# Emerging clean energy and decarbonization regimes: reimagining contestation in the multi-level perspective

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**Abstract:** Emerging global clean energy trends present challenges for transitions frameworks like the multi-level perspective. This paper introduces *emerging clean energy regimes* and *decarbonization regimes* as concepts for shifting the framing of clean-carbon contestation within this perspective to account for the regime-like scale of wind, photovoltaic and electric vehicle systems, as well as their extraordinary societal interactions in the age of climate change.

## 1. Introduction

Transition scholars are focusing more on whole system reconfiguration in response to emerging trends. One such trend is that photovoltaics (PV) and wind power have become impactful mainstream global players, while electric mobility is on a similar track. This development challenges common multi-level perspective (MLP) framing of carbon-clean contestation as being between dominant "regimes" and competing "niche-level" innovations which do not impact the exogenous "societal landscapes" [1,2]. In contrast, these emerging systems resemble dominant fossil regimes as much as they resemble niche innovations like hydrogen vehicles or wave power; and they appear to be impacting societies in major ways, particularly climate politics.

Accordingly, this paper proposes shifting the analytic focus on carbon-clean contestation from the niche-regime interface to the regime-landscape interface. It introduced the novel concepts of *emerging clean energy regimes* and *decarbonization regimes* as tools to do this. The aim of this shift is to maintain the parsimony of the MLP while facilitating investigation of clean-carbon contestation on the larger stage which it now occupies. This paper introduces these novel concepts by justifying their application to modern renewables (wind and PV) and lithium-ion driven electric vehicles (EVs).

Currently, MLP concepts can be awkward to apply to these rising systems and their societal interactions: the three levels offer too few distinctions between dominant regimes and non-dominant niches, while the variations in transition types may exclude unusual transition-accelerating dimensions of a deliberate climate-motivated transition. Regarding niches, since globally ascendant PV does not dominate any market nor regulatory system, UK solar or Dutch biogas can be grouped together as niche-level stories. Relatedly, MLP case study practice is limited for describing international patterns of increasing interest [3] and which distinguish modern renewables and electric mobility.

Regarding societal landscapes, defining them as exogenous – affecting but not materially affected by regimes [2] – can draw analytical attention away from deep society-shaping interactions like energy geopolitics. And while there is no need to point out that carbon energy regimes have reshaped the climate and driven societies to curtail them, imagining exogenous landscapes offers no structure for analysing the entanglement of energy systems, the climate and societies grappling with this existential threat to civilization.

The novel concepts of *emerging clean energy regimes* (or *clean regimes)* and *decarbonization regimes* offer ways to begin address these limitations. First, *clean regimes* distinguish emerging systems acting at the regime level and capable of impacting society at large. *Decarbonization regimes* describe those two-way socio-political interactions (rather than market/regulatory interactions) within the extraordinary landscape-level context of climate change.

- **Emerging clean regimes:** Emerging clean regimes are built around major low-carbon innovations; they are distinguishable from the niche-level pack by indicators of scale and maturation which enable them to become junior contestants against the dominant fossil fuel regimes across market, regulatory, and political systems.
- **Decarbonization regimes:** These are defined as dominant anti-fossil regimes of the future. They emerge as clean regimes begin to have mass societal interactions through market advantages, employment, or political clout across jurisdictions. They can lock-in [6] and displace carbon regimes if these interactions amount to an unusually broad [3] and landscape-shifting co-evolution between clean regimes and climate-motivated societal forces.

The shift in analytic focus to the regime-landscape interface can help assess the potential for an accelerated substitution-type transition pathway which is of increasing interest: one in which the weakening of dominant carbon regimes and establishment of new regimes feed off each other in a feedback driven process [1,4,5]. *Decarbonization regimes* advance theory of change by being conceptualized as having organizing logics which are *incompatible* with those of carbon regimes [6]. This approach builds socio-technical concepts including regime institutional logics and destabilization [7,8].

Next, I briefly expand on the concepts clean and decarbonization regimes and introduce the indicators for identifying them. Indicators of *clean regime* scale and further scaling potential are then applied to the cases of PV and (less so) wind, and lithium-ion EVs. Indications of potential for d*ecarbonization regime* formation are illustrated for modern renewables in terms of their typical entrenchments and atypical entanglement in climate politics in China and the West. The paper concludes with a summary of the findings and implications for transitions theory and accelerating decarbonization.

# 2. Methodology

For clean regimes, a set of distinct indicators are applied, while indications of potential for decarbonization regime formation are more illustrative. The indicators are derived from both a combination of innovation and industry literatures, and an inductive focus on available measures within public data sources which distinguish the case-study technologies. They are preliminary indicators, and other options are discussed in section five, while barriers to change are not a focus. The indicators are selectively applied to modern renewables and EVs with some comparisons to the other fossil and low-carbon options. This mix of two supply and one end-use technology reflects a unique potential to displace major portions of coal and oil demand.

## 2.1 Indicators of emerging clean regimes

Emerging global clean regimes are not defined like place-based regimes. They remain insurgent rather than being dominant in shaping the regulatory or political climate in a jurisdiction. While aspects of customer or regulatory systems may still be forming, the global industry is mature and competitive enough that niche-support is no longer necessary (a tipping point).

While even long-time critics like the International Energy Agency (IEA) [9] now recognize modern renewables and EVs as the breakout fossil-fuel-disrupting innovations, this emerging consensus is worth testing and explaining with a set of indicators or criteria that can clearly distinguish them from various still-niche low-carbon options, or troubled low-carbon regimes like nuclear power or biofuels. The first two broad criteria reflect the niche-to-scale transition: that a technology system (a) is *ready* to scale (b) has sufficient *scaling support* to reach critical mass. These focus only on silicone PV (si-PV) and lithium-ion EVs. The final general criteria, *regime scale*, is measured quantitatively and by qualitative factors that enable further scaling within the urgency of decarbonization regimes. The three general criteria are divided into specific indicators.

### 2.1.1 Readiness

Overlapping understandings of readiness in innovation and industry literatures emphasize the decades of development that are required before scaling. These perspectives are simplified here into the four following (and linked) criteria which emerging clean regimes should meet.

**Established technological paradigm:** The technology should have a decade plus of technical progress along an established direction or “technological paradigm” [10] (e.g. increasing wind-turbine size) and a “dominant design” [11] or configuration (e.g. li-ion battery format). Long-lasting energy technologies from wind to nuclear face particular risks from short-cutting this process [12,13].

**Proven learning curve:** Both scholars and industry use so called learning curves – the observed tendency of some technologies to improve by a relatively steady rate for each doubling of cumulative production – particularly for PV module costs [14,15]. The indicator is simply a positive trend, allowing for the uncertainty of learning curves as a predictive tool [14].

**Nurse market period:** The technology should already be a commercial product for a decade or more in a related or unrelated niche market, like li-ion batteries in mobile devices. This is an effective (overlapping) proxy for a broad range of scaling-readiness that emerges in industries over time.

**Bankability:** prominent in industry but not in transitions scholarship, bankability is defined as whatever criteria banks or other lenders use to decide on lending millions-to-billions for projects or factories [16]. Old technologies are de-risked by long physical and customer track-records – a test for scaling that no new battery can pass.

### 2.1.2 Supported scaling

PV and EVs share four scaling features indicative of their scaling-feedback driven launch out of niche "protective spaces" [17-19]. First, they received major market-pull deployment support from a few large and/or wealthy jurisdictions and saw major cost/price declines during an ensuing scale-up. Second, they established technological lock-in [20] against similar technology (e.g. si-PV left solar thermal power languishing). Third and fourth, their scaled supply chains were reinvented, while relatedly, one or more major actors placed a big bet on them.

### 2.1.3 Regime scale

Broad indicators of regime scale are basic quantitative measures of *established scale*, while *scaling legitimacy* and underlying *scaling drivers* reflect potential for further and rapid scaling within decarbonization regimes. Modern renewables are considered together relative to fossil, niche and older low-carbon options. Results for EVs feature fewer comparisons and reflect their more nascent state.

