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Exploring Technologies for the Clean Energy Transition of Tamil Nadu

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CONTENTS

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HIGHLIGHTS

- Nearly half (49 percent) of Tamil Nadu's (TN's) installed power capacity comes from renewable sources, and its installed renewable energy (RE) capacity is 14 percent of the total installed RE capacity in India. The state is in the process of increasing its renewable capacity (wind: offshore, onshore, repowering; solar; bioenergy) and the usage of technologies such as energy storage and green hydrogen.
- Offshore and onshore wind technologies are at high Technology Readiness Levels (TRLs), have been successfully deployed in other countries, and can be considered for the state.
- Technological advancements have made higher-capacity wind turbines available and repowering beneficial. Thus, repowering is one of the primary considerations for TN.
- Solar photovoltaic (PV) technologies, which are at various stages of development and maturity, have high market potential.
- Many green hydrogen technologies are under development and are currently being tested in laboratories and in practical settings. Similarly, battery energy storage systems (BESS) are also being developed, with the most mature options being commercially deployed. The estimated market size for these technologies is large.
- Bioenergy technologies with high TRLs and supply chains are available, but regulatory support and a focus on community-level plants are required for their further development.

EXECUTIVE SUMMARY

Context

TN is rich in RE, with a large capacity of both existing installations and projects in the pipeline. The state is transitioning to higher shares of RE. The International Energy Agency (IEA) Flagship Report on Energy Technology Perspectives 2020 (IEA 2021a) identifies advances in technology, speed of innovation, and scalability of new technologies as important variables determining the pace of the energy transition. This study provides insights into TN's energy mix and explores suitable technologies that the state can consider for its energy transition. Information on TRLs and many other aspects of different renewable/clean energy options for electricity generation are provided that could be relevant for effecting its energy transition.

About this working paper

This paper explores electricity generation technology options for the sustainable energy transition of TN. Renewable and clean energy options such as wind (onshore, offshore, small wind), solar PV, bioenergy, energy storage, and green hydrogen are selected, considering the available renewable resources in the state and the projected installation or market potential. The paper describes the current landscape of these renewable options in the state by looking at multiple aspects such as installed capacities, targets, technologies used, developments, policies, and barriers. Further, technology innovations and developments that are available now and those that will likely reach maturity over the coming years are reported. Barriers to the adoption of these technologies, along with information on the related stakeholders, are also described.

Key findings

- There is significant market potential for repowering because many of the wind turbines installed during the 1990s are reaching—or are close to reaching—the end of their stipulated lifecycles. To be specific, the immediate repowering potential in TN is 834 megawatts (MW), with a further 3,979 MW by 2027. This repowering can also enhance the overall RE capacity and generation because the replacement wind turbines available today have a higher rating and efficiency. The technologies and supply chains needed to repower onshore wind farms are available.[1] Policies and guidelines that address many of the challenges associated with repowering need to be instituted.
- Offshore wind is another sector with market potential that has high-TRL technologies which have been successfully deployed in other countries. The supply chains still need to be developed for the Indian offshore industry, along with port infrastructure and other requirements. This is considering India's first upcoming tender for a 4 gigawatt (GW) offshore wind project off TN's coast.
- Different solar PV technologies have reached various stages of development, with TRLs ranging from 4 to 10. The market potential for solar PVs is also high considering TN's capacity addition plans (20 GW). The share of monocrystalline is increasing; however, other newer technologies offering higher efficiencies are costly and will likely require policies to promote their installation.
- BESS technologies are already being commercially deployed, and economies of scale are helping drive down costs for the most popular options. The market potential of BESS is expanding, fueled by the rising share of variable RE. A BESS capacity of about 10 gigawatt-hour (GWh) is planned over a period of 10 years in TN.
- Green hydrogen is another fuel that is being considered as a possible alternative energy option. The required technologies are being validated in the laboratory and tested in practical settings. The National Hydrogen Mission is focused on producing 5 million metric tons (MMT) of green hydrogen by 2030. The TRL for the production of green hydrogen through proven technologies such as alkaline and polymer electrolyte membrane electrolyzers is 7–9. Thus, an immediate benefit can be obtained by replacing the existing fossil-fuel-based hydrogen utilized in industries such as fertilizers and refineries with green hydrogen. Incorporating green hydrogen into other hard-to-abate sectors such as steel and cement needs further assessment because the TRLs for these new processes are not high enough and state-level policies and roadmaps are limited or being developed. TN has been selected for setting up green hydrogen valleys for green hydrogen manufacturing and potential supply to suitable industries.
- Bioenergy technologies with high TRLs and supply chains are available, but regulatory support is required. The viability of community plants needs re-investigation in light of the availability of newer technologies, and policies can be developed that focus on this. Additionally, cogeneration power plants with an installed capacity of 90 MW are under way in TN.
- Many of the technologies outlined in this paper are largely proven in the Indian context and are therefore prime candidates for further deployment. However, stakeholder support is essential to facilitate the development of markets and the related ecosystems. Support is also needed to formulate policies and regulations.

