Research and Innovation Working Group

Priority Topic 2

Deliverable 2.1

International Energy Agency

The G20 overview of clean energy technologies to be targets of voluntary co-development, transfer, dissemination and diffusion of knowledge on mutually agreed terms, with the aim of lowering emissions and the achievement of the protection of the environment and of net-zero greenhouse gas emissions/carbon neutrality

Prepared by the International Energy Agency (IEA) at the request of the G20 Research and Innovation Working Group Presidency for the Ministerial meeting 19 September 2024 in Manaus, Brazil.

The International Energy Agency is grateful to all delegates of the G20 Research and Innovation Working Group who conceived the project and provided guidance and support throughout, including by reviewing early drafts and contributing technologies to be included. The work reflects the views of the International Energy Agency Secretariat but does not necessarily reflect those of individual G20 or IEA member countries or of any particular funder, supporter or collaborator. None of the IEA or any funder, supporter or collaborator that contributed to this work makes any representation or warranty, express or implied, in respect of the work's contents (including its completeness or accuracy) and shall not be responsible for any use of, or reliance on, the work.

Objective

The aim of this deliverable is to highlight a range of energy technologies as a resource for emerging market and developing economies (EMDEs) seeking to quicken the pace of clean energy transitions globally and reap economic benefits from technology innovation and adoption. The deliverable indicates the current status of the technologies, notable countries involved in their development and links to more information via an IEA database. While the heterogeneity of country contexts makes it impossible to shortlist technologies that are relevant to all EMDEs, the list in this deliverable represents an attempt to illuminate certain technology categories that are likely to resonate with the needs of many of them. While the future deployment of these technologies rests upon creativity in the design of effective policies, finance and business models, those aspects are not the focus of this deliverable. The focus is on the science, hardware, software and processes that can be targeted by enhanced R&D and other efforts to adopt and adapt them for new markets, especially in EMDEs.

Identifying important technologies for expansion and deployment in emerging market and developing economies

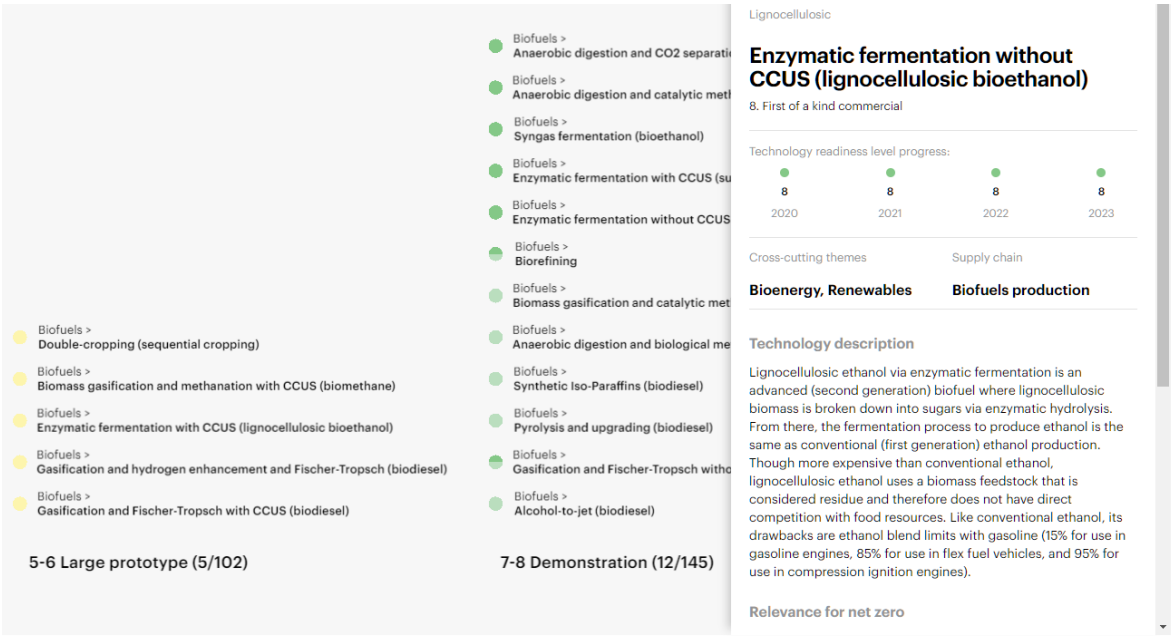
The global nature of the climate challenge means that all countries need to contribute to successful energy transitions. The last five years has seen the number of governments with net zero targets go from 77 in 2019 to 145 in 2023. More than half of global investment needs to 2050 in clean energy assets are in EMDEs in the IEA's Net Zero Emissions by 2050 Scenario. This share could be even higher when considering investments to secure and process supplies of critical minerals. These investments, which underpin economic growth and reliable infrastructure, will only be directed to low-emissions technologies if they are available, affordable and well-adapted to local contexts. Many countries, including some that previously had no stake in energy technology development, are evaluating opportunities to enter new value chains and move up them over the longer term.