**Established scale:** Scale itself enables mass interactions with society. Quantitative proxies for such scale are based on available data, with a focus on both deployment scale and growth. No thresholds are proposed, in part since the distinction between modern renewables and niche systems is readily identifiable.

**Scaling legitimacy:** This qualitative criterion speaks to whether countries, sellers, buyers and lenders are willing to bet on the emerging regime as energy for industrialism – a higher level of legitimation than in emerging innovation systems [21]. A first proxy is the state-of-consensus regarding techno-economic scaling potential. The second is legitimation via policy-implementation, for renewables, highlighting India's attempt to be first to industrialize without (further) fossil fueled electricity growth, while for EVs, considering both Chinese policy signals and automaker-investments.

**Regime growth drivers:** The same technologies have, so far, been quite responsive to policy feedback, from early deployment support to renewable energy auctions more recently. However, nuclear's rapid but stalled scale-up motivates a consideration of the mechanisms driving scaling and cost [13]. Strong drivers enable both self-sustaining market growth and socio-politically accelerated scaling. With a well-founded focus on price [22], the specific measures are as follows:

- **Simple cost:** Emerging clean regimes should have, or on the verge of having, a subsidy-free cost advantage across many markets. For renewables, it is levelized cost of energy over plant life-times (LCOE), and up-front price for EVs
- **Complex cost and qualitative advantages:** Various classes of purchasers and end-users have complex perspectives on price and the characteristics they value. For renewable, the focus is on customers like utilities or large corporations (in the US), and not just end-users [23]; for EVs, it is consumers and fleet customers who often consider total cost of ownership.
- **Responsive innovation profile:** Technology features like rapid innovation cycles promote responsiveness to increased policy support. Some features do not; hydro-power is subject to powerful decreasing returns to deployment scale since good dam sites are quickly exhausted [20]. This measure is only applied to modern renewables.

## 2.2 Indications of decarbonization regime potential

As clean energy systems reach regime scale, instead of just receiving one-way niche support, they have mass societal interactions that can drive co-evolution with climate politics. These interactions have potential to form decarbonization regimes if ordinary entrenchments – jobs, political power, etc. – provide a foundation for extraordinary positive feedbacks between (a) emerging clean regimes and (b) rising ambitions for climate action [4], clean air and economic interests. If decarbonization regimes emerge, we can increasingly expect carbon-clean contestation at the regime-landscape interface because industrial civilization is existentially dependent on both energy and a stable climate. A major portion of this landscape-level change is explored under the emerging theme of clean energy and geopolitics which is outside of scope of this paper.

This section first highlights, the high quality of typical socio-technical entrenchment for modern renewables in terms of *foundations of entrenchment* across social, political and economic fields. I compare only employment and the public standings of modern renewables relative to fossil fuels and other low-carbon energies. This indicator-style approach – which can include entrenchment in financial sectors or taxation-bases – reflects the general capacity for socio-technical change to consolidate around these industries, compared to past cases.

Second, I highlight illustrative examples of feedbacks where renewables aid pro-climate and/or anti-carbon politics and then gain from the socio-political outcomes. This goes beyond scaling phase feedbacks between technological progress and increased policy support (e.g. between PV cost declines and policy in China [24]). These feedbacks are also more encompassing and tightly reinforcing of renewables compared to "policy sequences" where renewables lead to increased support for carbon taxes [25]. The illustrations cover:

- How renewables helped China sign on to Paris Accord, and how the agreement benefits (China-led) already scale solutions
- How renewables' western political power protects regulatory-political gains and underpins increased climate ambitions including coal phase outs – with immediate benefits to renewables
- How anti-fossil fuel campaigns leverage renewables and their market impacts on fossil fuels, in a way that (more indirectly) redound to the benefit of renewables.

This approach also builds on the political science literature on green coalitions [e.g. 19,25] which focuses on the growing power of (western) networks directly relating to clean-energy legislation, and in which climate politics is an important but secondary factor. Decarbonization regimes is a broader theoretical concept, while the metrics-oriented approach to entrenchments is also novel.

The deeper conceptualization of decarbonization regimes [6] is worth briefly noting. Decarbonization regime contestation of carbon regimes is defined as increasingly zero-sum; they will not 'share the road' in the age of climate change. This is because they have *opposite* organizing logics to carbon regimes: carbon regimes depend-on and propagate minimizing of the climate problem and solutions while decarbonization regimes build on the viability of solutions and prioritizing rapid emissions reductions. This framing, developed by applying critical transitions theory [26] to decarbonization, is both descriptive and normative.

# 3. Results: emerging clean energy regimes

## 3.1 Readiness

Prior to a global scale-up period (see 3.2), si-PV and li-ion batteries met readiness benchmarks including those presented in table 1.

## 3.2 Supported scaling

### 3.2.1 PV

As shown in figure 1a, by 2008 cumulative PV installations were dominated by four jurisdictions with strong policy-support; Germany spent generously on Feed-in-Tariff programs [18], as did Spain [47], while US used states portfolio quotas (RPSs) and tax credits [19]. By 2008 PV prices began falling at their steepest rate to below $1/watt (fig. 1c) [15,46] and installations rose steeply with China taking the lead from Germany (fig. 1b).

**Table 1: Scaling readiness**

| **Readiness benchmark** | **Si-PV pre-2008** | **Li-ion for EVs pre-2015** |
|---|---|---|
| *Nurse markets* | A product for space applications in the 1960's, si-PV also served off-grid markets for decades pre-2000's [27]. | Sony launched the li-ion mobile device market in 1994 [28] which was foundational for the automotive li-ion industry [29-31]. The commodity 18650 laptop battery was used to launched li-ion EVs [33]. |
| *Technological paradigm* | Decades of incremental improvement to the dominant polysilicon PV design progressed along established avenues like thinning wafers, reduced shading by conductors, and increasing efficiency [15,32]. | Li-ion batteries improvements include a 2.5 times increase in energy density from 1990-2012 [34,35]. Automotive battery packs are converging on a flat-bottom dominant design architecture [36,37]. |
| *Learning curve* | PV module costs per watt fell from $90/watt in 1968 to $15/w in 1978 to $4.50/watt in 2008 (see fig. 1) | From 1990-2005, mobile battery costs fell from US$3200/kwh to $400/kwh [38]; EV battery packs from US$1000/kwh to $200-$300/kwh between 2010-2017 [39-41] |
| *Bankability* | In 2004 early Wallstreet financing involved extensive due diligence, satisfied based on a long track record (e.g. established 25-year panel reliability) [42]. Mostly private funded PV [43] is now a safe investment, acceptable for hyper-conservative investors like pension funds [44]. | Decades in mobile markets establish technology level reliability for energy storage [45] and EV applications. |

**Technological lock-in against direct rivals:** Si-PV dominated PV markets in 2008, but as silicone prices rose, thin-film PV [49] – as well as concentrating solar thermal (CSP) – offered competitive options. CSP prices were even with PV in 2010, but were overwhelmed by rapid si-PV cost declines (see fig. 5). Today, si-PV is hegemonic in the PV market [50], while solar thermal power has yet to pass 5GW installed [51].