Key recommendations

- New capacity additions for wind need to be promoted. Additionally, to better utilize wind resources, more efforts are required to repower older wind farms. Greater clarity is needed on aspects pertaining to repowering such as land and turbine ownership, power evacuation, tariffs, and safe disposal of old wind turbine blades. TN can develop its own repowering policy to promote repowering and address many of the associated challenges.
- To harness the 35 GW of offshore wind potential and facilitate the upcoming offshore activity, the state can upgrade its port infrastructure and promote skill- and capacity-building activities (MNRE n.d.-c). The state can also facilitate offshore-wind-related investments, develop local supply chains and manufacturing facilities, and explore various de-risking mechanisms to bring down the cost of offshore energy.
- To further increase wind capacities and promote decentralized RE generation, the state can increase the share of small wind turbines. Their total potential is estimated at about 4 GW, whereas the current installed capacity is less than 257 kW.
- For companies developing new solar PV technologies, opportunities need to be created to test out products and innovations in a real-world setting. Better training and skilling of the workforce are also needed to provide appropriate installation and maintenance, which is still a challenge. Climate-specific modules that take the climatology of TN into consideration need to be deployed, and certification standards for hot weather conditions can be explored in this regard.
- For the bioenergy sector, the focus should be on improving feed quality, segregation, and community-level plants. Although historically such plants have had limited success for a range of reasons such as feed quality, they need to be explored in light of the newer technologies that are available now.
- Training programs and courses outlining different aspects of energy storage technologies are required to build awareness and skills, and train the labor force needed to install and maintain energy storage systems. This can help the 10 GWh BESS installation planned in the state. Decentralized energy storage options can also be explored for TN.
- Comprehensive studies are required that map the green hydrogen potential, end users, and so on, in the state. More large-scale pilots, infrastructure upgrades, and development are needed to support the green hydrogen ecosystem. Safety concerns regarding the storage and transport of green hydrogen need to be addressed. Greater clarity is required on the procedure for green hydrogen certification, availability of tax relief, and the support mechanisms offered to an industry that plans to adopt green hydrogen.

INTRODUCTION

Rationale

The IEA identifies advances in technology, speed of innovation, and scalability of new technologies as the key determinants of the pace of the energy transition (IEA 2021a). This holds true for India, because the country is scaling up its renewable installations to meet the 500 gigawatts (GW) non-fossil-fuel capacity target by 2030 and generate at least 50 percent of its total energy requirements from renewables by 2030 to achieve its net-zero ambitions (PIB Delhi 2021). The country currently (as of July 2023) has about 185 GW of non-fossil-fuel capacity, which includes 130.3 GW of RE (solar, wind, small hydro, bioenergy), 46.8 GW of large hydro, and 7.5 GW of nuclear (CEA 2023).

This targeted scale-up necessitates an effective integration of emerging and advanced clean energy technologies within India's renewable energy (RE) ecosystem. Indian states are expected to play a key role in this energy transition. This is especially true of the RE-rich states, which is where most of the capacity would be added to meet the targets.

We chose the state of Tamil Nadu (TN) for this working paper due to its leading role in the deployment and production of RE. Further, the state plans to add more renewable capacity. For instance, about 49 percent of TN's installed power capacity is from renewable sources, accounting for about 14 percent of the total installed RE capacity in India (CEA 2023). This review of the renewable technology landscape in the states that are currently leaders in RE generation will prove useful in assessing the RE technology ecosystem that currently prevails across states and help derive valuable insights into where the gaps exist and how they can be plugged.

For this paper, the following clean energy options are considered: wind (onshore, offshore, small wind), solar photovoltaics (PV), bioenergy, energy storage, and green hydrogen. These options were selected considering the state's renewable resource availability (installation potential), current installed capacity, and future market potential, and the state government's priorities. The state has over 134 GW of wind potential, of which only about 10 GW has been utilized. The state is planning to add more capacity through onshore and offshore wind farms and by repowering old wind turbines. Similarly, the state has a solar potential of 260 GW and is planning to add 20 GW of solar by 2030. Bioenergy has been a focus area of the state, and about 12 new bioenergy plants are planned to be added over the coming years. Due to the increased share of variable RE (VRE), energy storage is key for the energy mix of the state, with the 2032 BESS requirement estimated at 2,349 MWh. Hydrogen is an energy vector that is expected to play a crucial role in the energy transition. TN is one of the states identified for setting up green hydrogen valleys for the production and distribution of green hydrogen for both domestic and international markets. The state is expected to play a crucial role in achieving the central government's green hydrogen production targets of 5 MMT by 2030.

Background

TN is the fourth-highest electricity-consuming state in India, with a per capita annual consumption of 1,844 kWh (CEA n.d.), which is nearly 52 percent more than the national average per capita consumption for the year 2019–20. During FY 2021–22, the peak power demand of TN was between 17,000 MW and 17,500 MW, with a daily average consumption of 340 Million Units (MU) (Government of Tamil Nadu 2022a) (1 MU = 1 GWh). As for the state's actual power generation, between April 2021 and February 2022, TN generated 80,384 MU of power against a cumulative annual demand of nearly 112,200 MU (National Power Portal n.d.). The policy notes (Government of Tamil Nadu 2021, 2022a, 2023) released by TN's Department of Energy provide insights into the state's current renewable installed capacities, future renewable targets, and projects in the pipeline. Between April 2021 and February 2022, the state generated over 570,00 MU of thermal power and about 21,000 MU of renewable power (CEA 2022a).

