the subject of proposed bans in Germany and opposition in principle by some in the USA.<sup>63</sup> Areas with significant energy demand are often densely populated, and the level of infrastructure expansion required in nearly all of these studies are likely to test the limits of social acceptability; greater transparency in future studies on the infrastructure footprint and its public acceptability would be useful.

Other noncost constraints are perhaps less clear but nonetheless relevant. For example, the studies

which assume majority to near universal penetration of electric vehicles in every region of the world fail to acknowledge consumer attitudes and convenience factors that have so far limited market penetration. Likewise, significant governance constraints may limit the safe expansion of nuclear energy in some regions or, arguably, even CCS. More granular analysis of these issues needs to be understood by decision-makers pursuing any of the scenario pathways.

## CONCLUSION

Several key findings emerge from this review as follows:

First, the empirical benchmarks introduced herein, including historical carbon intensity and energy intensity improvement rates and normalized energy technology capacity deployment rates, are useful comparators to assess the relative feasibility of global decarbonization scenarios. This kind of benchmarking can (and should) both guide the scenario building community in constructing and testing actionable decarbonization strategies and help policy makers interpret the results of such studies.

Second, all of the scenarios examined envision historically unprecedented improvements in the energy intensity of the global economy (see Figure 3). Since 1970, global energy intensity improved by greater than  $-1.5\%$ /year during only a handful of years. Yet, even the least aggressive scenarios herein entail sustaining worldwide improvements of  $-1.6$  to  $-1.9\%$  each year for the next four decades (and beyond). Achieving these rates would require a significant and discontinuous acceleration of worldwide energy efficiency efforts. Future studies should more closely examine the relative feasibility of the wide range of energy intensity improvement rates envisioned by global decarbonization scenarios.

Third, when normalized based on the scale of global economic resources available, total electricity capacity deployment rates are generally consistent with historical experience (see Figure 6). However, the decarbonization scenarios herein entail a wholesale and immediate shift to low-carbon electricity deployment and the rapid scale-up of several less-mature industries (i.e., solar PV and thermal, wind, and CCS).

Fourth, three studies stand out in this review as exceptional: Jacobson & Delucchi, Worldwatch, and WWF. Notably, these studies all aim to demonstrate the feasibility of energy efficiency and renewable energy-dominated decarbonization strategies and thus normatively constrain the available portfolio of low-carbon technologies by excluding, *a priori*,

nuclear energy and/or CCS. To accomplish deep decarbonization with this limited portfolio, this group of studies depends on sustaining global energy intensity improvements for decades at a rate twice as fast as the most rapid energy intensity improvement experienced in any single year in recent history and roughly 3.5 times faster than the average global rate sustained from 1970 to 2011 (Figure 3). Furthermore, these studies call for normalized capacity additions of the remaining eligible low-carbon energy technologies of 5–23 GW/year/\$T of GDP (Figure 6). In contrast, normalized global generation capacity of all types grew by just 1.5–3 GW/year/\$T of GDP from 1965 to 2010. Given the multiplicity of feasibility challenges associated simultaneously achieving such rapid rates of energy intensity improvement and low-carbon capacity deployment, it is likely to be both premature and dangerously risky to ‘bet the planet’ on a narrow portfolio of favored low-carbon energy technologies.

Fifth, these studies present comparatively little detail on strategies to decarbonize the industrial and transportation sectors, despite the importance of these sectors. With multiple low-carbon electricity generation options and the possibility of wider electrification, the power sector will invariably be central to global decarbonization efforts. Nevertheless, reducing industrial and transportation sector emissions will not be accomplished through electrification alone, and decarbonization scenarios should focus greater attention on the challenges associated with these sectors.

Finally, these studies tend to only superficially address the key technical, economic, infrastructural, and societal factors that may constrain a rapid energy system transition or how such constraints can be plausibly overcome. We recognize that detailed treatment of these factors is beyond the scope and purpose of many of these studies, which are intended to address at a relatively high-level the scope and pace of energy system transformation required under different assumptions or to suggest the portfolio of technologies necessary to decarbonize the energy sector. However, this point may be lost on lay audiences and the media through which these studies are reported. To be reliable guides for policymaking, these types of scenarios clearly need to be supplemented by more

detailed analyses addressing the key constraints on energy system transformation, including technological readiness, economic costs, infrastructure and operational issues, and societal acceptability with respect to each of the relevant technology pathways. Hopefully, this paper will provide additional context to the readers of such studies and to policy makers, who must move beyond thought experiments to identify practical paths forward.

## NOTES

<sup>a</sup> For a complementary effort to develop historical benchmarks for energy capacity expansion in decarbonization scenarios, see C. Wilson, et al. “Future capacity growth of energy technologies: are scenarios consistent with historical evidence?,” *Clim Change* 2013, 118: 381–395.

<sup>b</sup> Wilson et al. (2013) employ an alternative approach to benchmarking capacity addition rates, which normalizes capacity additions based on total primary energy consumption. However, as energy intensity of the economy declines over time, economic growth partially decouples from energy consumption. This implies that normalizing based on primary energy consumption, as in Wilson et al. (2013), may under-estimate the scale of societal resources available to deploy energy infrastructure in the future while simultaneously under-estimating the relative scale of societal resources invested in historical capacity additions. While the approach in Wilson et al. (2013) normalizes the capacity addition rates to reflect the growing scale of global energy systems, our approach should better reflect the changing availability of societal resources to invest in energy infrastructure over time. The practical result is that future deployment rates will compare more favorably to historical capacity addition rates under our normalization based on global GDP than under normalization based on global final energy consumption.

<sup>c</sup> This finding is consistent with Wilson et al. (2013) despite differing methods for historical benchmarking. <sup>d</sup> In particular, any cost estimates are highly sensitive to the choice of baseline relative to which incremental costs are assessed.

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