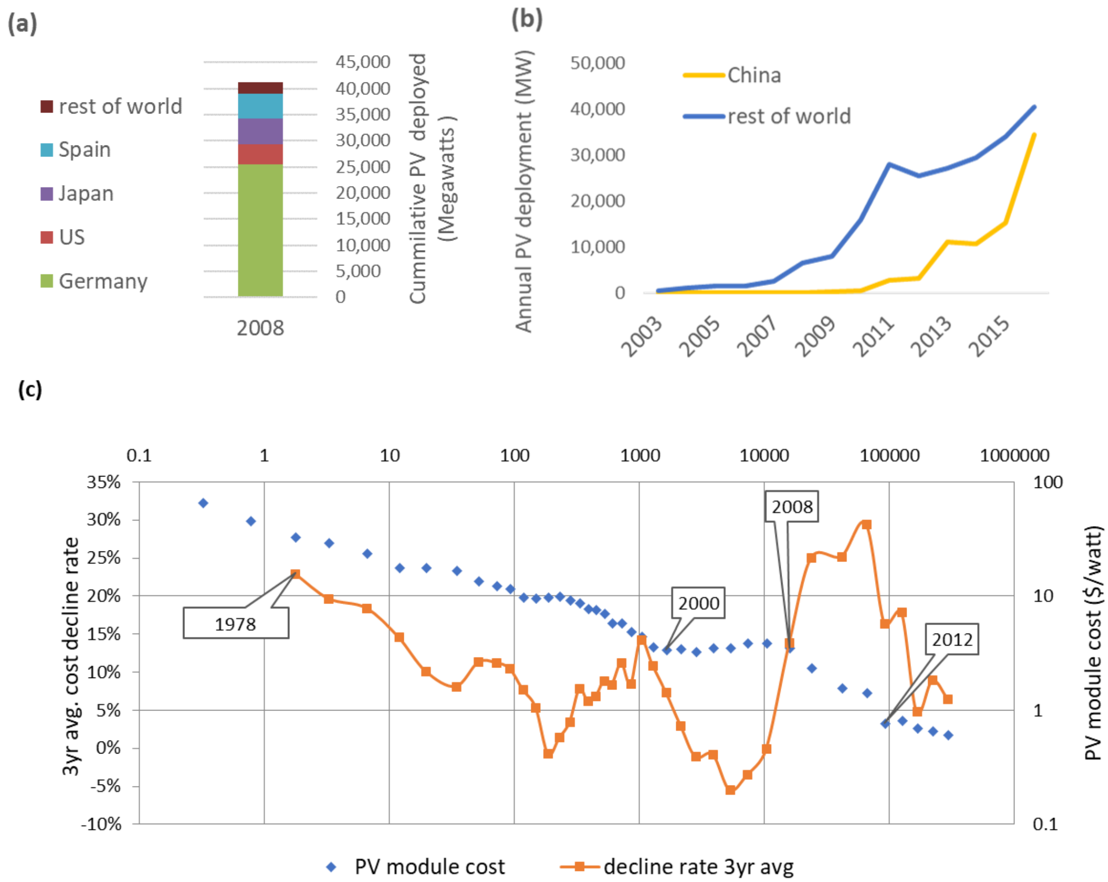


*Figure 1: (a) Cumulative PV deployment by 2008 by lead countries. (b) annual PV deployments rise at the same time. (c) si-PV module cost curve and cost decline rate, ~2008 turning point. Sources: Navigant, BP statistical review [14,48].*

**Maturing supply chains and a big bet:** Prior to scaling, the PV industry used silicone rejected from micro-chip manufacturing [15]. Following a silicone shortage, China developed the first dedicated si-PV supply chain with vertical integration, and economies of scale which were primarily responsible for the rapid cost declines [52,53]. China added PV to its strategic industries in 2009, including supports like $47billion in loans [54], and as the German market faltered, it added subsidies for the domestic market [55]. China's lead in manufacturing and deploying PV is now overwhelming [48,51].

### 3.2.2 Lithium-ion

Li-ion based passenger EVs began rapid scaling past 2012, from less than 200,000 in stock to over 3 million in 2017, with 1 million sold in 2017 [41] (fig. 2). Countries with market pull incentives [56] dominated early market growth during the period when pack prices began to fall rapidly (see table 1); eighty percent of EV stock growth between 2010-2015 was in the US, China, Japan, Netherlands and Norway which offered purchase subsidies – typically $5,000-$10,000 – along with incentives like access to highly coveted vehicle licences in China (IEA, 2016). As with renewables, a western start was followed by a bold Chinese scale-up.

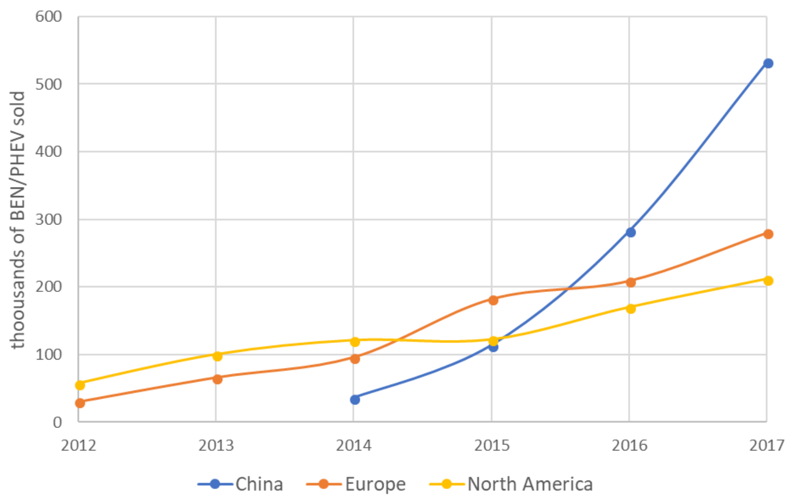


*Figure 2: Combined BEV-PHEV annual sales in leading markets. Source: UNEP-BNEF[57]).*

**Technological lock-in against direct rivals:** Much like with si-PV, the initially high cost of li-ion batteries for grid storage attracted competition from new technologies (e.g., compressed air storage, flow batteries [58]), but falling li-ion prices overwhelmed these low-readiness options. By 2015-17, li-ion market share in US grid storage was 95% [59]. Similarly, hybrid vehicles (PHEVs) also used a variety of battery types such as N-MH, but all major EV models now use a variety of li-ion battery [60]. At the vehicle scale, pure electric (BEVs) have advanced against PHEVs to 60% of the combined EV market share [61].

**Maturing supply chain & a big bet:** New supply-chain pressures arise from the fact that advanced batteries face greater price and performance pressures than the 60Gwh/yr consumer device market that they are outgrowing [61]. Optimization is likely taking place across re-organizing supply chains as the market grows from ~20 to an estimated 140GWh/yr from 2015-2020 [61]. Tesla is operating the first factory turning raw mine inputs into EV battery packs [62]. As with renewables, with forceful policy action, China has become the largest producer and consumer of EV li-ion batteries [41], while some automakers are also increasingly betting on EVs (see 3.3.2.2).

## 3.3 Regime scale

### 3.3.1 PV & wind

While some oil companies, utilities and experts remain skeptical, the scalability of renewables is now a consensus position readily adopted by governments and market actors, if not readily implement.

#### *3.3.1.1 Established scale*

Among electricity sources, modern renewables are distinguishable from both niche clean energy and from older growth-limited lower carbon technologies. Each receives investment at a scale matching investment in coal and gas plants combined, far exceeding often loan-guaranteed nuclear (fig 3). Figure 4a shows capacity additions increasing over time to surpass those of fossil fuels or low-carbon sources. Figure 4b shows modern renewables far ahead of niche renewables in both total capacity and annual capacity additions (fig. 4b). Even though (simpler) capacity comparisons greatly overstate modern renewables relative sources with high capacity factors, PV and nuclear electricity growth is similar (assuming 20% and 90% capacity factors, respectively).