TN has the third-highest installed capacity of renewables in India, which accounts for nearly 49 percent of the total energy mix of the state (see Table 1). Along with Gujarat, TN is a leader in wind power generation, with both states having installed capacities of about 10 GW each, followed by Karnataka, Rajasthan, and Maharashtra with about 5 GW of installations each. Since 2012, TN has also been expanding the share of solar in its RE mix by commissioning large solar farms (Government of Tamil Nadu 2022a). The state aims to add 20 GW of solar-power-generating stations by 2030 and is expected to increase investments in renewables, including solar and wind. The Tamil Nadu Generation & Distribution Corporation Limited (TANGEDCO) signed a memorandum of understanding (MoU) with the Indian Renewable Energy Development Agency (IREDA) in 2021 to use its technical expertise for developing RE projects and for fund raising (Government of Tamil Nadu 2022a). According to an announcement by the Chief Minister of TN in December 2022 (Gautham 2022), the state is expected to achieve net zero ahead of 2070 (the national target). Other RE generation sources being used in the state include biopower, small hydro, and other off-grid renewable installations such as small wind (MNRE 2019). See Table 2 for further details.

Considering the renewable capacity addition planned and the state's ambitions, it is useful to explore the state's current landscape of renewable technologies along with their development trajectory.

Table 1 | **Installed capacity of power utilities in TN (as of July 2022)**

GENERATION MODE	FUEL	INSTALLED CAPACITY (MW)	
Thermal	Coal	12,762.26	15,917.71
	Lignite	1,916.57	
	Gas	1,027.18	
	Diesel	211.70	
Renewable			16,774.92
Hydro			2,178.20
Nuclear			1,448.00
Total			**36,318.83**

Notes: MW = megawatts; TN = Tamil Nadu.

These capacities include allocated shares in joint and central sector utilities. As of July 2023, the state has the following installed capacities: Thermal – 15,813 MW, Renewable – 18,381 MW, Hydro – 2,178 MW, Nuclear – 1,448 MW.

Source: CEA 2022b, 2023.

Table 2 | **Grid-connected RE capacity installed in TN (as of April 2022)**

GENERATION MODE	INSTALLED CAPACITY (MW)
Wind	9,835.4
Solar	5,303.5
Biopower	1,019.1
Small hydro	143.9
Total	**16,301.9**

Notes: MW = megawatts; TN = Tamil Nadu.

As of April 2023, the State has the following installed capacities, Wind – 10067 MW, Solar – 6689 MW, Biopower – 689 MW, Small hydro – 144 MW.

Source: Government of Tamil Nadu 2022a, 2023; MNRE n.d.-a, n.d.-b; CEA 2023.

Literature survey

The purpose of this paper is to give decision-makers in TN an accessible compilation of relevant technologies. A number of publications survey various clean energy technologies and provide information on innovations, market developments, and the role of such technologies in the global energy transition. For example, the report Advancing the Landscape of Clean Energy Innovation (Breakthrough Energy 2019) lists various emerging clean energy and other technologies along with their near, intermediate, and long-term development projections. Besides highlighting other technologies, the report emphasizes the role of BESS technologies in the electricity value chain and the use of hydrogen as a clean energy carrier and storage medium. This report helps understand the various clean energy technologies and future development projections. However, other than the sections that highlight various technologies, which are of general applicability, the rest of the report is focused on the U.S. ecosystem and cannot be directly applied to other regions.

To understand how different renewable technologies and interventions have been used by different countries and regions, along with information on various power sector innovations, the 2019 report by International Renewable Energy Agency (IRENA) titled Innovation Landscape for a Renewable-Powered Future (IRENA 2019) can be studied. The study highlights the broad range of innovations available for accelerating RE deployment and for integrating higher shares of VRE across the world. Real-world examples of the challenges faced and of clean energy interventions and innovations are provided for countries and regions such as Denmark, Ireland, Texas, California, Southern Australia, Uruguay, Germany, and Tasmania. The report also briefly looks at TN and its plans to increase its share of electricity generation from wind and solar, suggesting energy storage as an option to facilitate this goal. The coverage of TN in the report is limited and dated. The various clean technologies options must be explored considering the current scenario in TN with respect to targets, the current levels of technology maturity, and other factors.

One of the parameters used by decision-makers to understand the maturity of a technology is Technology Readiness Levels (TRLs). The report Energy Technologies Perspectives 2020 presents an overview of the TRLs as defined by the IEA (IEA 2021a). The report is also useful for its overview of the clean energy innovations required for a sustainable future and key technologies and approaches—for example, electrification of end-use sectors such as heating and transport; carbon capture, utilization, and storage; low-carbon hydrogen; and hydrogen-derived fuels and bioenergy. The technologies covered are also assigned a range of TRLs. This report is helpful as it outlines the TRL classification scale and TRL ranges of various technologies.

The history, development, and conventions pertaining to TRLs are given in Héder (2017). Here, readiness levels from 1 to 9 are assigned based on the different stages of technological evolution spanning research, development, and deployment. However, the IEA (2021a) uses the extended TRL classification developed by the International Renewable Energy Agency (IRENA) (see Appendix A), where levels are assigned numbers from 1 to 11. The new technologies identified in this research are assigned a TRL level that is decided by the authors after a literature study, stakeholder consultations, and so on. The methodology for this TRL assignment is explained in the next section.

