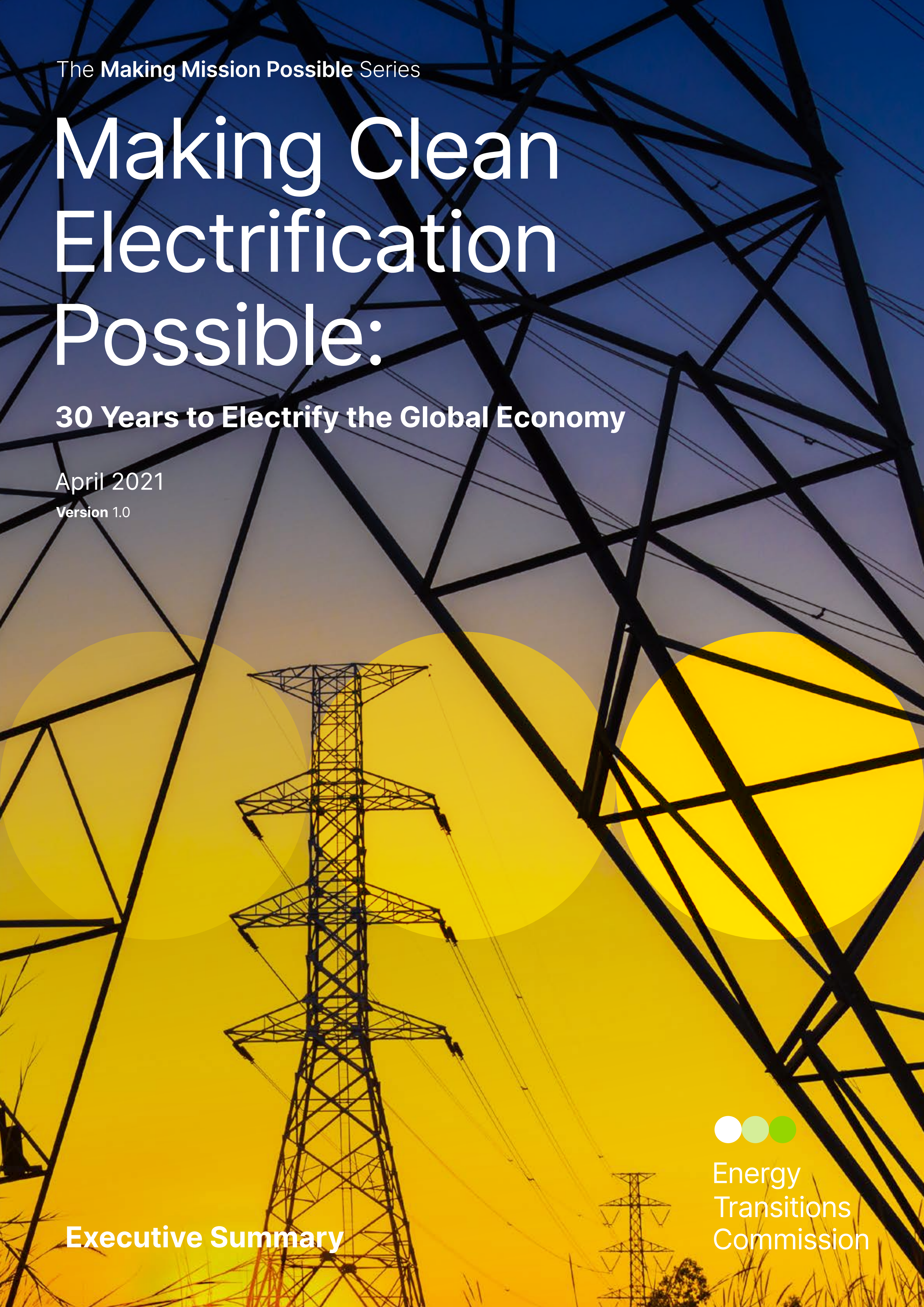


The **Making Mission Possible** Series

Making Clean Electrification Possible:

30 Years to Electrify the Global Economy

April 2021

Version 1.0

Energy Transitions Commission

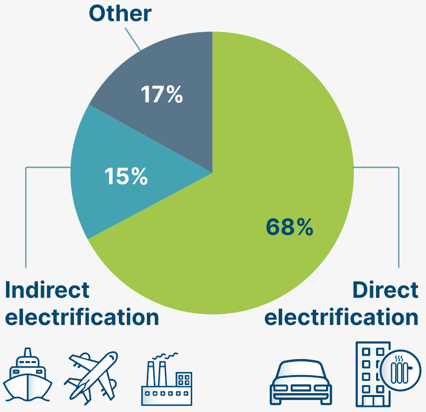
Executive Summary

Energy Transitions Commission

MAKING CLEAN ELECTRIFICATION POSSIBLE

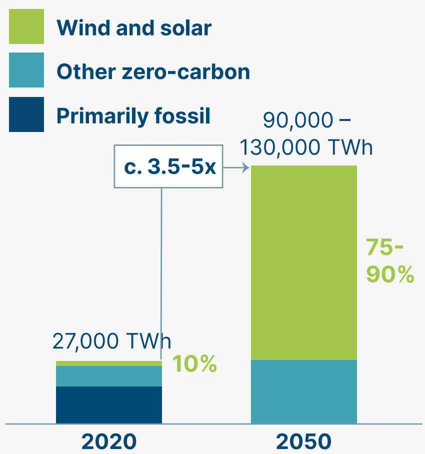
AN ELECTRIFIED ECONOMY

Final energy demand – ETC 2050 Indicative Scenario



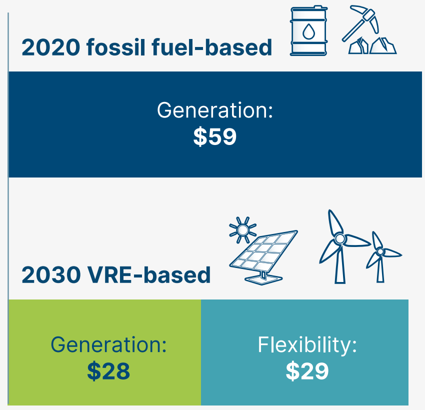
A MASSIVE INCREASE IN CLEAN POWER PROVISION