The highlighted technologies match the latest update of the IEA Clean Energy Technology Guide (CETG). The CETG is a unique resource for identifying and tracking clean energy technologies. It currently contains more than 550 separate technology designs, split into five sectors, 25 subsectors and tagged with ten cross-cutting themes. For each technology entry in this dataset that is freely available online, there is a description of the technology, its applications, the latest projects, key countries, and changes in the maturity level.

The CETG does not distinguish technologies that have high potential impact in developing economies, as there is no reason why all countries should not contribute to the availability of the most high-tech and low-emissions products, whether through technology innovation, equipment manufacturing or as pioneers of deployment. The CETG and this deliverable are therefore technology neutral and should not be interpreted as recommendations in relation to any specific types of policy support. However, to manage the breadth of the work, the technologies listed in this deliverable reflect characteristics that are of particular relevance to most developing countries this decade. These characteristics include: energy service needs (such as the growing demand for cooling and cleaner cooking); resources (high availability of solar and, in some countries, potential for sustainable biomass use); economics (a reliance on fuel export revenues in some countries); and infrastructure (a lack of universal connection to electricity grids).

Our definition of "clean energy technology" is deliberately broad, covering technologies across all elements of energy production, distribution, storage and end use (including products and services that can help consumers avoid unnecessary energy consumption to satisfy their energy service needs). What they have in common is that they can meet energy needs with a lower environmental impact, based on new approaches to hardware design, new scientific principles and advances in software. In general, clean energy technologies are those compatible with energy systems that have net zero greenhouse gas emissions.

Screenshot from the IEA Clean Energy Technology Guide, bioenergy subsection



Source: IEA Clean Energy Technology Guide (accessed August 2024).

The technologies are at different stages of maturity, and this is reflected using the metric of technology readiness level (TRL) in the tables. The most mature among them (TRL 9+) can be procured from commercial sources today but, as in the early stages of deployment in any country, there are still major opportunities for innovations in installation techniques and adaptation of the technologies to local preferences. Less mature technologies require further R&D efforts, testing and demonstration. Given the importance of these technologies to the achievement of clean energy transitions in emerging market and developing economies, there are opportunities for the necessary innovation projects to be in these regions. This can help ensure a good fit between the direction of the research and the context in which the technologies will need to be adopted by end-users.

The more mature technologies have costs that can vary widely between countries and products. For example, the costs of geothermal energy and hydropower are highly dependent on the local resource base. The costs of electric vehicles and efficient appliances depend on which market segment they have been designed for and, in almost all countries, there are examples of policies helping make these accessible to the poorer sections of the population. Furthermore, the competitiveness of these technologies depends on their future cost trajectories, as well as the cost trajectories of today's incumbent technologies. These are uncertain, interdependent and depend on global trends and events. It is therefore not possible to generalise about the affordability or social implications of all technologies. Further work could potentially explore these aspects for a subset of technologies.

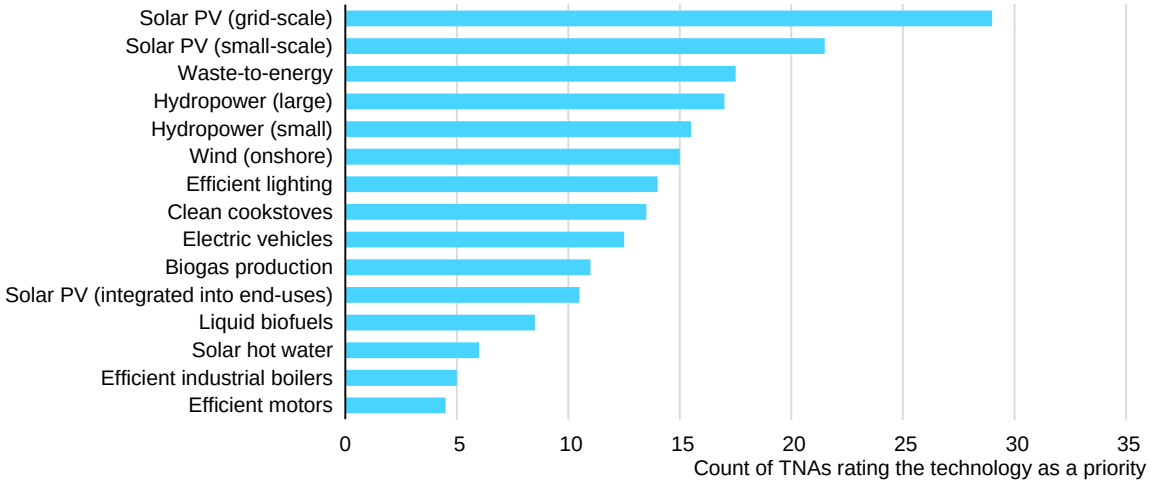
Identifying technology areas relevant to emerging market and developing economies