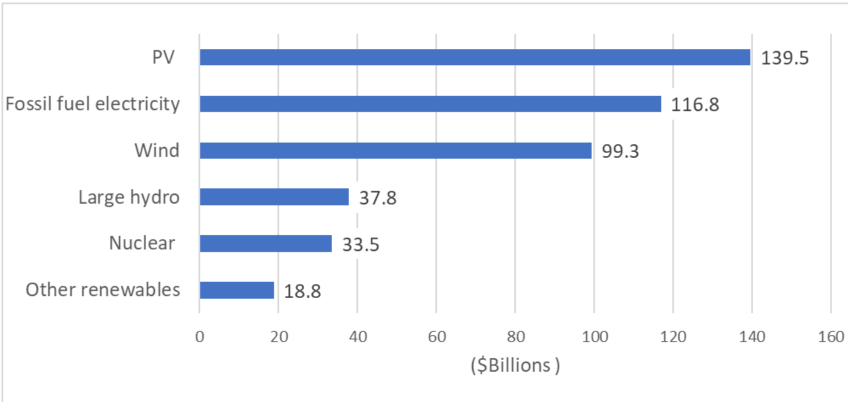


*Figure 3: Average annual investments in power genration assets by type, 2012-2017. Reproduced from UNEP-BNEF[57].*

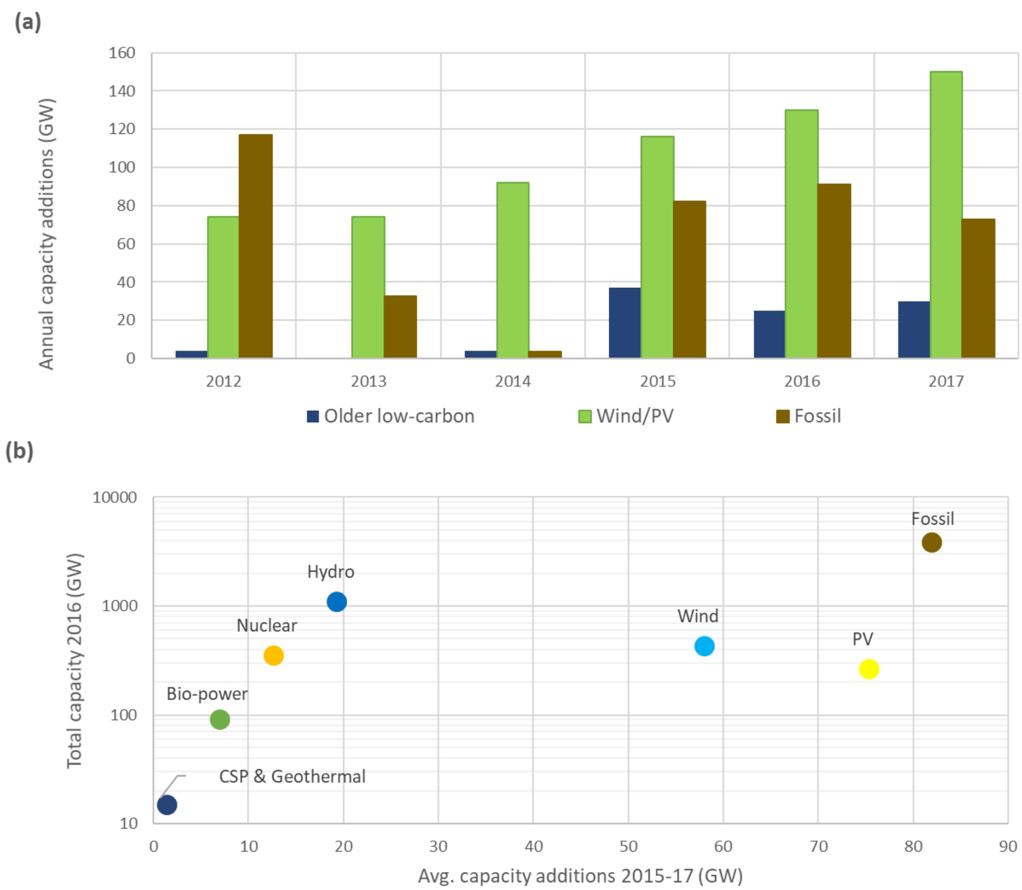


*Figure 4: (a) Annual capacity additions by category; older low-carbon is nuclear and hydro. (b) 2016 power capacity and capacity growth by technology. (sources: REN21[51] IRENA[63];IEA[64])*

#### *3.3.1.2 Established scale – scaling legitimacy*

To continue scaling – and wield the power of regime-level systems – scaled clean energy industries (as a set) need to be seen as highly scalable and capable of driving industrial growth.

**India:** Indian market and government activity suggests that renewables are truly contending with a faltering coal sector for the role of 'engine of power sector growth'. The consensus across international agencies and analysts is that Indian renewables prices are falling below those from *existing* coal plants [65-68]. New auction bids are estimated to be [68]. It is estimated that 2017 renewable prices fell below those of the state coal utility, auction bids were 20% less than wholesale coal prices, and more capacity was added in wind and PV than thermal plants for the first time (15.7GW to 7.7GW) [68]. Government electricity authorities plan to halt all new coal plant construction through 2027 and to meet new demand with renewables [68]. The relative standings of coal and renewables is muddied by the multi-faceted crisis in the coal industry; continued over-building and slower demand growth have contributed to a major stranded asset crisis [69] as capacity factors dropped below 60% in 2017 [68,70]. Renewables, however, are essential to coal's problems; it is unlikely that future demand growth will absorb coal over-supply because distribution utilities now prefer signing lower-cost long-term purchasing contracts (PPAs) with renewables and are even seeking exits from older coal PPAs [71]. Renewable growth is threatened by India's poor capacity to manage a high-renewables grid, while coal will face new clean air standards (in 2022) which most current plants cannot afford to meet [71].

**Scalable grid integration:** The consensus on how much intermittent renewable generation grids can incorporate has improved dramatically as modern renewables have scaled. Prior to 2013, many experts argued that 10-20% wind and PV penetration represents an upper limit of technical viability without major grid investments [24]. Since, academic, government [72] and industry [73] research has pushed the understood boundary of the cost-effective integration steadily upwards. Today, the debate is focused on whether 80% renewables (50%+ wind/PV with hydro) or 100% is viable and cost-effective [74]. The case for 100% renewables remains contentious, but is no longer fringe [75] with iterations modelled for all major regions globally [76-80]. Eighty percent renewables is now a safe position, backed by sophisticated models: major US government studies [72,81] found (respectively) that 50% modern renewables (with 50% EVs) is viable – which others found cost-competitive [82] –, and that 55% is economical to implement by 2030, while phasing out coal and reducing emissions by 80%. Renewable-led electrification is also recognized as a uniquely viable pathway to decarbonize other sectors including in China [83-85].

### *3.3.1.3 Scaling drivers*

**Simple price**

Wind and PV increasingly undercut fossil fuel generation prices, a spear-tip for broader disruption. Figure 5(a) shows a consensus across estimates of levelized cost of energy (LCOE): modern renewables have entered the price range of fossil fuels and are increasingly competitive. Figure 5b shows that, as even the IEA noted **"**Cost trends for hydropower, geothermal and bioenergy technologies remain less dynamic compared to wind and solar." [65, p144]. LCOE's for nuclear are also estimated to be much higher (BNEF $174 [57]; Lazards $148 [87]).