Power generation, TWh



AT NO EXTRA SYSTEM GENERATION COST

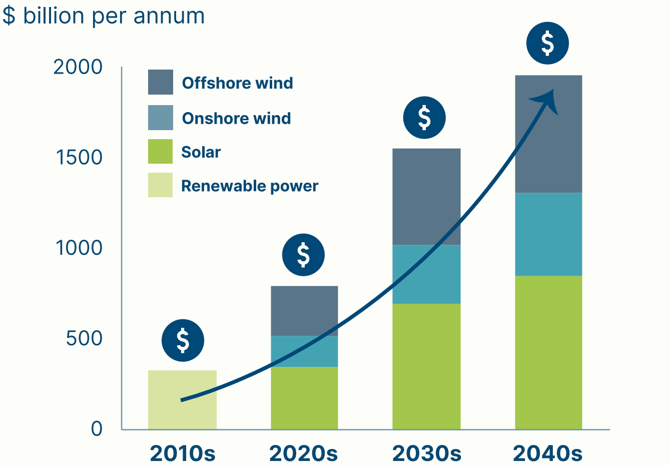
All-in generation cost, $/MWh



What will it take?

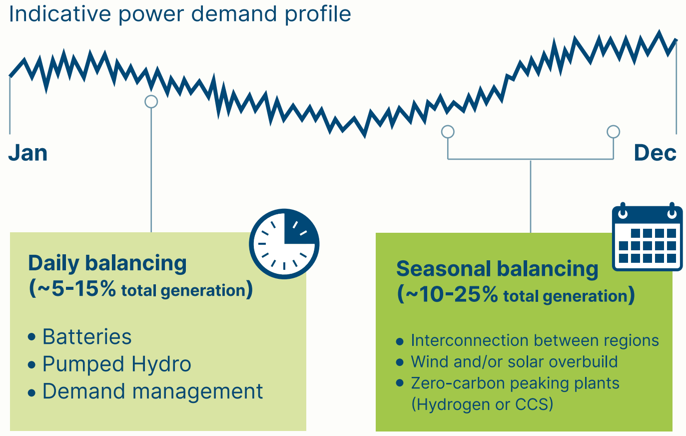
RAPID RAMP-UP IN WIND AND SOLAR INVESTMENT

$ billion per annum

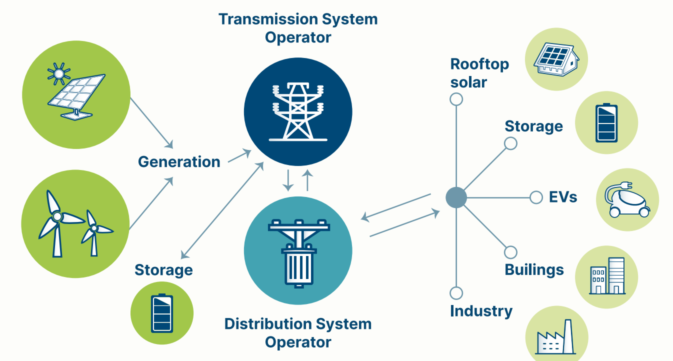


INCREASING FLEXIBILITY PROVISION

Indicative power demand profile



UPGRADING AND DIGITALISING T&D NETWORKS



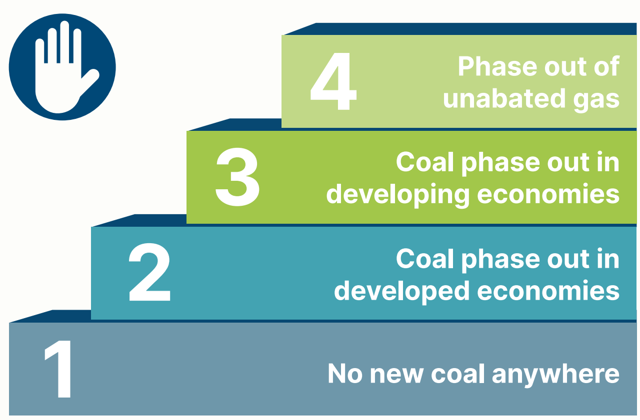
Transmission

Integrated across network vision
Connecting remote renewables
Employing new technical capabilities

Distribution

Digitalised
Connected to new infrastructure (e.g. EV charging)
Moving 2-way power flows

PHASE OUT OF UNABATED FOSSIL FUELS GENERATION



Executive Summary

To limit global warming to below 2°C and as close as possible to 1.5°C, the world must reduce net greenhouse gas emissions to net-zero by mid-century. To achieve that, we must electrify as many economic activities as possible, use hydrogen primarily made from electricity in many others, and totally decarbonise electricity supply. Other technologies such as carbon capture and storage or use (CCS/U) and sustainable bioenergy will also need to be deployed. But clean electricity is necessarily at the core of a zero-carbon economy.