The literature available on the different technologies and innovations in the RE sector provides only general insights and recommendations. There is, however, a need to explore the technologies covered in these reports in the context of TN, which is aiming to expand its renewable capacity by repowering old installations and setting up new installations. The state has high renewable capacities and is planning to add more capacity to meet its renewable targets. Further, older renewable installations, especially wind, are aging and need to be upgraded. The options available to TN for new renewable installations and upgrades need to be explored. Information from the general literature and other reports is combined with the available state-specific literature, expert consultations, and discussions to achieve a TN-specific focus.

CONTEXT, SCOPE, RESEARCH QUESTIONS, AND METHODOLOGY

Context and scope

TN is rich in RE, with existing installations having a large capacity and projects in the pipeline. The state has prioritized the transition to higher shares of RE. Moreover, older renewable installations, especially wind, are aging and need to be upgraded. From the literature, it is seen that advances in technology, speed of innovation, and scalability of new technologies are important variables that determine the pace of the energy transition. Hence, different renewable and clean energy electricity generation technologies must be explored to achieve a sustainable energy transition in TN. Options such as wind (onshore, offshore, small wind), solar PV, bioenergy, energy storage, and green hydrogen have been selected considering the available renewable resources in the state and the projected installation or market potential. Technology developments and innovations the state can consider must be examined in light of its current electricity generation landscape. The literature that policymakers in the state can consult for a comprehensive coverage of these aspects of TN is limited. Our compilation of this information, as presented here, will be useful to stakeholders.

This paper describes the current landscape of renewable options in the state, such as wind (onshore, offshore, small wind), solar PV, bioenergy, energy storage, and green hydrogen, by examining installed capacities, targets, technologies used, developments, policies, and barriers. Other aspects such as the overall potential, the availability of domestic production and supply chains, and estimation studies are reported. Further, technological innovations and developments that are available now and those that will likely reach maturity over the coming years are described along with the associated TRLs. Information is also provided on the problems and challenges related to the adoption of these technologies. A stakeholder mapping is also provided because stakeholder interventions at multiple stages of technological development and implementation are key for a successful and timely deployment.

Research questions

This paper addresses the following questions:

- What is the current landscape of renewable options in the state, such as wind (onshore, offshore, small wind), solar PV, bioenergy, energy storage, and green hydrogen?
- What are the available and upcoming technologies and developments for the renewable options mentioned above that TN can consider for its energy transition, and what are the associated TRLs?
- What are some of the main problems related to the adoption of these technologies?

Methodology

The methodology followed for the research is as follows:

- The latest available data on the energy mix of the state and its RE installations—wind (onshore, offshore, small wind), solar PV, and bioenergy—are collated. Further, the developments in energy storage and green hydrogen are noted. This information was gathered from the TN energy department policy notes, reports, other industry publications, and the academic literature on these topics. This review of the literature is complemented with stakeholder convenings and expert discussions, individually and through webinars. These discussions and convenings included individuals from government, academia, think tanks, industrial associations, and companies working in the domain.
- The information collected is used to provide an overview of the current clean energy landscape of TN by outlining the installed capacities, targets, technologies used, developments, and policies pertaining to each of the renewable/clean energy options considered. This information is summarized in the section titled "The current clean energy landscape in Tamil Nadu: Capacities, targets, potential, technologies, policies, and problems."
- Information on new technological developments, innovations (for the renewable/clean energy options considered), and the associated technology maturity is collated from the literature, stakeholder convenings, and expert discussions. This information is summarized in the section titled "Available and upcoming technology developments for TN."
- Information on barriers to the adoption of technologies is collected from stakeholders and from the available literature. This information is summarized in the section titled "Available and upcoming technology developments for TN."
- The information is then analyzed, and conclusions are provided in the section titled "Conclusion."
- The key findings and recommendations are highlighted in the Executive Summary.

THE CURRENT CLEAN ENERGY LANDSCAPE IN TAMIL NADU: CAPACITIES, TARGETS, POTENTIAL, TECHNOLOGIES, POLICIES, AND PROBLEMS

Wind energy

Capacities, targets, potential, and technology

India has about 44 GW of installed wind energy capacity (CEA 2023). The central government aims to achieve 100–140 GW of wind energy by 2030, of which 30 GW is expected to be offshore. A recent strategy paper on the establishment of offshore wind energy projects by the MNRE specifies an auction trajectory for achieving 37 GW by 2030 (MNRE 2022).

Among Indian states, TN has one of the highest installed wind energy capacities (10 GW) due to its favorable geography, facilitative policies, and early adoption. India's largest wind farm, with a capacity of 1.5 GW, is located at Muppandal in Kanyakumari district of TN. The state is planning interventions in the wind energy sector; toward this end, it is evaluating offshore wind, repowering older machines, and installing new wind turbines (on land). Most of the turbines installed in the early 1990s have unit capacities ranging between 90 kW and 225 kW, with hub heights of 25–30 m (IDAM 2018). By the mid-1990s, larger capacity units of about 500 kW were installed. The hub heights and supporting structures were consequently increased in size to accommodate the larger blades. Land-based wind turbines installed today are usually in the range of 2–3 MW with hub heights of about 100 m.