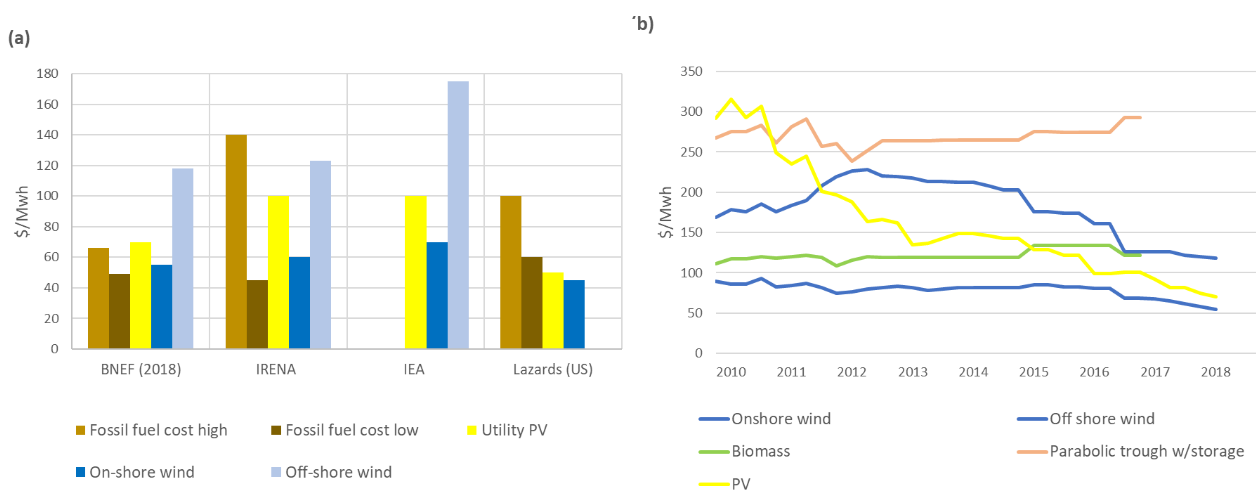


*Figure 5: Unsubsidised LCOEs: (a) 2017 estimates for modern renewables and fossil fuels – Lazard's and BNEF fossil-costs are US focused. Sources: [65,67,86,87]. (b) renewable LCOE's over time, reproduced from UNEP-BNEF [43,67]*

Record bids of $20-30/Mwh [88] in the now 50GW/yr [57] competitive renewable bidding market have sent shockwaves through the industry. Developers might fail to fulfill these bids, but modern renewable price declines do continue to outpace predictions [89], as utility-project panels average $0.35/watt in 2017 [90]. According to the IEA, *average* bids for 2018 and 2020 project completion are ~$65 and ~$30 per Mwh (PV) and ~$55 and ~$35 per Mwh (wind) [65]. These mostly subsidy-free bids represent the lowest cost of new electricity across much of emerging and developed markets (IEA, 2017; IRENA, 2017) and probably outcompete some *existing* coal plants, especially where pollution controls are mandated [91].

**Customer views of qualitative advantages and complex price**

For utilities and corporate customers, most renewable advantages relate to predictability. Unlike nuclear plants, for example, modern renewables (PV especially) can be quickly built (15-30 months) for predictable costs [92]. Corporations can lock-in costs with fixed-price 20 year PPAs, while promoting their green image, as Google or Ikea have done [93]. Such arrangements are unworkable for nuclear or hydro given their large scale, controversial profiles, cost-uncertainty and long development cycles.

US utilities have purchased higher cost renewables to hedge against long-term fuel cost uncertainty [94], future carbon levies or increased public pressure. They are also affordably improving the management of intermittence – by combining wind, PV and batteries. Xcel Energy (3.3mill customers) is replacing coal plants with record-low median mixed-resource bids for 2023 [88]: $21/Mwh for wind with batteries (5.7GW bid); $30/Mwh for wind/PV with batteries (4GW bid); and $36/MWh for PV with storage (16.7GW bid). Other large utilities, announcing gigawatts of immediate coal closures [95], similarly expect unsubsidised combinations that "…provide an around-the-clock, nearly firm, shaped product..." at less than the $35-50 it costs to operate *existing* coal plants [96].

For residential or community renewable customers, there are a different set of qualitative advantages. While subsidies matter, customers appear to be increasingly willing to pay premiums for "renewables" "wind" and "solar" across developed economies, perhaps $100/yr [97], but far less so for hydro or biomass [98]. Lower prices may amplify such qualitative preferences, as in Australia where a quarter of homes now have a PV system [99,100].

**Reinforceable trends**

The sustained improvement trends of modern renewables across core technology, power plants and industry structure are receptive to acceleration thanks to innovation-friendly characteristics. Wind turbines continue [12] to increase in size and capacity factor [65], while power-plant design is just becoming a sophisticated science [101]. The wind industry continues to consolidate in the US and EU [65] and seek out lower-cost manufacturing locations [102] while off-shore supply chain remains nascent [103]. PV panel costs are expected to continue declining based on current technology-paradigm trends, including increasing module efficiency [104]. PV power-plants have also established sustained improvement trends [105].

Characteristics underlying these trends include zero-cost fuels – since the incentive to reduce convertor costs is not diminished by the inevitability of fuel costs – and of particular note, an ease of modularity, the benfits of which include:

- Smaller physical scale so innovations from lab to field facilitates rapid affordable design iterations, especially compared to nuclear power [13].
- In-factory construction facilitating learning, efficiency and repeatable precision; it is easier to achieve “geometric returns to scale” [106], where more is done with less material via larger turbines [12] and thinner PV wafers.
- Faster cost-predictable project development of 18-30 months relative to near decade time scale for hydro, nuclear and geothermal [92], and even rapid factory construction times [107].

With economies of scale achievable at hundreds of megawatts, PV projects can also avoid disadvantages of mega-scale, like the environmental permitting challenges which solar thermal plants face. Generally, PV (but wind less so) does not face the decreasing returns to deployment scale of hydro [20], nor those of nuclear due to safety-driven regulatory and design complexity [13].

Global renewable innovation systems are also robust. NREL, US DOE and German Fraunhofer institutes are seasoned in PV and wind research going back to their post-energy crisis origins. This century, they have been joined by the multi-stakeholder REN21 network and multi-national agency IRENA which provide high-resolution knowledge services covering market, trends, policy and emerging issues.

## 3.3.2 Li-ion

### *3.3.2.1 Established scale*

Hydrogen vehicles, numbering in the thousands, are clearly still-niche. EVs, however, may be exiting the niche-level as sales top a million annually [41] out of ~80 million total automobile sales [108], and EVs displace <0.3% of oil consumption. They are increasingly comparable to biofuels (fig. 6): they displace 279,000 barrels of oil per day with E-buses included (2018-estimate)[40,109], an order of magnitude less than biofuels [65]. If biofuel growth rates remain very low – after averaging 24% during 2005-2009 (EIA excel biofuels) – EV scale could easily surpass biofuels around 2025.

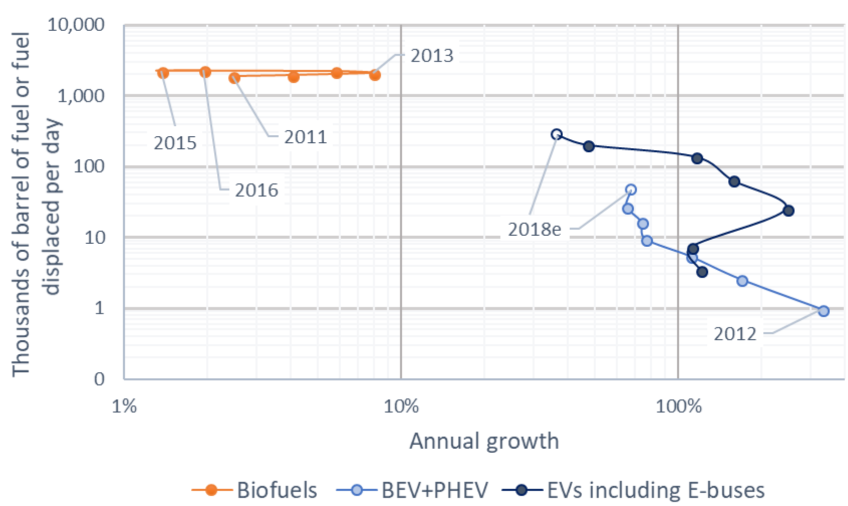


*Figure 6. Biofuels and EV scale and growth by fuel displaced annually (simple accounting). Sources: EIA[110], Renewable Fuels Association[111]; BNEF[109].*

Tangible short-term commitments from legacy automakers and China are baking-in additional scaling as they collectively aim to produce 22 million EVs by 2020 [112]. Automakers are investing tens of billions – where Nissan spent US$5.6 billion to launch its first EV[113]: Volkswagen, stung by the emissions scandal, committed €34billion within a €72billion plan through 2022; Tesla invested $17.5billion in battery packs, while EV-laggard Ford committed $11billion through 2022 to electrify its mainstream vehicles [114-116].