Emerging market and developing economies are highly heterogeneous in terms of their resource endowments and energy needs. Some have access to fossil fuel resources while others already rely extensively on clean energy, particularly hydro- and solar energy, and have extensive opportunities to expand their use of energy crops or harvest solar energy. Some have high average temperatures and rapidly growing demand for air conditioning, which is placing a burden on electricity supplies, while a smaller number have cold winters or high altitudes that demand heating provision. Many, but not all, emerging market and developing economies have populations that are exposed to air pollution from cooking or are not connected to power grids – 760 million people still lack access to electricity worldwide, while 2.3 billion people lack access to clean cooking solutions.

This heterogeneity makes it impossible to shortlist technologies that are relevant to all the countries. However, existing studies shed light on certain technology categories that are likely to resonate with the needs of many of them. One such resource is the library of Technology Needs Assessments (TNAs) that have been

conducted under the guidance of the United Nations Environment Programme and United Nations Framework Convention on Climate Change.[1] Since 2009, 71 national TNAs for emissions mitigation technologies have been produced and each one uses a common methodology to score technology priorities for the country. The combined results of this process guide the focus technology areas in this deliverable.

Top 15 energy technologies across 71 national Technology Needs Assessments, by counts



Notes: PV = photovoltaic; technologies are counted once each time they appear among the top three priority technologies in a TNA for energy technologies and counted as 0.5 if they are ranked fourth or fifth. Energy-related technologies that feature among the top three priority technologies in a TNA for transport, waste, buildings or other relevant mitigation sectors are also counted once. While most TNA reports cover energy, not all of them cover other sectors consistently.
Source: IEA analysis based on the TNA database. (accessed April 2023).

Solar PV is prominently represented in the TNA results. Grid-scale solar PV is the most frequently prioritised technology, with smaller-scale off-grid, stand-alone and mini-grid solar PV installations coming second. When including technologies reliant on solar PV that are integrated into end-uses such as pumps, solar PV is a feature of one-fifth of all prioritised technologies in the analysis of the 71 TNAs. Hydropower is also frequently ranked highly, both in its large-scale and mini/micro formats, and the additional presence of onshore wind energy among the top six most cited technologies shows the importance of supply side electricity technologies. The supply side of clean energy is also represented strongly by the bioenergy and waste technologies, with many TNAs highlighting waste-to-energy conversion, including from agricultural residues and landfill gas. On the demand-side, efficient lighting (including light-emitting diodes, LEDs), clean and efficient cookstoves, electric vehicles, efficient industrial boilers, efficient motors, and

[1] The development of TNAs has been undertaken within the framework of a project funded by the Global Environment Facility and supported by the Green Climate Fund.

waste heat recovery are all considered to have widespread opportunities to reduce emissions in emerging market and developing economies.

For the technology areas that score most highly in the TNA analysis the associated technology entries in the CETG are tabulated in separate sections below.

Many of the TNAs were conducted more than a decade ago. Since then, there has been significant change in international expectations for certain technologies, as well as an increased focus on decarbonisation of sectors such as manufacturing and industry to meet net zero emissions goals. For example, low-emissions hydrogen production and its use to make steel without fossil fuels are the focus of several recent and large projects in emerging market and developing economies but are absent in the early TNAs. To account for some of these changes, a section on alternative fuels for energy and industrial exports has been added. The interest of some emerging economies in small nuclear reactors is another example and has been included.

Assessing technology maturity: the Technology Readiness Level (TRL) scale

One way to assess where a technology is on its journey from initial idea to market is to use the technology readiness level (TRL) scale. The scale provides a common framework that can be applied consistently to any technology to assess and compare the maturity of technologies across sectors. Conceptually, it can be applied to any potential new product, a modification of an existing piece of equipment, or a proposed improvement to a process.

Originally developed by the National Aeronautics and Space Administration (NASA) in the United States in the 1970s, the TRL provides a snapshot in time of the level of maturity of a given technology within a defined scale. The US Department of Defense has been using the TRL scale since the early 2000s for procurement, while the European Space Agency adopted it in 2008. In 2014, it was formally applied for the assessment of projects as part of the EU Horizon 2020 framework programme. It is now widely used around the world to set research priorities.