TN also ranks third in India in installed small wind turbine (SWT) capacity (MNRE 2019). SWTs are wind turbines with a rated capacity of less than about 50 kW (Wood 2013). They usually operate as decentralized units and are installed close to locations that need power. They are used mainly for electricity generation and water pumping for agriculture in urban, rural, and coastal applications (Kajol and Suresh Kumar 2021b). The certified units in India have rated capacities between 500 W and 10 kW (CECL 2020). SWTs could be deployed far more widely. As of 2017, India had only about 3.7 MW of small wind capacity, of which TN had an installation base of 257 kW (small wind+ small wind hybrids) (MNRE 2019). This is despite the presence of large swaths of windy areas in TN. Recent studies point to the small wind potential of the state being as high as 4 GW (Kumar et al. 2022).

The estimated potential of offshore winds along the coasts of TN is about 35 GW (from fixed platforms) (MNRE n.d.-c). Progress in the deployment of offshore wind has, however, been very slow. The Facilitating Offshore Wind in India (FOWIND) prefeasibility report of 2015 (FOWIND 2015) and the complete feasibility study of 2018 (FOWIND 2018) forecasted the following potential for offshore wind power in TN. This, however, remains largely untapped. Table 3 summarizes this potential.

Table 3 | **TN wind energy profile**

WIND ENERGY IN TAMIL NADU	CURRENT INSTALLED CAPACITY (GW)	FORECASTED POTENTIAL (GW)[a]
Onshore wind	10	95
Offshore wind	0	35
Small wind	Negligible (257 kW)	4
Total	**10**	**134**

Notes: a. Technical potential.

Sources: Kumar et al. 2022; MNRE n.d.-c ; NIWE 2023.

Policies, developments, and problems

In the domain of wind energy policies, TN is yet to implement a policy for repowering wind power projects that was released by the MNRE in 2016 (MNRE 2016) at a large scale. The central policy was aimed at creating a facilitative framework for repowering old wind generators with a capacity of 1 MW or less, and state nodal agencies were designated as the implementors of the policy. Subsequently, TANGEDCO had submitted a petition to the Tamil Nadu Electricity Regulatory Commission (TNERC) for repowering old generators, in line with the MNRE guidelines. However, TNERC clarified that it would not make repowering mandatory for the wind power generators (TNERC 2021), considering the fact that the MNRE policy was mainly aimed at providing information to stakeholders and was optional; the state lacked its own repowering policy; and other related factors. Recent media reports suggest that the state is in the process of developing its own repowering policy (The Hindu Bureau 2023).

This decision is complicated by the twin problems of fragmented land and multiple turbine ownership. When the wind farm land is owned by multiple parties, it becomes difficult for all those involved to reach a consensus on repowering (Kajol and Suresh Kumar 2021a). When the lands and turbines have different owners, costs and revenue sharing become a challenge. Besides, any kind of repowering would require the upgrading of existing grid infrastructure to make it capable of handling large amounts of generated power (Kajol and Suresh Kumar 2021a). Currently, TN is in the process of repowering the 110 state-owned older wind generators (of capacity 17.5 MW) with new turbines to arrive at a repowered capacity of 41.5 MW. Up to now, repowering has been carried out on 47 old privately owned wind generators, which were replaced by 36 new machines having a capacity of 13.2 MW (Government of Tamil Nadu 2022a).

The state has about 1.7 GW of turbines with capacities of 500 kW or below with another 2.3 GW of turbines with capacities between 500 kW and 1,000 kW (Idam 2018). The older models (Martino 2014), however, are not at par with the current standards of the wind energy industry and do not incorporate recent advances in areas such as rotors, controls, electronics, and gearboxes, resulting in low-capacity utilization factors (CUF) of about 10–14 percent and low availability of wind power across the state. The repowering study by Idam (2018) calculated the total repowering potential in TN as 834 MW, which is expected to rise to 3,979 MW by 2027.

Some of the problems faced by large wind farms (utility scale) in TN concern the variable nature of power scheduling. Power scheduling is the process of planning physical power flows to maintain a balance between demand and supply. Reasons for the low uptake of SWTs in the state include complexities in the installation process, difficulties in maintenance, the lack of skilled technicians, and the unavailability of comprehensive resource mapping. Another factor affecting the uptake of SWTs is the need for favorable business models and policy frameworks.

Solar energy

Capacities, targets, potential, and technology

The installed capacity of PV in India is about 71 GW. Within this, TN has an installed capacity of 6.6 GW of solar energy as of April 2023. The state is well equipped for tapping solar energy due to its reasonably high insolation figures (5.6–6.0 kWh/m2) and clear sunny days (Government of Tamil Nadu 2012). Insolation is the actual amount of solar radiation incident upon a unit horizontal surface over a specified time for a given locality. Annually, there are about 300 clear days, which amounts to about 3,000 hours of sunshine. Cognizant of this abundant resource, TN is increasing the share of solar in its renewable mix, mainly through utility-scale solar farms. Table 4 summarizes the current solar energy profile of the state.

Table 4 | **TN solar energy profile**

PROFILE	
Current solar installed capacity	6.6 GW
Estimated solar potential	259.7 GW[a]

Notes: a. Technical potential.

Sources: Government of Tamil Nadu 2013, 2023; WISE 2012.