Direct electrification will be key to decarbonising many sectors of the economy, including road transport and building heating, with electricity's share of final energy demand growing from only 20% today to over 60% by mid-century. Hydrogen will also play a major role in decarbonising harder-to-abate sectors which cannot easily be electrified, such as steel and long-distance shipping, and will likely account for another 15-20% of final energy demand [Exhibit A]. Taken together, this requires a dramatic increase in global electricity supply, from today's 27,000 TWh to as much as 130,000 TWh by 2050. Improved energy productivity should be a key priority, but will not remove the need for a massive increase in electricity supply.

Achieving massive clean electrification will be a major challenge, but if managed effectively the transition will pay for itself. Total system generation costs for electricity systems as much as 90% dependent on variable renewables will be no higher than for today's fossil fuel-based systems. Clean electrification will also deliver major local environmental benefits with better air quality and reduced noise pollution.

Achieving early power decarbonisation – ahead of economy-wide decarbonisation – must therefore be at the heart of all countries' paths to net-zero emissions. The Energy Transitions Commission believes that:

- **All developed economies** can and should commit to be net-zero economies by 2050 and to achieve near total electricity decarbonisation by the **mid-2030s**, eliminating coal use almost immediately and with clear plans to phase out unabated gas. In these regions, total electricity use will typically grow 2-2.5 times by 2050.

- **Developing economies** can and should commit to be net-zero economies by 2060 at the latest, and to achieve near total decarbonisation of power by the **mid-2040s**. Electricity use will often need to grow 5-6 times by 2050, with the growth in electricity generation being met almost entirely by zero-carbon sources, and a phase out of existing coal plants in the 2030s and 2040s.

- **Low-income economies** (e.g. in Sub-Saharan Africa) can and should aim to **"leap-frog"** fossil fuels. They can massively expand electricity provision – to meet as much as a tenfold growth in electricity use by 2050 – by building zero-carbon power systems while never going through a fossil fuel phase.

These objectives are undoubtedly within our reach. But they will only be achieved if countries set out clear strategic plans for both electrification and power decarbonisation that unlock massive investments.

This report covers in turn:

- Electrification plus hydrogen as key routes to decarbonisation;
- How to deliver zero-carbon electricity at low cost;
- How to build and finance zero-carbon power systems;
- Summary of key actions required in the next decade.

Indicative final energy mix in a zero-carbon economy

EJ/year

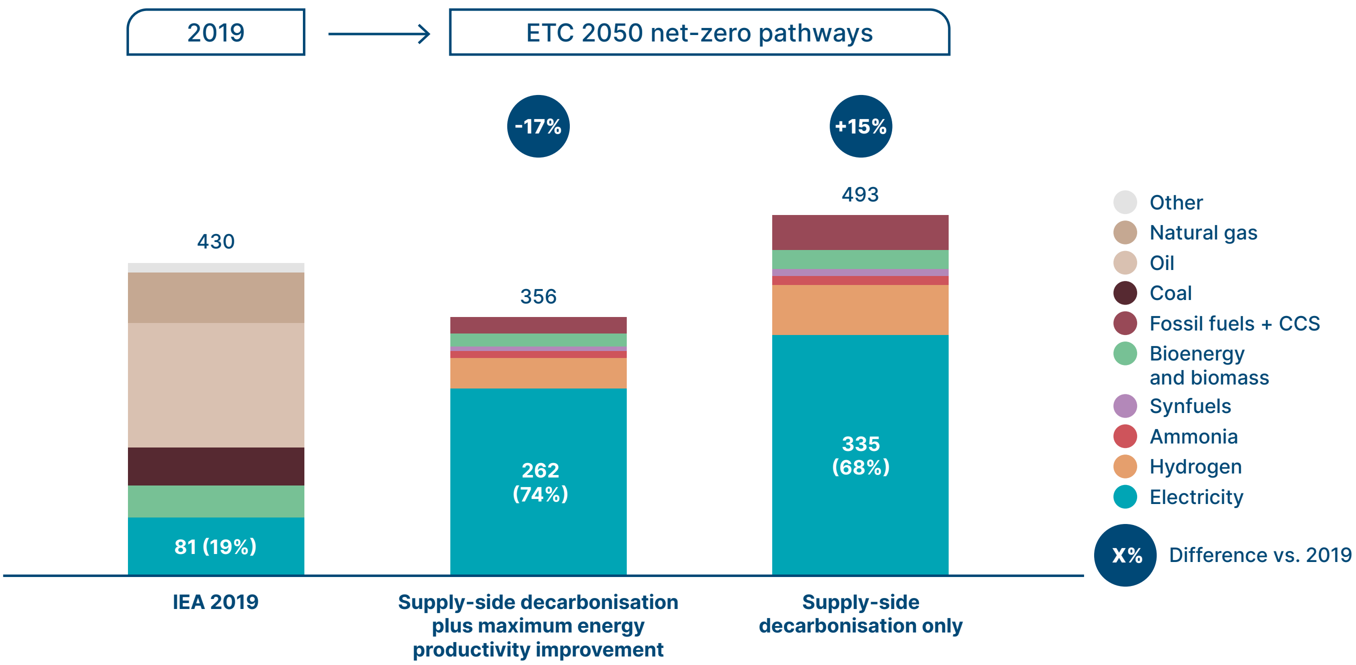


Exhibit A

SOURCE: SYSTEMIQ analysis for the Energy Transitions Commission (2021); IEA (2020), *World Energy Outlook*

I. Driving massive electrification to deliver a zero-carbon economy

All expert analyses of the route to a zero-carbon economy assume a dominant role for electrification. Our ETC scenarios suggests that global electricity demand is likely to grow from 27,000 TWh today to 90-130,000 TWh by 2050.

Mass electrification – the massive growth in electricity and hydrogen demand

Economic growth and rising prosperity will drive increasing electricity demand in existing applications. In addition, major new applications for electricity or hydrogen will emerge.