China's cap-and-trade program sets quotas for automakers to sell 10% new-energy vehicles in 2019 (equivalent to ~4% pure EVs)[117], up from 1.8% market share in 2016 [56]. With 30% of the global auto-market [118], China is forcing global automakers to commit to EVs. And China's electric bus segment is already mass-scale: the world's 386,000 municipal E-buses by 2017 (99% in China) are 13% of the global municipal fleet, with ~90% of them sold in 2015-17 (80% being pure EVs) [40,109].

#### *3.3.2.2 Established scale – scaling legitimacy*

EV scaling does not face the highly problematic and controversial issues which cloud biofuel scaling legitimacy; biofuel carbon emission benefits are highly uncertain [119], or incremental at best [120], while arable land limits production. It may require 30% of arable land to produce just 10% of global fuel demand. By contrast, modern renewable and EV land and conversion efficiencies raise no such concern [121], and together can drastically cut transportation emissions [120]. In general, signals of EVs legitimacy are so far strong and tangible.

### Techno-economic scaling potential

Even as many questions remain [41,122], a great deal has been established regarding the techno-economic scaling potential of EVs, including the following:

- **Mid-term li-ion-driven growth:** In addition to falling battery pack prices, lithium ion manufacturing capacity is scaling well beyond demand, reaching ~120Gwh/yr in 2018–

compared to 43Gwh of EV and E-bus demand [40], while manufacturer's plans, suggest capacity will remain ahead of demand [122].

- **Scaling across segments:** With today's batteries, EVs are succeeding across market segments. The average pure EVs (US) now has a range over 200km [123]**.** Telsa's SUV is outselling other luxury brands in the US [124]. And maintenance and fuel savings provide a robust driver for E-buses and fleet vehicle growth [40] and possibly for the Tesla semi-truck which Walmart and others have ordered in sizable numbers [125].
- **Charging infrastructure:** Many challenges remain [122], but upstart Tesla has deployed an extensive fast-charging network on multiple continents [126] – an impossibility for hydrogen.

**Policy and legitimation**

The slew of policy proposals aimed towards a complete transition to EVs are a sign scaling legitimacy. Such bold-sounding plans can turn out to be unfeasible – or timid. US and German EV goals for a million EV by 2015 and 2020 have been far underachieved [127-129]. However, PV goals and forecasts were also underachieved before scaling while proving entirely too modest since [89], while the US is likely to reach a million EVs in 2018 [130]. Either way, such technically plausible proposals confer legitimacy and drive scaling.

China announced the most substantial phase-out targeting petro-car sales *and* manufacturing (though without a date). France, the UK and other EU nations have announced similar resolutions or (more rarely) legislative bans to be implemented mostly in the 2030-2040 timeframe [131,132], while California is following suit [133]. India announced a 2030 ban in 2017, but then scaled it back to 30% EV sales [134] (and as with renewables India might be unlikely to move boldly until costs are favorable). Cities, especially in Europe, are also proposing bans on diesel vehicles to combat air pollution for the early to mid 2020s [132]. Finally, companies (or cities) which own fleets are also legitimizing EV scaling. Copying the renewable purchasing coalition [93], an "EV100" pledge (100% EV fleets) was launched in 2017 and includes Ikea, Unilever and California utility PG&E [135].

#### *3.3.2.3 Scaling drivers*

**Simple price**

Up-front costs for EVs across segments are higher than conventional options (assuming no subsidies). However, EVs are expected to achieve an upfront price advantage in 10-15 years [122,41] and policy and investment momentum are set for much of that period. Those estimates may be conservative since some automakers already claim battery-pack costs below $150/kwh [29,136], close to the assumed $100/kwh parity mark [122]. E-bus premiums (~20% in Europe) are similarly expected to disappear [40].

**Customer views of qualitative advantages and complex price**

**Consumers:** EVs may become competitive in total cost of ownership (TCO) by 2020 or soon after [137], though the impact of that remains unclear. Qualitatively, if range and charging problems are sufficiently resolved in the minds of consumers, EVs also have enticing advantages: reduced maintenance needs (i.e. hassles), convenient home charging (for some), and (for fewer) super-car acceleration at fractional prices (Tesla). Quitting oil also motivates some [138], as may policy-certainty in the future as cities restrict diesel vehicle access (for example).

**Fleets:** With higher usage rates, fleets are more likely to achieve break-even TCOs via fuel and maintenance savings. They are also more likely to base decisions on TCO, the more so as the price-premium narrows. E-bus TCO already matches diesels' in many use-cases and will match most use-cases and most locations in 2-3 years [40]. Cities – and other fleet owners – are also motivated to reduce pollution as well are organized in studying the shift to electric [40,135].

**Reinforceable trends**

While it is beyond the scope of this paper, strong EVs' receptiveness to policy-reinforcement is at least plausible. Batteries and battery packs are modular much like PV panels, there are signs of similar cost decline responses to scaling while EV drive-trains are simpler than their internal-combustion counterparts, while auto-manufacturing is already at scale (though ideally, li-ion e-mobility will do more to boost cycling rather than auto-oriented development).

# 4. Results: indication of decarbonization regime potential

Modern renewables have begun to have socio-technically important interactions which are only possible at the regime scale at which they threaten major and permanent reductions in fossil fuel demand. Such interactions with potential to drive decarbonization regime formation include entrenchments across social fields and mutual reinforcements with climate politics.

## 4.1 Foundations of entrenchment

### 4.1.1 Employment

Clean energy jobs – especially in PV – have grown enough to form an economic interest of a similar order to that of fossil fuel employment. As they continue to grow rapidly, they may be increasingly leveraged by climate-advocates. Of the 7.2 million global clean electricity jobs in 2016, 4.2 million were in modern renewables (fig 7a). Job-intensive PV provided more jobs than any renewable energy including liquid biofuels (1.7 million). Wind and PV jobs also grew the fastest since 2012, at 55% and 127% respectively [139]. In the US power sector (2016), about half a million modern renewable jobs already greatly outweighs fossil fuel jobs, though all US fossil fuel jobs total over a million (fig 7b). Wind technician and solar installer are project by US labour statistics to be, by far, the two fastest growing jobs for a decade [140]. Finally, despite limited media attention, some regional non-profits are championing clean energy jobs and economic impacts [141]

### 4.1.2 Public opinion

At their current scale, modern renewables remain very popular relative to fossil fuels or other low-carbon sources. Public opinion surveys – including those commissioned by oil [143] and renewables industries [144] – show strong support for increasing wind and especially PV: ~80% or higher across North America, China, Japan and South Korea, with especially strong support in the EU – even in coal-dependent Poland [145, 146]. This support appears robust. First, the perceived benefits cited for support are real: environmental benefits including air-quality are cited by majorities of supporters as are economic benefits (jobs, growth) [144-147]. Second, support may increase with time: proximity to developments in Germany increased support for wind and PV [146], while anti-fossil-fuel sentiments, and interest in purchasing PV, is strongest among younger demographics [143,145]. Cost savings are also shown to enhance support among cost-sensitive publics (US, Japan) [146,147], even as elsewhere (e.g. Germany) majorities are willing accept substantially higher costs for renewables [146].

By contrast, phasing out coal is supported across these regions, typically by over 80% (85% average), and by a surprising 93% in China [144]. US sentiments on expanding fossil fuels are relatively evenly split with supporters still in favor of renewables at least as much [145]. Other low carbon energy also fairs less well, especially nuclear, but also "sustainable bioenergy" with a 50% "use more" rating in one study [144]. These low-carbon sources are also likely to lose support with further scaling due to the already noted challenges such as cost or questionable environmental benefits.