Policies, developments, and issues

Utility-scale solar projects in the state were initiated, for the first time, after the release of the TN solar energy policy in 2012. Up to 2012, the solar capacity of TN was limited to 10 MW from rooftop installations that were promoted as part of the Small Solar Power Generation Programme (RPSSGP) scheme. The TN Solar Policy of 2019 (Government of Tamil Nadu 2019) sets a combined solar target of 9 GW of solar energy capacity by 2023. The policy also envisions the creation of green jobs and a single window system for support and cooperation between government departments to facilitate processing, approvals, and clearances for setting up a business. Further, the policy aims to encourage public-private partnerships and joint ventures in solar energy projects, manufacturing of PV and other components, and research and development on new and innovative technologies.

In this regard, the Government of Tamil Nadu has also announced plans to provide land for the development of solar system component manufacturing and set up a solar energy research fund to support research in the solar energy sector. Companies such as First Solar, Tata Power, and so on, are in the process of setting up solar PV cell and module manufacturing plants in TN. This is expected to create green jobs (Power Technology 2022) as envisioned by the state's solar policy and promote self-sufficiency in the long run.

The state has been unable to reach its annual targets for combined solar capacity addition. Land availability and land acquisition for setting up utility-scale projects is a challenge. Although the contribution from decentralized renewable energy (DRE) to the total installed capacity is limited, distributed renewables are an important aspect of the energy transition. The lack of uptake of DRE projects across the state is also a concern (Guruvanmikanathan 2022). DRE has not received the required support in terms of policies and regulations, even with the 2022 MNRE Framework for the promotion of decentralized RE for livelihood applications (MNRE 2022). Distribution companies are not in favor of DRE, because they are of the opinion that it can adversely affect the stability of the grid due to the injection of variable energy into the grid at multiple points. DRE can be explored under different categories; for example, DRE from the livelihood perspective and DRE for urban residential households, where, in addition to a positive environmental impact, an additional income generation benefit is gained because energy is added to the grid (MNRE 2022).

In TN, the use of rooftop solar installations has been suffering from the non-availability of net meters (bidirectional meters), leaving several plants in an idle state for months (Prabhakar 2019). Net meters are bidirectional meters that are used for net metering; that is, to track the difference in energy supplied to and consumed from the grid. Rooftop solar installations are also promoted under the net-metering scheme, providing an opportunity for consumers to reduce their electricity bill or earn an income by supplying energy to the grid.

Bioenergy

Capacities, targets, potential, and technology

Bioenergy is important, given that the availability of biomass in India is estimated at 750 MMT yearly. Recent studies estimate the surplus biomass availability at 230 MMT from agriculture residues, which corresponds to a potential of 28 GW (ASCI 2021; MNRE n.d.-a). Other benefits include reducing the dependence on crude oil imports (biofuels being a substitute) and effective utilization of available agricultural by-products. Large-scale bioenergy technologies include biomass power plants and cogeneration units (non-bagasse and bagasse together). The total bioenergy capacity in India is about 10 GW, of which 1.8 GW is derived from biomass by independent power producers and the remaining 8.3 GW from bagasse-based cogeneration units. A cogeneration facility is defined as one that simultaneously produces two forms of useful energy such as electric power and steam, electric power, and shaft (mechanical) power.

As of April 2023, TN had 688.64 MW of installed bioenergy, of which 164.84 MW was from biomass combustion plants and the remaining 523.80 MW from bagasse-based cogeneration plants. The main feedstock used in these biogas plants includes bagasse and organic manure. Biogas plants in industries, mainly for captive consumption, utilize specific input material and technologies depending on the industrial by-products. The biomass power potential for the state is estimated at 1,560.08 MW (ASCI 2021).

The bioenergy program is being implemented in the state with the main objective of "promoting technologies for the optimum utilization of the state's biomass resources for grid power generation and captive power production" (TEDA n.d.). TN has grid-connected biomass gasifiers and several grid-connected waste-to-energy plants. Biomass gasifiers are used to produce thermal energy for meeting the requirements of various industries, such as "rice mills, jaggery, textile and dying, tiles, steel and other industries." These are also used for generating grid-interactive and off-grid power (TEDA n.d.).

Policy, developments, and problems

In 2011–12, the MNRE and Tamil Nadu Energy Development Agency (TEDA) developed programs to encourage bioenergy plants and provide subsidies to install biogas-based power generation systems. About 6.65 MW of waste-to-energy plants were established under this program. In 2018, the Compressed Bio-Gas Scheme (CBG) was launched, and it was estimated that from the existing waste and biomass sources, TN can utilize about 2.4 million metric tons per annum (MMTPA). In addition to the above, media reports indicate that about 600 plants are planned to be installed across the state with an investment of about Rs. 210 billion and a direct employment potential of about 10,000 (PIB Delhi 2020). A 15 tons[2] per day (TPD) capacity biogas plant at Namakkal and another in Salem were inaugurated in 2020 to provide green fuel to two industries and for transport purposes. The state has about 12 cogeneration projects in the pipeline that can add 120.11 MW of power that is exportable to the power grid (Government of Tamil Nadu 2022a). Six cogeneration plants have been commissioned with an installed capacity of 93 MW, and work on the remaining six is under way.

Bioenergy projects have been explored and implemented since the 1990s; however, the overall progress on scaling and replication has been slow due to several challenges. The major constraints have been the variable composition of the feedstock (input), high cost of installations and inadequate subsidies, the need for larger investments, institutional coordination, and environmental challenges, all of which need to be addressed at the policy level. The processing and logistics costs are significantly high, considering the heat content is low. However, transportation of any kind beyond 50 km becomes unviable for a 10–15 MW power plant.