The technology journey begins from the point at which its basic principles are defined (TRL 1). As the concept and area of application develop, the technology moves into TRL 2, reaching TRL 3 when an experiment has been carried out that proves the concept. The technology now enters the phase where the concept itself needs to be validated, starting from a prototype developed in a laboratory environment (TRL 4), through to testing in the conditions it which it will be deployed (TRL 6). The technology then moves to the demonstration phase, where it is tested

in real-world environments (TRL 7), eventually reaching a first-of-a-kind commercial demonstration (TRL 8) on its way towards commercial availability (TRL 9).

As technologies pass through each stage, the level of risk associated with technology performance is reduced, but the level of overall risk can rise as capital expenditure requirements grow. However, innovation is rarely a linear progression. Not all technology designs make it to market or get deployed at scale. Stages of development can accelerate or slow down depending on technical or cost factors, and a given technology can be at different stages in different applications. As the development of a technology generates new ideas for improvements, alternative configurations and potentially better components can appear even once a given technology configuration has become competitive. Stages overlap and run concurrently, feeding on one another.

Arriving at a stage where a technology can be considered commercially available (TRL 9) is not sufficient to describe its readiness to meet energy policy objectives, for which scale is often crucial. Beyond the TRL 9 stage, technologies need to be further developed to be integrated within existing systems or otherwise evolve to be able to reach scale; other supporting technologies may need to be developed, or supply chains set up which, in turn, might require further development of the technology itself.

Grid-scale power generation

Pre-commercial technologies in need of further innovation efforts

Technology	Technology area	TRL	Examples of countries currently involved[2]
Closed-loop and hybrid closed-loop systems (geothermal)	Geothermal	5	United States, Germany, Canada, United Kingdom
Direct lithium extraction (brine) (geothermal)	Geothermal	7-8	United States, Germany, France, Canada, Argentina
Enhanced geothermal systems	Geothermal	6	Austria, Belgium, Croatia, El Salvador, France, Germany, Hungary, Netherlands, United Kingdom, United States
Kalina process (geothermal)	Geothermal	6	Germany, Iceland, Japan

[2] These examples are provided to assist governments in finding more information about technologies and projects. Where it is difficult to identify the countries that could serve as useful sources of experience and information, or where many countries are equally active, this column is left blank.

Technology	Technology area	TRL	Examples of countries currently involved[2]
Floating solar PV	Solar PV	8	The People's Republic of China (hereafter "China"), France, India, Japan, Korea, Netherlands, Singapore, United Kingdom, United States
Organic thin-film PV cell	Solar PV	5-6	Germany, Australia
Perovskite PV cell	Solar PV	4-5	Australia, Canada, China, Germany, Japan, Poland, Singapore, Sweden, Switzerland, United Kingdom, United States
Thin-film PV	Solar PV	8	Germany, Japan, Singapore, United States
Airborne wind energy system	Wind energy	4-5	Netherlands, United States, Germany
Ocean Thermal Energy Conversion (OTEC)	Ocean Energy	5	European Union, France, India, Indonesia, Japan, Korea, Netherlands
Light-water reactor-based small modular nuclear reactor	Nuclear	6-7	Argentina, Canada, China, Finland, France, India, United Kingdom, United States
Post-combustion: chemical absorption (natural gas with carbon capture, utilisation and storage [CCUS])	CCUS	8	Canada, Japan, Netherland, United Kingdom, United States
Supercritical CO_2 cycle (natural gas with CCUS)	CCUS	5-6	Japan, United States
Post-combustion: membranes polymeric (coal with CCUS)	CCUS	6	Australia, Brazil. Japan, Norway, United States
Supercritical CO_2 cycle (coal with CCUS)	CCUS	5-6	Japan, United States
Post-combustion: chemical absorption (coal with CCUS)	CCUS	8-9	Canada, China, United States
Post-combustion: solid adsorption (coal with CCUS)	CCUS	6-7	-
Pre-combustion: physical absorption (coal with CCUS)	CCUS	7	China, Japan, United States
Chemical looping combustion (coal)	CCUS	4-5	-
Oxy-fuelling (coal)	CCUS	7	Austria, Denmark, Germany, Italy

Technologies under deployment that may need further adaptation to local contexts

Technology	Technology area	TRL	Examples of countries currently involved
Dry steam (geothermal)	Geothermal	9+	Indonesia, Italy, Japan, United States
Flash process (geothermal)	Geothermal	9+	Nicaragua, Costa Rica, El Salvador, Iceland, Türkiye, Kenya, Japan, New Zealand, Mexico, Indonesia, United States, Philippines
Organic rankine cycle (geothermal)	Geothermal	9+	Croatia, Japan, Nicaragua, Portugal, Germany, Honduras, Chile, Guatemala, Philippines, Costa Rica, Kenya, Indonesia, New Zealand, Türkiye, United States
Hydropower (grid-scale)	Hydropower	9+	Brazil, Canada, China, Ethiopia, India, Norway, the Russian Federation (hereafter “Russia”), United States
Concentrated PV	Solar PV	9+	China, Italy, South Africa, Spain, United States
Crystalline silicon PV	Solar PV	9+	Australia, China, Germany, India, Italy, Japan, Korea, Mexico, Türkiye, United States
Multi-junction cell PV	Solar PV	9	Germany, United States, France, Japan, Spain
Onshore wind	Wind energy	9+	-