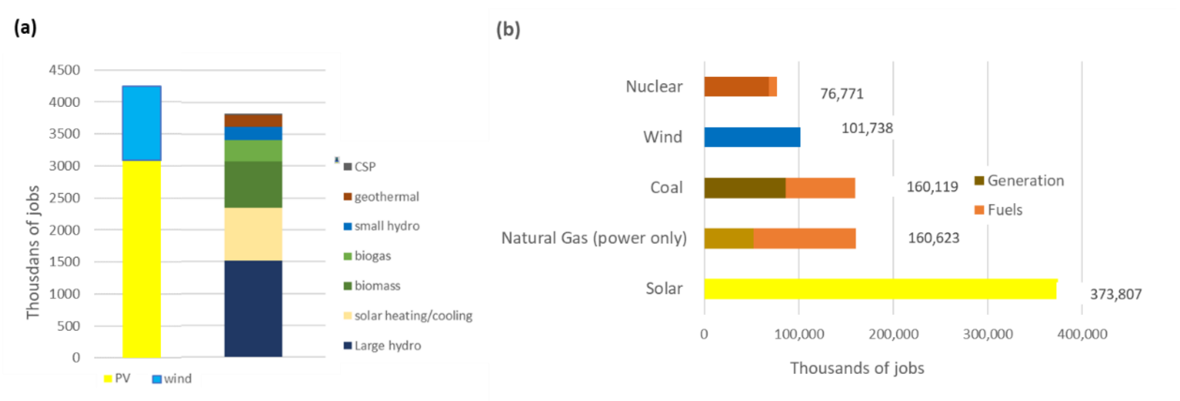


*Figure 7: (a) 2016 global renewable electricity employment by type. Biomass and gas include non-electricity uses. Source: IRENA[139]. (b) 2016 US power sector employment by energy type. "Fuels" includes non-power and export-driven jobs except for gas, for which total gas-supply jobs were multiplied by the fraction of US gas used for power generation.* Source: US DOE [142]

## 4.2 Clean regime socio-political feedbacks

Feedbacks, in which renewables aid climate politics and benefiting from that political progress, suggest a synergy may be forming between these emerging clean energy regimes and the increasingly landscape-level imperative to decarbonize.

### 4.2.1 China renewables and the Paris Accord

Now that renewables – and EVs – can combat air pollution and serve Chinese industrial leadership ambitions, the (western) climate motives that spurred China's renewables leadership have become aligned with China's self-interest in renewable advancement. This alignment involves an emerging positive feedback that ties renewables to climate diplomacy, starting with two steps: (a) China's renewables boom enabled its constructive participation in the Paris Accord, then (b) the agreement – to the extent it spurs action – enables China-led renewables growth as countries must rely on scaled solution to reduce emissions in the short-to-mid-term.

The renewables boom was among the factors flattening China's emissions trajectory pre-2015. This enabled their pivotal Paris Accord pledge (INDC) to peak emissions by 2030. The role of renewables was less important than a structural economic shift away from heavy manufacturing and high-growth, while China's goal to be seen as a constructive great power was also a key factor [148]. But renewables' role was strategic. China's INDC includes obtaining 20% of primary energy from non-fossil sources in 2030 (15% by 2020), a goal also prioritized as one of five mandatory energy targets in its 13$^{th}$ five-year plan [149]. Meeting this goal requires action on all "new energy" fronts (nuclear, solar, wind and biomass) and on "clean energy vehicles", two of seven "strategic emerging industries" identified in the (2010) 12$^{th}$ five-year plan [150].

Both scholarly scenario analyses and official plans include major nuclear hydro power and efficiency goals. However, continued wind and PV scaling are invariably essential to cost-effective implementation, given limited additional hydro-site availability and the high per kwh cost of nuclear [151]. One study found that achieving 40% non-carbon electricity (an estimated share of the broader goal) requires 18-25% wind and PV electricity, if it is to be cost-effective and economically beneficial [151]. Another found carbon markets could produce an emissions peak with below status-quo renewable deployments, but unless renewable deployment grows faster, electricity prices would increase substantially and socio-economic benefits would be lost [152]. Even the IEA projects modern renewables' share of electricity edging towards 20% by 2030 [153]. *If* China can master high-renewable grid design, there are several indications that renewables can easily meet these projections, and even rise to 30% of electricity by 2030 [151,152]; China continues to set and surpass ambitious deployment goals [152], wind already out-produces nuclear [153], and current projections still greatly underestimate PV scaling and cost-declines[1].

Renewables not only helped enable the Paris accord, the accord now also benefits China-led renewables growth. Prodded by the agreement, many countries' pledges (INDCs) rely on increasing renewables for emissions reductions, including the EUs pledge to increase renewable energy from 16% to 27% by 2030 [156]. A model of INDCs and technology costs (with now outdated PV price forecasts) found top-emitters would increase renewable generation capacity from 13% to 33%, translating to 17% electricity from modern renewables [157]. This strategic role for China-dominated clean energy may motivate China to support a climate-accelerated re-invention of these sectors – especially if that transformation can help it tackle politically-prioritized air pollution and reduce its own emissions. China already dominates the global PV module market and li-ion manufacturing, and is especially keen to break into the global automotive market through its EV leadership [153]. At the same time, the climate-benefit of Chinese clean energy is already growing, (conservatively) estimated by the IEA to go from 0.2Gigatonnes/yr in emissions reductions to ~1Gigatonne/yr by 2040 [153].

### 4.2.2 Western renewable-climate synergy

One-directional climate policy support for renewables is being replaced by mutual-reinforcement between renewables and climate politics in the west as well. In the US, economic entrenchment by the solar industry [19] and by wind in conservative states [158] limited attempts to roll-back federal tax-credits in 2016 and 2017, as Democrats fought for them on emissions-reductions grounds [159]. In

[1] With China's cummilative PV deployment at 130GW and another annual deployment of 50GW possible in 2018, Liu et al. [154] call PV deployment at 24GW/yr in 2025 ambitious, while Mu et al.'s [152] BUA PV scenario has only 171GW cumulative deployment by 2025; pre-2015 modules cost projections of $0.40/w by 2030 are still in use [155] while 2017 utility-project module prices are $0.35/w [90].

California, a much friendlier environment for renewables, similar entrenchment enabled aggressive new climate policy: after its utility commission concluded the 2030 target of 50% renewables would be met by 2020 [160], the state is now debating a goal of 100% renewables by 2045, with strong public support for such measures [161]. The dynamic extends to EVs: past targets were abandoned before EVs scaled [19], but now, California's 2017 emissions-reductions plan relies on achieving 1.5 million EVs by 2025 through aggressive regulation and diverting hundreds of thousands of carbon levy dollars to EV infrastructure [162].

Across the OECD, the co-evolution of renewables and thermal coal bans is reflected in the rapid time-frames for the implementation of these phase-outs (Canada-2030, UK-2025, France-2023 [163,164]). First, these timeframes are viable because alternatives are affordable and readily scalable, while coal industries are politically vulnerable due to competition from renewables and, in the US, natural gas [165]. Second, the climate-motivated rush ensures only ready technologies reap the benefits. For example, Alberta, Canada – under pressure to reduce emissions as it sought pipeline permits in the US – legislated a 2030 phase out, starting from a 50% coal-fired system in 2015 [166]. It was rewarded with wind bids at $37/MWh [167], while utilities are closing coal plants ahead of schedule [166]. The UK government has also moved rapidly on its coal-phase out [168] and on increasingly affordable off-shore wind (see fig. 5), installing half the European total in 2017 [169]. By contrast, the UKs forthcoming Hinkley nuclear station struggles with costs and controversies.

Now that the transition away from coal has become relatively easy (for some), Canada, the UK and 25 other jurisdictions have turned these policies into a climate soap-box, launching a "powering past coal" coalition [170]. Given favorable politics and renewable economics, a slew of other jurisdictions are debating phase-outs, moratoriums (e.g. South Korea) or implementing them de-facto [163].