Energy storage

Capacities, targets, potential, and technology

Energy storage is crucial to expand RE in India and mitigate some of the challenges involved. Implementing energy storage systems is seen as a solution for grids with a high share of VRE. It is seen as a solution that offers stability and balance to the grid. Studies estimate the 2027 BESS requirement for India at 240 MU (ISGF 2019). The grid-level energy storage technology in use so far has been pumped hydro. Here, excess energy is used to run pumps that move water from a lower to a higher elevation. When energy is needed, the system operates like a hydropower plant. Of the 90 GW of pumped storage hydropower (PSH) potential available in the country, only 4.8 GW is ready for storage. The main operational PSH station in TN is located at Kadamparai (400 MW), with Kundah (125 MW) likely to be commissioned by the end of 2023. The major challenges to setting up PSH stations include high costs, long lead times and gestation periods, and limits on where they can be located. They typically require large areas of land and cause adverse environmental impacts such as deforestation and loss of biodiversity. PSH technologies are well understood, and innovations and new developments that need to be discussed are limited. For these reasons, PSH and similar mechanical storage options are not considered in this study.

Another form of storage technology such as large-scale grid-connected battery energy storage systems (BESS) is currently not widely deployed in TN because it is still not cost competitive. Projections estimate a requirement of about 1.3 GW/1.9 GWh of BESS by 2025 (Sundararagavan et al. 2021). Decreased battery costs and advances in battery technology offer an opportunity to encourage the use of large-scale battery-based storage options for the grid (Gupta 2021). TN, with its major share of VRE, is a prime location for implementing this technology. The BESS estimation for TN is given in Table 5.

Another emerging possibility is the use of secondary energy carriers such as hydrogen for energy storage (MNRE 2023). Hydrogen manufactured by using RE is termed green hydrogen and is important as an energy storage medium. Studies that estimate the green hydrogen storage potential in TN are limited. However, a study by TERI suggests that seasonal storage would be feasible and cost competitive by 2040.

Table 5 | **Future battery energy storage estimations for TN**

	2027	2032
Annual energy estimate (MU)	244,703	337,491
Recommended storage (MWh)		
Battery: low volt	1,290	1,785
Battery: medium volt	451	564
Total	**1,741**	**2,349**
BESS required as a percentage of the annual energy estimate (%)	0.7	0.7

Notes: BESS = battery energy storage systems; MU = Million Units; MWh = megawatt-hour.

Source: ISGF 2019.

Policy, developments, and problems

In March 2022, the Ministry of Power had issued guidelines for the procurement and utilization of BESS as part of generation, transmission, and distribution. Media reports suggest that the central government is in the process of developing a production-linked incentive scheme to encourage the setting up of grid-scale battery storage systems (Baruah and Narayanan 2023). TN is in the process of installing 10,000 MWh of BESS over the period of 10 years, with 2,000 MWh of BESS being implemented during the first phase. Recently, TNERC permitted a Dindigul-based company to install a 4 MWh BESS system coupled to a solar project for captive consumption. The state is also in the process of amending its RE purchase obligation regulations to include energy storage. The shortage of batteries for storage due to a global surge in demand also remains a problem for TANGEDCO. The lack of policy frameworks and regulations to integrate energy storage is also a challenge.

Hydrogen energy: Green hydrogen

Capacities, targets, potential, and technology

In India, the share of hydrogen in the energy market is expected to increase. The implementation of fuel cell systems and demonstration projects along with the increasing demand for green fuels are the likely contributing factors. Hydrogen is seen as strong contender to decarbonize the economy. As of now, most of the hydrogen used is derived primarily through steam reforming in large chemical industries. Currently, green hydrogen production or storage facilities are being developed. In January 2023, the cabinet approved the National Green Hydrogen Mission, which targets an annual production of 5 MMT of green hydrogen by 2030. In a recent budget order, INR 197 billion was allocated to the mission to achieve this target. Various efforts are under way to set up pilot green hydrogen plants and green hydrogen–natural gas blending units by various entities such as Oil and Natural Gas Corporation (ONGC), NTPC, and Gas Authority of India Limited (GAIL). On April 2022, Oil India commissioned its first 99.99 percent pure green hydrogen production plant in Assam. The plant is expected to produce 10 kg/day of hydrogen, utilizing 500 kW of solar power and 100 kW alkaline electrolyzer. Apart from focusing on green hydrogen production for existing industrial usage and fuel substitution, efforts are also being made to set up a green-hydrogen-based pilot micro-grid in the Ladakh region.

Policy, developments, and problems

In India, work on hydrogen energy was initiated with the National Hydrogen Energy Board in 2003, which comprised high-level representatives from the government, industry, research institutions, and academia. The objective of the committee was to develop a roadmap for the deployment of hydrogen fuel and identify solutions to utilize hydrogen energy to solve the country's energy security problems sustainably.

The National Green Hydrogen Policy was notified by the Ministry of Power in February 2022. The policy provides guidelines on securing open access, 30 days of power banking provision, a waiver of interstate transmission charges, and renewable purchase obligations (RPO) benefits for green hydrogen/ammonia producers. Later, in April 2022, the MNRE included the steel sector as a stakeholder in the Green Hydrogen Mission to explore the opportunity of using hydrogen as a fuel replacement of natural gas for direct reduced iron (DRI) production. This can also help scale up the demand for green hydrogen. The TN government has also announced plans to develop a hydrogen policy for the state, with the aim of developing both the green and blue hydrogen sectors (PTI 2022).