Road Transport

In the light duty vehicle (LDV) sector, falling battery prices now make it inevitable that EVs will be cheaper than internal combustion engines (ICEs) (both upfront and in operation). In the heavy goods vehicle (HGV) sector, it is likely that BEVs will play an important role, alongside hydrogen fuel cell electric vehicles (FCEVs) for large trucks traveling very long distances. In total, electric and hydrogen road transport could produce demand for 12,000-18,000 TWh of electricity by 2050.

Shipping and aviation

Direct electrification will play a significant role in the decarbonisation of short-distance shipping and aviation. But the primary path to decarbonisation of long-distance shipping and aviation will likely involve the use of liquid fuels burnt in largely unchanged engines. Our scenarios for these sectors suggest potential demand for 8,000-12,000 TWh of electricity by 2050, with the majority used to produce green hydrogen and hydrogen-based fuels.

Commercial and residential buildings

Electricity use in commercial and residential buildings will in part be driven by existing applications: electrical appliances, air conditioning, and information technology equipment. In addition, electricity is almost certain to play a greatly expanded role in space heating. In total, electricity use in building heating could reach around 20,000-22,000 TWh by 2050.

Industry

Most manufacturing processes are already electrified. Furthermore, direct electrification and use of hydrogen can be solutions to decarbonise harder-to-abate sectors such as steel, cement and chemicals. Overall, for heavy industrial sectors we estimate a demand for 8,000-16,000 TWh of electricity by 2050, primarily to produce green hydrogen.

Green vs blue hydrogen: implications for electricity demand

Future demand for electricity will depend not only on the role of electricity and hydrogen in end applications, but on whether clean hydrogen is produced via a “blue” route (which combines a gas-based Steam Methane Reforming (SMR) or Autothermal reforming (ATR) production technology with CCS) or a “green” route with hydrogen produced by electrolysis of water.

The ETC’s parallel report on hydrogen explains that while both routes will likely play a significant role, green hydrogen will probably be lower cost than blue hydrogen in most locations by the 2030s.[1] Our scenarios therefore assume that 85% of hydrogen will be produced via the green route in 2050. Total electricity demand of around 130,000 TWh in 2050 could therefore include around 30,000 TWh used to produce hydrogen [Exhibit B].

1 ETC (2021), *Making the Hydrogen Economy Possible: Accelerating clean hydrogen in an electrified economy*

Improving the energy productivity of the global economy

Improving energy productivity – through technical energy efficiency, materials efficiency, service efficiency, and behavioural change – is an essential lever to reduce the scale of the investment required in the decarbonisation of energy provision and should therefore be a key focus of policy and private-sector interventions. Clean electrification will itself drive a major improvement in energy efficiency. However, even maximum conceivable progress would still see electricity demand increase to something like 90,000 TWh globally by 2050, three times today's level.

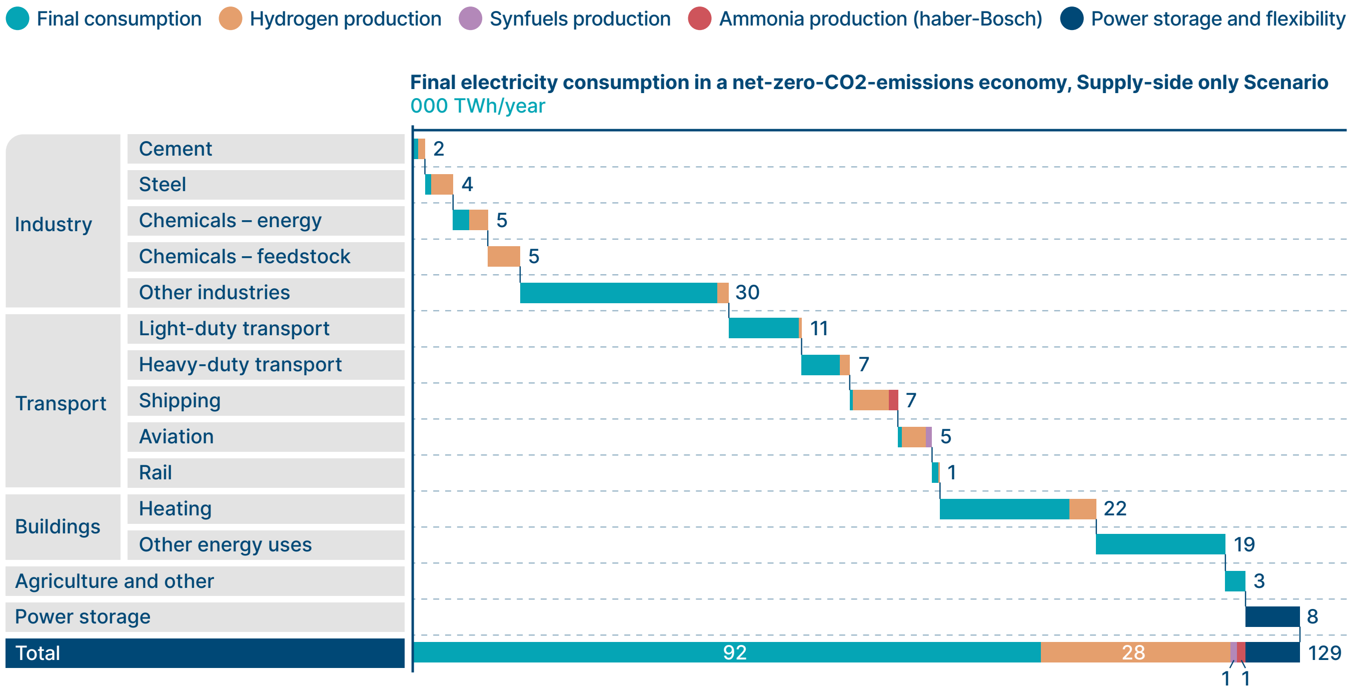
Global and regional ramp-ups

Achieving a zero-carbon economy will require big increases in electricity supply across all decades, but with the highest demand additions in the early 2040s. Scale and pace of growth will vary by country:

- Already rich developed economies could see increases of 2-2.5 times by 2050.
- China is likely to see similar total growth by 2050 (from 7,000 TWh to 15,000 TWh by 2050).
- In developing countries (e.g. India), economic growth and rising living standards will likely drive fairly rapid growth equally across the decades, with total electricity use growing 5-6 times by 2050.
- Low-income economies could see massive growth in electricity use (e.g., 10 times over 30 years), with the profile over time determined by the success of economic and social development strategies.

Electricity will play a major role across sectors

Exhibit B



SOURCE: SYSTEMIQ analysis for the Energy Transitions Commission analysis (2021)

II. Delivering zero-carbon electricity at low cost: high variable renewable power systems are technically feasible and cost-effective

Massive clean electrification can be achieved at minimal cost to the global economy and in most countries. All countries should therefore plan for all growth of electricity supply to come from zero-carbon sources, and should develop plans to phase out unabated fossil fuel generation.

Decarbonising power generation at low, nil or negative cost

Dramatic falls in the cost of renewable generation and of key storage technologies now make it possible to decarbonise power generation at nil or in some cases negative cost. Over the last 10 years, the cost of renewable electricity has plummeted. BloombergNEF forecasts a further 70% fall for solar, 50% for onshore wind and 45% for offshore by 2050[2]; but faster still decline is possible. Even at current cost levels, renewable electricity is cheaper than new coal or gas plants in countries representing 90% of current electricity generation.[3] In many countries indeed, new wind and solar is already cheaper than the marginal cost of running some existing coal and gas plants, and this advantage will grow over time.[4]

Balancing VRE-based power systems – a vital but manageable challenge

The critical question is therefore no longer the relative cost of renewable- versus fossil fuel-based generation, but how to cost-effectively balance supply and demand in systems with an increasing share of variable renewable energy (VRE) supply. The scale and nature of this challenge varies by region, but in almost all countries an increasing array of storage and flexibility options can provide cost-effective solutions to the three major types of balance challenges [Exhibit C]: daily balancing (e.g., via batteries), predictable seasonal balancing (e.g., via overbuild of VRE capacity), and unpredictable week-by-week balancing (e.g., via peaking plants using hydrogen).

Exhibit C

Range of dispatchable generation, energy storage, demand-side flexibility options

			Daily	Seasonal (predictable)	Week-by-week (unpredictable)
Dispatchable generation	Other zero carbon	Hydro, nuclear[1]	✓	✓	✓
	Fossil	Fossil (or bioenergy) + CCS	✓	✓	✓
		Fossil – very low utilisation	✓	✓	✓
Energy storage		Pumped hydro	✓	✓	✓
		Lithium ion battery[2]	✓		
		Emerging technologies	✓		
		Power-to-X-Power[3]	✓	✓	✓
Demand side flexibility		EV (smart charging, V2G)	✓		
		Heating load	✓		
		Industrial load[4]	✓	✓	

NOTES: [1] Limited nuclear capacity for flexible ramping. [2] Li-ion storage is utility-scale and behind-the-meter. [3] Examples of Power-to-X-Power include the production of hydrogen from electrolysis and re-conversion of hydrogen into power via gas turbines or fuel cells. [4] Including hydrogen electrolysis, where production can be shifted to optimal times.

SOURCE: Adapted from Climate Policy Initiative for the Energy Transitions Commission (2017), *Low-cost, low-carbon power systems*

2 BloombergNEF (2020), *2H 2020 LCOE Update*
3 BloombergNEF (2020), *2H 2020 LCOE Update*
4 BloombergNEF (2020), *2H 2020 LCOE Update*

Given these increasingly cost-effective balancing options, estimates of maximum cost-effective VRE generation shares in the power system have increased significantly in recent years. Our ETC scenarios illustrate a range from 70-90%.

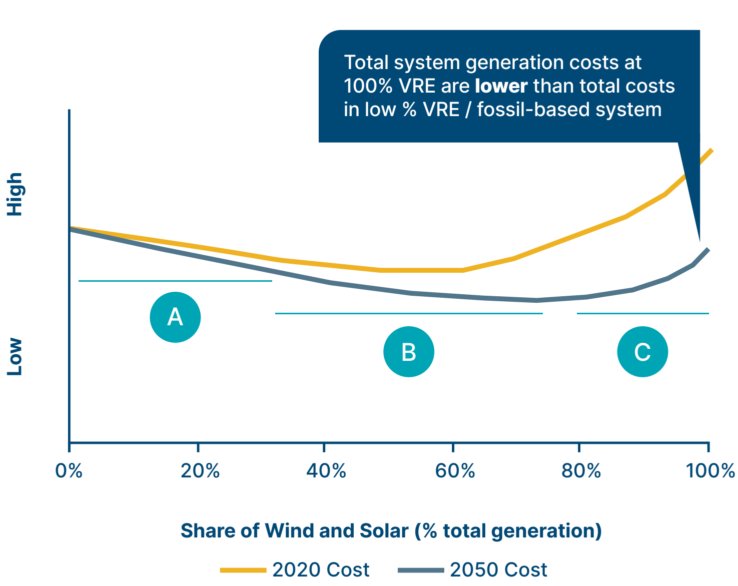
Total system generation costs – fully competitive with fossil fuels

Fully decarbonised power systems are thus feasible and will be able to deliver electricity across days, weeks and year at costs fully competitive with today's fossil fuel-based systems ($57/MWh in average geographies). Providing the storage and flexibility needed to balance VRE-based systems will entail additional costs, especially beyond 80% VRE penetration, but these will be offset by the fact that VRE generation costs are lower than for fossil fuels [Exhibit D].