### 4.2.3 Renewables and anti fossil fuel campaigns

Grassroots anti-carbon campaigns may also be boosted by renewables, and then reinforce renewables growth. For example, the global campaign to push institutional investors like universities and pension funds to divest their holdings from fossil fuels gained steam quickly in the lead-up to the Paris Accord and now cover $6 trillion in assets [171]. Notably, of the $2.6 trillion in assets divested by 2015, $2.1 trillion was divested only from coal stocks [172] after they had lost 71% of their value over the previous five years [173]. Short-term drivers of the down-turn were varied [174], but as discussed above, renewables were key to the poor long-term prospects that made investors ready to permanently walk away. Since then, coal companies have acknowledged divestment as a material risk [175], and daily effects on fossil fuel stocks are detectable when large funds announcement divestment [176]. This benefits renewables somewhat indirectly; as investors see coal declining, they likely also see opportunities likely to be fulfilled by low-cost renewables.

The well-funded Beyond Coal campaign leverages and promotes renewables more intentionally. Launched by the US Sierra Club before the renewables boom, the campaign targets vulnerable coal plants with varied tactics, including law suits over environmental violations, and interventions in utility-regulation proceedings [177]. By 2015, they were already using renewables to make their case whereever possible [178], in order to limit switching from coal to natural gas. In Oklahoma they pointed to ultra-low wind contracts in neighboring states, countering utility analyses of transmission capacity with their own [177]. A recent study found renewables did displace ~20% or recent coal retirements, though natural gas was the central factor [174]. However, the synergy of economics, environmental law and activism is unique to renewables: Beyond Coal used a renewables pitch to organize local support and build coalitions in ways they could not with gas – even if they wanted to [174]; and Sierra Club's much smaller Beyond Gas campaign may soon gain traction as renewables and storage prices increasingly threaten gas peaking plants [181]. The efficacy of Beyond Coal has not been publicly measured, but its benefactor (Michael Bloomberg) more than doubled his original 2010 investment following the 2016 election with another $64 million in the US [179] and contributed $50 million more to expand Beyond Coal into Europe [180].

# 5. Discussion and conclusion

I've presented evidence for considering modern renewables as regime-level systems with potential for landscape-shaping entrenchment. This final section summarizes the extent and limits of these results. It then highlights implications for transitions theory, both for the MLP and broadly for conceptualizing carbon-clean contestation.

## 5.1 Summary of findings and indicators

The formation of transition-accelerating decarbonization regimes may be possible now that the new clean energy systems have reached (or nearly reached) emerging clean regime status.

### 5.1.1 Clean regimes

The results here confirm the mainstream label for modern renewables and EVs. *Readiness* and *supported scaling* results for renewables are less important since *regime scale* results supersede these, but they help establish that li-ion EVs are on a similar path since they meet every indicator met by renewables.

Investments and capacity additions, while simplifying, clearly show modern renewables at a scale rivalling longer-standing electricity sources. Potential for further scaling, both market-driven *and* policy accelerated, is found based on lower costs, predictability and environmental benefits favored by customers, and innovation-enabling technology and industry characteristics. These results reflect 'positive potential', not prospects as weighed against barriers like the socio-technically complex challenges of implementing high-renewable grids.

EV cost and scaling trajectories show them to be nearing regime scale within a decade. EVs currently lack self-sustaining market momentum; they lack cost-competitiveness, while formalized automaker capital commitments are not yet spent. However, li-ion readiness and EV scaling support suggest only a major near-term disruption – like battery technology failure [61] or Chinese political instability – could derail accent to regime scale.

Additional measures suggested in the literature include: (a) quantifying scaling-support investments (b) assessing legitimation via the experience of front-runner jurisdictions like Norway for

EVs (c) proxies for out-growing protected niches like a technology being attacked by incumbents [19] or successful deployment rendering direct subsidies too expensive [18]. However, extensive indicator refinement may be of limited value because (a) few niche energy systems ever rise to global regime scale, limiting additional case studies, and (b) any number of scaling proxies for these three cases seem likely to produce similar results.

### 5.1.2 Decarbonization regimes

In a very limited and preliminary fashion, this study identifies initial indications of potential for decarbonization regime formation – based on the combination of typical entrenchments and extra-ordinary feedbacks between emerging clean regimes and climate politics.

In terms of certain entrenchments, renewables appear at least ordinary. Their job-benefit profile, with PV standing out as by far the most job-intensive, shows renewables could out-employ (if not out-pay) fossil fuels, as is already the case in the US power sector. Public support for increasing renewables across much of the world is clearly much higher than for other energies. How these entrenchments are being leveraged was not considered, nor were other important entrenchments, especially (a) taxes, land-rents and payments [158], and (b) entrenchment in financial and business fields where billions are invested by lenders and corporate buyers who already have established records defending renewables [25]. In general, as the research on green coalitions grows, so will opportunities to synthesize indicators from it for socio-technical analysis.

The limited illustrations of feedbacks between clean regime and climate politics suggests that the relationship between clean energy and the climate imperative (with co-benefits) can form at multiple scales, and in multiple jurisdictions or fields. It show that a breadth of actors are now able to tie their fortunes to renewables from China and UN negotiations, to western climate policy and informal multi-lateral coalitions (coal bans), to groups battling fossil fuel legitimacy and individual coal plants. Since such interaction have just recently become possible for *emerging clean regimes*, and they offer potential to accelerate decarbonization, this general line of inquiry deserves further attention.

## 5.2 Implications for transition theory and carbon clean contestation

The overarching proposal in this paper is to account for emerging trends energy and in climate-politics by shifting an MLP framing of carbon-clean contestation from the niche-regime interface to the regime-landscape interface. This shift carries several theoretical implications. *Clean regimes* offer a new degree of distinction that narrows the bounds of "niche", but leaves the distinction between dominant and emerging global regimes unexamined. *Decarbonization regimes* introduce an endogenous landscape-level, which I would argue could be constructive in select cases, if it is based on empirical justification. For jurisdictional case studies, both concepts are designed to promote and facilitate (a) synthesizing from case studies to the global scale and (b) relating cases to the unique global position of *emerging clean energy regimes*. For example, Geothermal power's promise of base-load power may now need to be replaced by a flexible-generation sales pitch. More broadly I would argue, a key factor to account for is that these first three 21st century clean energy regimes may be path-setting such that political progress and technological change in the transition will tend to agglomerate.

### 5.2.1 Decarbonization regimes and overcoming carbon lock-in

There is an emerging view of how the lock-in of carbon regimes [182] may be overcome in global energy transition; a sense that the establishment of new energy systems and the weakening of dominant carbon regimes may feed off each other [1,4,5]. To help advance this line of thinking, *decarbonization regimes* are defined by anti-carbon bias and organizing logics. This framing, only implicitly addressed here, is part of a broader project [6] which describes carbon-clean contestation using the theory of critical transitions [26]. This theory describes how runaway feedbacks drive comprehensive and rapid regime shifts when complex systems enter an unstable middle ground between two resilient but incompatible states.

Thus, by definition, the co-existence or attempted integration of carbon and decarbonization regimes would be unstable. This framing raises major high-level questions. For one, will EVs and conventional cars really share the road for decades as the climate passes the threshold of collapse?

Currently, every major transition forecast implies the answer is “yes” [91,153]. For another, is contestation between green and brown coalitions over fair treatment in markets or over decisive favor? After all, both side know that a fair accounting of costs from the climate and health perspectives would give a decisive edge to already competitive clean energy.

With the new reality of scaled clean energy, and the growing need for rapid emissions reductions, the concept of *decarbonization regimes* is meant to be both descriptive and normative. It offers a way to investigate the emerging trend of synergy between clean energy and climate action, and it can be a basis for identifying way to leverage these trends as a way to accelerate the shift towards a decarbonizing world order.

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