Off-grid and mini-grid

Pre-commercial technologies in need of further innovation efforts

Technology	Technology area	TRL	Examples of countries currently involved
Transactive energy	Electricity trade	4	Germany, Colombia, United States
Smart inverter	Power quality	8	

Technologies under deployment that may need further adaptation to local contexts

Technology	Technology area	TRL	Examples of countries currently involved
Redox flow batteries	Electricity storage	9+	Australia, China, South Africa, United States
Flywheel	Electricity storage	9+	Germany, Netherlands, Ireland

Bioenergy and waste

Pre-commercial technologies in need of further innovation efforts

Technology	Technology area	TRL	Examples of countries currently involved
Anaerobic digestion and CO_2 separation with CCUS (biomethane)	BECCS	8	Italy
Biomass gasification and methanation with CCUS (biomethane)	BECCS	5	-
Post-combustion: chemical absorption (biomass with CCUS)	BECCS	6-7	United Kingdom, Japan, Sweden
Post-combustion: solid adsorption (biomass with CCUS)	BECCS	6-7	-
Pre-combustion: physical absorption (biomass with CCUS)	BECCS	3	-
Anaerobic digestion and biological methanation with hydrogen (biomethane)	Biogases	7	Germany, Austria, United States, Denmark
Anaerobic digestion and catalytic methanation with hydrogen (biomethane)	Biogases	8	Germany, United States, China, Switzerland, Netherlands, France, Austria, Japan
Biomass gasification and biological methanation (biomethane)	Biogases	4	-
Biomass gasification and catalytic methanation (biomethane)	Biogases	7	Sweden, United Kingdom, Germany,
Double-cropping (sequential cropping)	Bioresources	5	Finland, Uruguay
Micro-algae and Macro-algae (biogas)	Biogases	3-4	-
Alcohol-to-jet (biodiesel)	Liquid biofuels	7	United States, Japan, Sweden,
Gasification and Fischer-Tropsch with CCUS (biodiesel)	Liquid biofuels	5	-

Technology	Technology area	TRL	Examples of countries currently involved
Gasification and Fischer-Tropsch without CCUS (biodiesel)	Liquid biofuels	7-8	United States, United Kingdom, Japan, France
Gasification and hydrogen enhancement and Fischer-Tropsch (biodiesel)	Liquid biofuels	5	European Union
Hydrothermal liquefaction and upgrading (biodiesel)	Liquid biofuels	4	Denmark
Hydrothermal liquefaction and upgrading of micro-algae (biodiesel)	Liquid biofuels	3-4	-
Hydrotreating (biodiesel)	Liquid biofuels	4	-
Transesterification (biodiesel)	Liquid biofuels	4	Brazil, China, France, India, Japan, Spain, Korea, United States
Pyrolysis and upgrading (biodiesel)	Liquid biofuels	7	-
Synthetic Iso-Paraffins (biodiesel)	Liquid biofuels	7	United States, France
Enzymatic fermentation with CCUS (lignocellulosic bioethanol)	Liquid biofuels	5	-
Enzymatic fermentation without CCUS (lignocellulosic bioethanol)	Liquid biofuels	8	Brazil, United States, Europe
Enzymatic fermentation with CCUS (sugar and starch bioethanol)	Liquid biofuels	8	Canada, United States, United Kingdom, Belgium, Netherlands
Syngas fermentation (bioethanol)	Liquid biofuels	8	-

Technologies under deployment that may need further adaptation to local contexts

Technology	Technology area	TRL	Examples of countries currently involved
Fluidised-bed boiler fueled with biomass (high temperature heating)	Bioenergy combustion	9+	-
Fluidised-bed boiler fuelled with biomass (low temperature heating)	Bioenergy combustion	9+	-
Anaerobic digestion and CO_2 separation without CCUS (biomethane)	Biogases	9+	Germany, France, Sweden, Netherlands, Denmark, United Kingdom, United States, China, Canada
Biomass gasification - small-scale (biomethane)	Biogases	9+	China, Japan, India, Thailand, Germany, Denmark, Sweden
Non-algae feedstock (biogas)	Biogases	9+	-