Exhibit D

Total system generation costs in zero-carbon power systems likely to be below those of fossil-based power systems

Total system generation costs as function of VRE penetration, $/MWh, 2020 and 2050 cost scenarios



SOURCE: Adapted from TERI/ETC India (2020) *The Potential Role of Hydrogen in India*

A

0-30% VRE penetration

Declining system generation costs as cheaper renewables replace fossil in baseload generation; no balancing needs

B

30-80% VRE penetration

Further cost declines as renewables + storage increasingly cheaper than fossil for dispatchable generation

C

80-100% VRE penetration

Increase in total system generation costs as significant costs required to provide zero carbon answers to the "last 10%-20%" of generation

Additional costs in transmission and distribution

Transmission and distribution (T&D) needs will rise dramatically to support massively increased electricity use. The impact of T&D networks strengthening on cost per MWh will reflect a balance of factors, and will vary by specific location. T&D costs may on average increase, driven for instance by higher transmission costs to connect remote renewable resources, but intelligent time-of-day demand management and flexibility levers could offset those network cost increases by lowering overall system generation costs.

Natural resources – clearly sufficient at global level

At the global level there are easily sufficient natural resource to support massive clean electrification. For example, if 100,000 TWh of annual electricity production were produced entirely from solar PV, only 1-1.2% of the land area of the world would have to be devoted to solar farms.[5] There is also plentiful mineral resource to meet the battery and electricity system needs of a deeply electrified economy (including lithium and nickel). But potential short-term supply bottlenecks and local environmental effects must be tightly managed. The development of materials circularity represents a key lever to reduce reliance on primary resources.

5 Assuming 1.2-1.7ha/GWh/annum based on NREL (2018), *Land-use Requirements for Solar Power Plants in the United States*. See ETC (2018), *Mission Possible.*

Challenges and solutions in resource-constrained countries

Where some geographies may face challenges around resource availability of wind and solar, these can be overcome either by long-distance energy transport or through deployment of land-efficient zero-carbon generation options (e.g., nuclear, CCS on thermal generation or new forms of renewable technologies like floating offshore wind turbines). Given the dramatically low solar and wind costs in some favourable locations, clean energy transport is likely to be economic over even very long distances. Maximising these opportunities will sometimes require international cooperation and trust to overcome concerns about energy security.

Phasing out unabated fossil fuel plants

All countries should ensure that the near totality of electricity generation growth now comes from zero-carbon sources. In addition, countries must develop strategies for the eventual phase-out of unabated fossil fuel generation. In many locations, this will entail minimal or nil economic cost as VRE generation costs fall below the marginal cost of running either gas or coal plants. Capacity utilisation will therefore naturally decline, with many fossil plants shifting to become providers of flexible response in systems increasingly dominated by VRE and others retiring early. However, policymakers should address factors that may delay progress, including existing long-term fixed price supply contracts and regional employment challenges.[6]

- Developed countries should commit to phase out all coal generation as soon as possible and by 2030 at the latest, and set future dates for the elimination of unabated gas generation.
- Developing countries should commit to not build any new coal plants (which would be uneconomic) and set clear dates for the elimination of unabated coal in the 2040s at the latest.

III. Building and financing zero-carbon power systems

Delivering the clean electricity needed in a zero-carbon economy requires a massive increase in investment in renewables, other zero-carbon generation technologies, as well as in electricity transmission and distribution networks. In global macroeconomic terms, this investment is easily affordable (less than 1.5% of global GDP), but it will only occur fast enough if governments create sufficient market certainty.

Scale and timing of require investment needs

For VRE to provide 75% to 90% of electricity generation by 2050, total installed capacity of wind would have to grow from today's 640 GW to between 14,000 and 16,000 GW by 2050, while solar capacity would have to increase from today's 650 GW to between 26,000 and 35,000 GW by 2050.[7] To achieve these 2050 capacity levels, annual deployment of solar and wind must increase 10 to 15 times above current levels over the next two decades, to reach 700-800 GW per annum for wind and 1,400-2,000 GW for solar.[8]

In addition, countries will need to invest in a mix of nuclear, hydro, and CCS plants, along with battery and other storage capacity. Total investment requirements in electricity generation could therefore increase from today's $300 billion per annum to a peak of about $2 trillion in 2040-45 before declining slowly thereafter.

Investment in transmission and distribution also needs to rise dramatically. Reasonable estimates suggest that transmission investment could grow from today's $300 billion per annum to around $1 trillion, with distribution investment rising from $180 billion per annum to $900 billion.

Total power system investment needed over the next 30 years could therefore amount to over $80 trillion (or over $2.5 trillion per annum) – and would account for around 80% of all the investments needed to build a zero-carbon energy, building, industrial and transport system [Exhibit E].