Technology	Technology area	TRL	Examples of countries currently involved
Fatty acid methyl ester (biodiesel)	Liquid biofuels	9+	Europe, Indonesia, United States, Brazil, Germany, Argentina, France
Hydrogenated vegetable oil / Hydroprocessed esters and fatty acids (biodiesel)	Liquid biofuels	9+	Finland, Singapore, United States, France, Italy, Netherlands, China
Enzymatic fermentation without CCUS (sugar and starch bioethanol)	Liquid biofuels	9+	-

Lighting

Pre-commercial technologies in need of further innovation efforts

Technology	Technology area	TRL	Examples of countries currently involved
Fibre-optic daylighting	Lighting	6	Sweden, United States, Japan
Direct current lighting	Lighting	7	-

Technologies under deployment that may need further adaptation to local contexts

Technology	Technology area	TRL	Examples of countries currently involved
Building orientation for lighting performance	Lighting	9+	-
Advanced lighting control system	Lighting	9+	-
Conventional LED	Lighting	9+	Australia, Canada, China, Denmark, France, Korea, Sweden, United Kingdom, United States, India
Organic LED	Lighting	9+	-
Polymer LED	Lighting	9+	-

Clean cooking

Technologies under deployment that may need further adaptation to local contexts

Technology	Technology area	TRL	Examples of countries currently involved
Bag digester for cooking	Clean cooking	9+	-
Composite material digester for cooking	Clean cooking	9+	-
Onsite-constructed digester for cooking	Clean cooking	9+	-
Improved biomass cooking stove	Clean cooking	9+	-
Electric stove	Clean cooking	9+	-
Induction cooking	Clean cooking	9+	-
LPG stove	Clean cooking	9+	-
Solar cooking	Clean cooking	9+	-

Electric vehicles and mass transit

Pre-commercial technologies in need of further innovation efforts

Technology	Technology area	TRL	Examples of countries currently involved
Battery designed for recycling	Vehicle batteries	5	European Union
Automatic battery recycling	Vehicle batteries	4	-
Cell-to-chassis battery technology	Vehicle batteries	7	-
Li-Air battery	Vehicle batteries	2	-
Li-S battery	Vehicle batteries	4	United States, China, United Kingdom, Korea, European Union
Manganese-rich cathode battery	Vehicle batteries	4	Europe and North America
Medium-high silicon content and silicon anode battery	Vehicle batteries	6-7	United States, Germany

Technology	Technology area	TRL	Examples of countries currently involved
Multivalent ion battery	Vehicle batteries	2	-
Potassium-ion battery	Vehicle batteries	3	-
Solid state + Li-metal battery	Vehicle batteries	5	United States, Japan, Korea and China, European Union
Zinc-manganese oxide battery	Vehicle batteries	4	-
Polymer electrolyte membrane hydrogen fuel cell as range-extender	Electric vehicles	8-9	Japan, Korea, North America
Battery electric truck	Electric vehicles	8-9	China, United States, Germany, France

Technologies under deployment that may need further adaptation to local contexts

Technology	Technology area	TRL	Examples of countries currently involved
Battery electric light commercial vehicle	Electric vehicles	9+	China, Germany, France
Battery electric passenger car	Electric vehicles	9+	China, European Union, United States
Battery electric urban transit bus	Electric vehicles	9+	China
Polymer electrolyte membrane hydrogen fuel cell	Electric vehicles	9+	Japan, Korea, North America
Cell-to-pack battery technology	Vehicle batteries	9+	-
Lithium-ion battery	Vehicle batteries	9+	China, Korea, Sweden, Japan, Finland, United States
Low silicon content graphite anode battery	Vehicle batteries	9+	United States, Germany
Module-to-bracket battery technology	Vehicle batteries	9+	-
Sodium-ion battery	Vehicle batteries	9+	-
Flexible-fuel vehicle/hybrid flexible-fuel vehicle	Hybrid vehicles	9+	Brazil, Japan

Alternative fuels for energy and industrial exports

Pre-commercial technologies in need of further innovation efforts

Technology	Technology area	TRL	Examples of countries currently involved
CO_2 and H_20 co-electrolysis	Hydrogen-based fuels	6	Germany, Norway, Finland, Netherlands, United States
CO_2 reduction	Hydrogen-based fuels	6	Germany, Norway, Netherlands, South Africa
Concentrating solar fuels	Hydrogen-based fuels	4	Spain, Switzerland, Germany
Direct CO_2 to dimethyl ether	Hydrogen-based fuels	3	Netherlands
Biological CO_2 methanation	Hydrogen-based fuels	7	Germany, Denmark, Japan, Switzerland
Chemical methanation	Hydrogen-based fuels	7	Germany, France, Japan
Biomass gasification (ammonia)	Hydrogen-based fuels	5	Sweden
Cryogenic capture (ammonia)	Hydrogen-based fuels	7	New Zealand
Co-firing and mono-firing of ammonia in coal power plants	Hydrogen-based fuels	5	Japan
Co-firing of ammonia in gas-turbines	Hydrogen-based fuels	5	Japan
Ammonia turbine	Hydrogen-based fuels	4	Japan
Co-firing and mono-firing of hydrogen (hydrogen-fired gas turbine)	Hydrogen-based fuels	8	Australia, France, Germany, Italy, Japan, Korea. United States
Aluminum oxidation	Hydrogen production	4	United States
Biomass-waste gasification with CCUS	Hydrogen production	5	United States
Biomass-waste gasification without CCUS	Hydrogen production	6	United States
Biomass-waste pyrolysis	Hydrogen production	6	United States
Chemical looping with CCUS	Hydrogen production	4	United States