6 RMI (2020), *How to Retire Early,* TERI (2018), *Coal Transition in India* and RMI/ETC China (2019), *China 2050: A fully developed rich zero-carbon economy.*
7 Historic data from BloombergNEF (2020), *New Energy Outlook*
8 Historic data from BloombergNEF (2020), *New Energy Outlook*

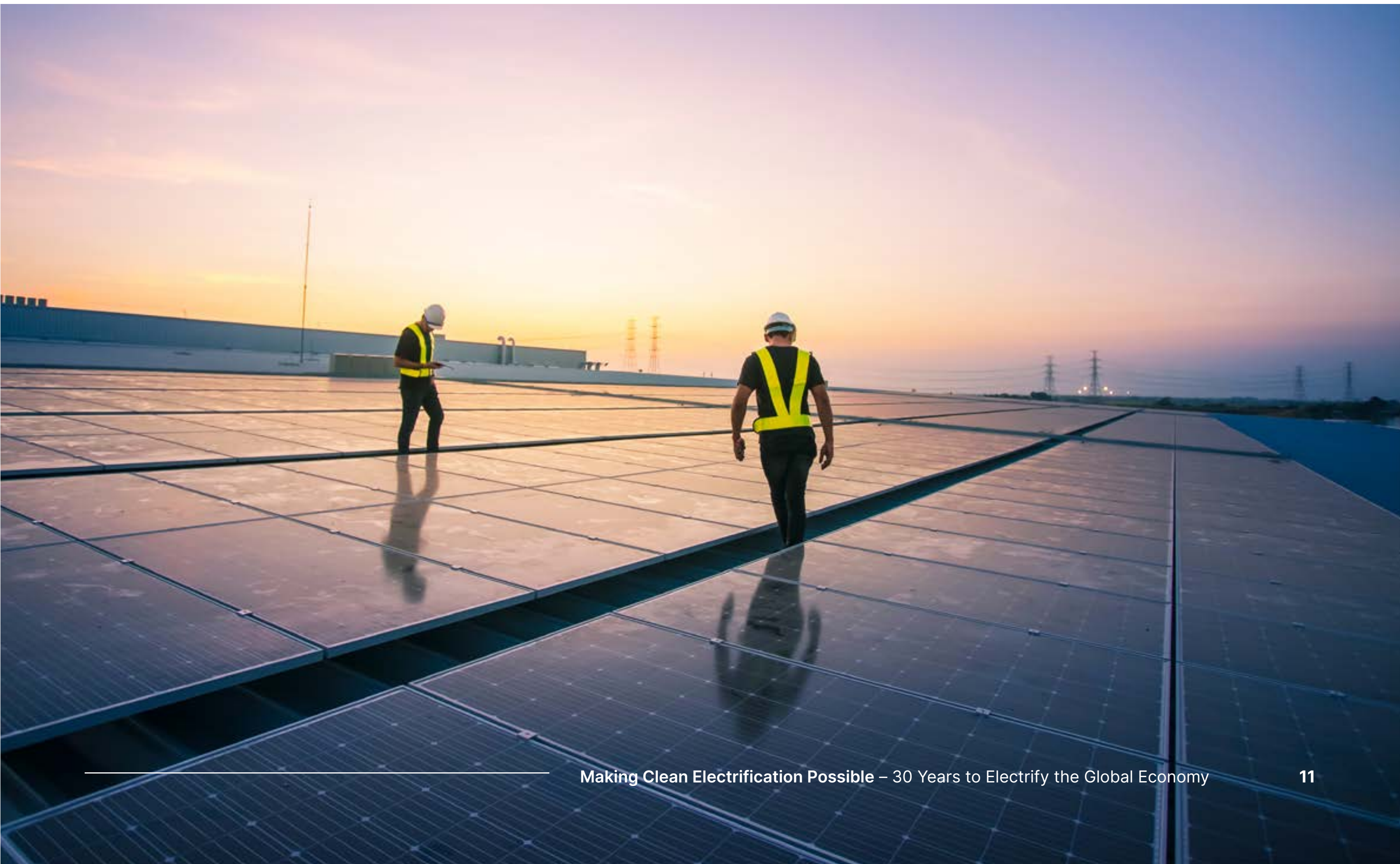
Power sector represents vast majority of total investments to reach net-zero across the energy sector

	2050 vision		Key investment needs	Total investment 2020-2050, US$bn	Total annualised investment, US$bn pa	Share of GDP %
Power	**Total power generation** 110,000 TWh / year **Total capacity required** 27-35 TW solar 14-16 TW wind 2-4 TW of hydro, nuclear, other zero-carbon	**Renewables & other zero-carbon**	26-34 TW solar 14-15 TW wind 3.5 TW other zero carbon	~46,000-47,000	~1,500-~1,600	~0.8%
		Transmission & Distribution	~50% of generation, front-weighted	~36,000	~1,100	~0.6%
		Battery storage	14 TWh per day (5% of daily generation)	~1,500	~50	~0.03%
		Seasonal storage: H_2 storage and/or CCS on thermal plants	4 TW thermal capacity equipped with CCS (5% of generation)	~3,800	~130	~0.07%
			1.5 TW electrolysis (2% power shifted)	~430	~15	~0.05%
Hydrogen in final use	800 Mt/year for final sectoral energy use	**Production**	7.6 TW electrolysis 0.7 TW blue hydrogen capacity	~1,200	~40	~0.02%
		Transport and storage	Salt caverns and other storage Gas pipeline retrofit	~1,100	~40	~0.03%
Industry	Steel, cement and petrochemicals industries achieve zero-carbon		CCS application to cement Hydrogen DRI or CCS for steel Multiple forms of changed chemical production process	~1,600	~50	~0.03%
Transport	**Road charging infrastructure**	Total decarbonisation road transport ~2bn electric cars and~200m electric trucks & buses	~1000bn slow residential, 200m moderate speed public and 10million superfast chargers, + truck and bus chargers	~2,000	~70	~0.04%
	Aviation and shipping	All long haul routes running with zero carbon fuels	Aviation and green shipping R&D, SAF plant investment and ship / fuel supply retrofit	~900	~30	~0.02%
Buildings Energy efficiency	IEA estimate of additional required investment in better insulation and more efficient lighting and HVAC systems			~12,000-15,000	~400-500	~0.2%
Total				**~106-110,000**	**~3,600-3,700**	**~1.8%**

Exhibit E

NOTE: Wind and solar capacity for hydrogen production is included in renewables generation.