Technology	Technology area	TRL	Examples of countries currently involved
High capture rates (coal gasification)	Hydrogen production	5	Australia, China
Anion exchange membrane electrolyser	Hydrogen production	7	Germany, Italy
Solid oxide electrolyser cell	Hydrogen production	8	Denmark, Germany, United States
Seawater electrolysis	Hydrogen production	5	Australia, China, United States
Waste water electrolysis	Hydrogen production	3	-
Catalytic decomposition (methane)	Hydrogen production	7	Australia
Plasma non-thermal decomposition (methane)	Hydrogen production	3	-
Plasma thermal decomposition (methane)	Hydrogen production	8	Germany, United States
Thermal decomposition (methane)	Hydrogen production	3-4	-
Electric-powered steam reforming (methane)	Hydrogen production	4	Denmark, Germany
Sorption enhanced steam reforming with CCUS (methane)	Hydrogen production	4	United Kingdom, United States
High capture rates (steam reforming)	Hydrogen production	5	Canada, Netherlands, Saudi Arabia, United Kingdom, United States
Underground reforming with CCUS	Hydrogen production	5-6	Canada
Natural hydrogen extraction	Hydrogen production	3	Australia, Brazil, Mali, Oman, Spain, United States
Partial oxidation with CCUS	Hydrogen production	6	Netherlands, Middle East
Photobiological water splitting	Hydrogen production	3	-
Photocatalytic water splitting	Hydrogen production	3	-
Nuclear (water splitting)	Hydrogen production	3	Canada, China, Japan, United States
Solar (water splitting)	Hydrogen production	3	Europe
Adsorbents storage	Hydrogen storage and transport	2-3	Austria, France, Germany, Greece, Italy, Morocco, Spain, United Kingdom
Metal hydrides storage	Hydrogen storage and transport	4-5	Australia, Norway, Italy, United States
Aquifer storage	Hydrogen storage and transport	3	France
Depleted gas fields storage	Hydrogen storage and transport	5	Argentina, Austria, Italy, Ireland

Technology	Technology area	TRL	Examples of countries currently involved
Fast-cycling salt cavern storage	Hydrogen storage and transport	5	France
Lined hard rock cavern storage	Hydrogen storage and transport	5	Sweden
Ammonia cracking for transport	Hydrogen storage and transport	4	France, Germany, Saudi Arabia, Singapore, United Arab Emirates
Liquid organic hydrogen carriers	Hydrogen storage and transport	6-7	China, Japan, Germany, Finland, Brunei Darussalam
Hydrogen blending in natural gas network	Hydrogen storage and transport	7	Australia, China, Denmark, Germany, Italy, Netherlands, United Kingdom, United States,
Hydrogen deblending	Hydrogen storage and transport	4	United Kingdom
Hydrogen turbo compressors	Hydrogen storage and transport	6	Japan, Germany, United States
Liquid hydrogen tanker	Hydrogen storage and transport	7	Japan, Korea, France, Netherlands
Repurposed natural gas pipelines	Hydrogen storage and transport	8	Netherlands

Technologies under deployment that may need further adaptation to local contexts

Technology	Technology area	TRL	Examples of countries currently involved
Chemical absorption (ammonia)	Hydrogen-based fuels	9+	Malaysia, Japan, India, United Arab Emirates, Pakistan, Viet Nam, China, United Kingdom, Norway
Partial capture (coal gasification)	Hydrogen production	9+	Australia, China
Alkaline electrolyser	Hydrogen production	9+	China, Denmark, Germany, France, Norway
Polymer electrolyte membrane electrolyser	Hydrogen production	9+	Australia, Germany, Norway, United Kingdom, United States
Partial capture (steam reforming)	Hydrogen production	9+	Canada, Netherlands, Saudi Arabia, United Kingdom, United States
Ammonia storage	Hydrogen-based fuels	9+	Japan, Norway