SOURCE: IEA (2020), SYSTEMIQ analysis for the Energy Transitions Commission (2021)



Appropriate power market design

Until now, rapid growth in renewables capacity has typically been driven by long-term contract structures, via auctions. With VRE generation costs now falling below fossil fuel costs, the need for subsidy is disappearing or soon will. However, countries cannot now switch to relying on short term markets alone to support VRE investment. Long-term contracts (without subsidy, but providing price certainty over the long term) will still be required to create low-risk investment opportunities which can attract low-cost capital on the scale and at the speed required.

These should be combined with (i) appropriate short-term markets to support efficient dispatch, including new markets for the procurement of ancillary services; (ii) long-term peak capacity mechanisms, (iii) the development of flexibility enablers, such as real-time pricing as well as smart charging facilities, and (iv) other market enablers, such as system operator capabilities at the distribution network level.

Specific additional priorities in developing countries include (i) progressive evolution towards liberalised markets, (ii) reforms to improve rate of cost recovery and off-taker creditworthiness, and (iii) regulations to ensure improved grid connection access for VRE generation.

Planning, permitting and land acquisition systems to support rapid VRE development

Renewables development is often greatly delayed by lengthy planning and permitting procedures, and/or by local opposition on the grounds of localised impact or noise pollution. Countries therefore need to develop explicit strategies for future VRE development which include establishing a "one stop shop" for approval processes with coordination across regulatory bodies and encouraging distributed generation and/or community ownership models to build local support.

Frameworks for anticipatory transmission and distribution investment

The planning and permitting dimensions outlined above are also relevant for investment in T&D networks. In addition, electricity network regulation will need to be reformed to allow for long-term integrated planning, identifying integrated network developments needs far in advance and enabling "anticipatory investment". Designation of some projects as national infrastructure priorities and investments in more expensive solutions to overcome political resistance to essential developments (e.g., undergrounding) might also help fast-track developments.

Developing supply chains to support rapid investment growth

Adequately fast investment in clean power generation and networks will require the development of extensive supply chains, including key materials and capabilities such as expanded solar PV and wind turbines production, as well as significant growth in battery production. These developments are physically feasible within the required timescale, but recognition and anticipation of the scale of the required supply chain are essential to pre-empt potential local bottlenecks in skills and capabilities, and global bottlenecks in key material resources.

Financing challenges in some developing countries

In most countries, the four sets of actions just described, underpinned by strategic vision and quantitative targets, will be sufficient to drive rapid investment growth. However, in some developing and emerging economies, the cost and availability of capital could be a significant barrier to rapid growth. Rapid development of clean power systems will therefore rely on a large-scale role for multinational and national development banks, which can provide policy design advice alongside finance.[9] Clean power system investment (and coal phase-out) should therefore be a priority focus for "climate finance" flows from developed economies and for China's "Belt and Road" programme.

9 See Blended Finance Taskforce (2018), *Better Finance, Better World*

Energy Transitions Commission

CLEAN ELECTRIFICATION IN THE 2020S

2030 TARGETS:

ELECTRIFICATION

Global electricity use up 1.5 times

- EVs near 100% of new car sales in developed countries, 50%+ in developing countries
- Heating increasingly electrified, building retrofits under way

WIND AND SOLAR DEPLOYMENT

Wind and solar ~40% global generation

- 5-7x increase in annual wind + solar installations
- Scaling storage and flexibility deployment

FOSSIL PHASE OUT

Grid emissions intensity

Developed countries <80 gCO_2/kWh | Developing countries <180 gCO2/kWh

- Immediate stop to new coal
- Meet all new electricity growth with wind and solar

6 CRITICAL ACTIONS / KEY EXAMPLES

TARGETS — 1. Clear medium-term targets

- Clear quantitative targets for zero-carbon electricity (e.g. wind and solar capacity, grid emissions intensity) and electrification (e.g. EV sales)
- Future bans on fossil technology (e.g. ICE)

DEPLOYMENT — 2. Incentives for clean electrification

- Remove all remaining fossil fuel subsidies
- Appropriate power market design (e.g. long-term contracts, appropriate short-term markets incl. ancillary services, long-term peak capacity mechanisms, flexibility enablers)
- Electrification incentives & subsidies (where required, e.g. heat pump incentives)
- Standards & regulations (e.g. AC min. efficiency standards)

NETWORKS & SKILLS — 3. Infrastructure and capabilities

- Regulatory frameworks to enable anticipatory investment in power networks
- Network infrastructure (e.g. grids, EV charging, building retrofits)
- New Distribution System Operator capability to manage distribution network
- Clear plans for supply chain expansion and workforce training

PLANNING — 4. Integrated vision, planning and permitting

- Integrated vision for power system and network design
- Streamlined planning, permitting, and land acquisition

FINANCING — 5. Financing, mainly in developing countries

- Instruments to scale investment in developing countries, e.g. blended finance, concessional finance, asset securitization
- Fossil phase out mechanisms, e.g. PPA modification, debt restructuring

INNOVATION — 6. Technologies and business models

- Long-term energy storage solutions (e.g. hydrogen)
- Continue VRE cost declines and increased range (e.g. floating wind)
- Aggregators and virtual power plants (VPPs)

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