Technology	Technology area	TRL	Examples of countries currently involved
Liquid hydrogen storage tank	Hydrogen storage and transport	8-9	United States, Japan
Pressure vessel storage	Hydrogen storage and transport	9+	-
Salt cavern storage	Hydrogen storage and transport	9+	United Kingdom, United States, Netherlands, Germany
Hydrogen liquefaction for transport	Hydrogen storage and transport	9+	United States, Japan, Korea, Germany, France
Ammonia tanker transport	Hydrogen storage and transport	9+	Korea, Japan, China
Liquid organic hydrogen carrier tanker	Hydrogen storage and transport	9+	Japan
New hydrogen pipelines	Hydrogen storage and transport	9+	United States, Netherlands, Spain, Germany, China
Truck transport	Hydrogen storage and transport	9+	-

Technologies for which emerging and developing countries are already key players

Emerging market and developing economies already contribute to clean energy technology innovation. In some technology areas it is emerging economies that are leaders in R&D, manufacturing or skills. The CETG includes the following technologies that feature emerging market and developing economies among the key countries for their development or early uptake so far.

Pre-commercial technologies in need of further innovation efforts

Technology	Technology area	TRL	Examples of EMDE countries currently involved
Electrolytic hydrogen-based produced with variable renewables (ammonia)	Hydrogen production	8	Chile, Trinidad and Tobago, Oman, Morocco
Alumina refining through the use of electricity in the Bayer process	Aluminium production	7	Brazil
Alumina refining through the use of high % biomass fuel in the Bayer process	Aluminium production	7	Brazil
Chemical absorption (full capture rates)	Cement production	7	China, India

Technology	Technology area	TRL	Examples of EMDE countries currently involved
Primary smelting with inert anode	Iron and steel production	7	Russia
Based on natural gas with high levels of electrolytic hydrogen blending (DRI)	Iron and steel production	7-8	China, Mexico
Open automated demand response	Power grids	8	India
Partial oxidation with CCUS	Hydrogen production	6	Middle East
Double-cropping (sequential cropping)	Bioresources	5	Uruguay
Depleted gas fields storage	CCUS	5	Argentina
Chemical absorption - Process gas hydrogen enrichment and CO_2 removal for use or storage (blast furnace)	Iron and steel production	5	China, India
Alumina refining through the use of concentrated solar thermal in the Bayer process	Aluminium production	6-7	Saudi Arabia
Primary smelting with CCUS	Iron and steel production	3	Bahrain
Depleted oil and gas reservoir	CCUS	7-8	Saudi Arabia, United Arab Emirates, Indonesia

Technologies under deployment that may need further adaptation to local contexts

Technology	Technology area	TRL	Examples of EMDE countries currently involved
High reflectivity paint	Building envelope	9+	Asia Pacific
CO_2-enhanced oil recovery	CCUS	9+	Brazil, China, United Arab Emirates
CO_2 sequestration in inert carbonate materials (mineralisation)	Cement production	9+	China, Viet Nam
Calcined clay	Cement production	9+	Brazil, Ghana
Pyrolysis recycling	Cement production	9+	Saudi Arabia, Malaysia
Chemical absorption (ammonia)	Chemicals production	9+	Malaysia, India, United Arab Emirates, Pakistan, Viet Nam

Technology	Technology area	TRL	Examples of EMDE countries currently involved
Chemical absorption (methanol)	Chemicals production	9+	Brazil, Bahrain
Redox flow batteries	Electricity storage	9+	China, South Africa
Dry steam (geothermal)	Geothermal	9+	Indonesia
Flash process (geothermal)	Geothermal	9+	Nicaragua, Costa Rica, El Salvador, Kenya, Mexico, Indonesia, Philippines
Organic rankine cycle (geothermal)	Geothermal	9+	Nicaragua, Honduras, Chile, Guatemala, Philippines, Costa Rica, Kenya, Indonesia
High vacuum flat plate collectors heat pump	Heating	9+	United Arab Emirates
Hydropower (gid-scale)	Hydropower	9+	Brazil, China, Ethiopia, India, Russia
Upgraded biomass partially replacing injected coal (blast furnace)	Iron and steel production	9+	Brazil
Chemical absorption for CCUS (DRI)	Iron and steel production	9+	Mexico, United Arab Emirates, Venezuela
Fatty acid methyl ester (biodiesel)	Liquid biofuels	9+	Indonesia, Argentina,
Fermentation (ethylene)	Liquid biofuels	9+	Brazil, India,
Biomass gasification - small-scale (biomethane)	Liquid biofuels	9+	India, Thailand
Large-scale light-water nuclear reactor	Nuclear	9+	China, Russia
Tidal range	Ocean energy	9+	China, Russia
HVDC power transmission	Power grids	9+	Brazil, India
Ultra-High Voltage	Power grids	9+	Brazil, India
Concentrated PV	Solar PV	9+	China, South Africa