Facilities for manufacturing green hydrogen are being developed in the state. BGR Energy Systems, along with Fusion Fuel Energy, is planning to set up a facility near Cuddalore to generate green hydrogen from solar power (Djunistic 2021). The green hydrogen would then be supplied as a feedstock (input material) to the chemical and fertilizer industries. Similarly, Amplus Solar, the Petronas group, and ACME Green Hydrogen and Chemicals Pvt. Ltd. signed an MoU with the TN government during the state investment drive held in July 2022 for setting up green hydrogen and ammonia plants (Goswami 2022; Government of Tamil Nadu 2022b).

Many of the technologies for manufacturing, storing, and transporting green hydrogen are in the early stages of development, and currently its price is too high for it to be a viable alternative to other sources of hydrogen.

Renewable technologies landscape summary

Wind energy: Central policies for developing offshore wind and repowering have been formulated, but the state is yet to formulate policies for them. Studies that map the wind resources potential, both onshore and offshore, have been done. However, only a few studies have mapped the small wind potential. The previous central scheme for the promotion of small wind energy was not renewed after 2017. The state is in the process of repowering many of the state-owned turbines. A domestic manufacturing base and supply chain for onshore wind turbines exists; however, it is limited to offshore and small wind.

Solar energy: National and state policies have been formulated for promoting solar installations. The state is in the process of adding about 20 GW of solar capacity. Studies have been done that map the solar potential and irradiation of the state. Domestic supply chains and manufacturing facilities are being developed.

Bioenergy: Multiple central policies and schemes support bioenergy installations and offer financial assistance for setting up bioenergy projects. TN has schemes in place, and recently the state has launched the Ethanol Blending Policy with the aim of further utilizing existing mills and diversifying to dual feedstock. Detailed studies that map out the potential in the country are available. Technology providers and domestic supply chains are available. Stakeholders are of the opinion that policy interventions are required for promoting smaller community-level plants.

Energy storage: The estimated growth for BESS systems is large. Supply chains and domestic manufacturing capacity exist for the well-established technologies. Reports are also available that estimate the upcoming energy storage requirements of the country and the state. Specific policies can help increase the uptake.

Green hydrogen: Central policies and targets are in place, and TN is also developing its own policy. It is in the process of setting up green hydrogen manufacturing projects. Due to the novel technology, manufacturing facilities and domestic supply chains are limited, and the infrastructure needs to be developed. Only a few studies have comprehensively mapped the green hydrogen sector and its potential in TN.

A summary of the main points discussed above and in the previous section is provided in Table 6.

Table 6 | **Summary of the current clean energy landscape of TN**

CLEAN ENERGY TECHNOLOGY	INSTALLATION OR PRODUCTION TARGETS (STATE LEVEL)	PROJECTS (BEING DEVELOPED OR IN THE PIPELINE)	EXISTING POLICIES/ SCHEMES (STATE LEVEL)	STUDIES/REPORTS THAT MAP INSTALLATION POTENTIAL/ SUITABLE AREAS	DOMESTIC PRODUCTION FACILITIES AND SUPPLY CHAINS FOR STATE CAPACITY ADDITIONS	ESTIMATED MARKET SIZE AND GROWTH POTENTIAL
Wind						
Onshore	Yes	Yes	Yes	Yes	Yes	Medium
Onshore (repowering)	Yes	Yes	No[b]	Yes	Yes	Medium
Offshore	Yes[a]	No[a]	No	Yes	Limited	High
Small wind	No	No	No	Yes	Limited	Low
Solar	Yes	Yes	Yes	Yes	Limited	High
Bioenergy	Yes	Yes	Limited	Yes	Yes	Medium
Energy storage	Limited	Yes	No	Yes	Limited	High
Green hydrogen	Limited	Yes	No[b]	Limited	Limited	High

Notes: a. Tender for 4 GW offshore wind to be released shortly. b. Policy being developed by the state.

Source: The literature and stakeholder consultations.

AVAILABLE AND UPCOMING TECHNOLOGY DEVELOPMENTS FOR TN

The details of each of the renewable and clean energy technologies outlined in this working paper are provided in Appendix C, such as their classifications, specifications, and technical parameters. Technologies of significance to TN along with their key aspects are described in the following subsections.

Wind technology

Presently, the market is shifting toward the use of high-capacity wind turbines with longer blades, higher hub heights, and benchmark technologies, considering the lower per unit cost of energy generated. These technologies are mainly applicable to onshore, offshore, and SWTs. The major technology developments in the wind sector and their advantages are described in Appendix B.

Onshore wind

TN has 95 GW of onshore wind potential and has formulated plans for adding more capacity and repowering; therefore, examining the technologies, innovations, and developments in the sector could prove immensely useful. As discussed in the previous section, TN's wind energy sector suffers from a lack of repowering. Repowering can improve the CUFs to 25–30 percent and increase the RE capacity of the state. Considering this, the advanced machines discussed above are the ideal candidates because they can economically enhance the power generation from the same land area using fewer machines. Additional features such as low voltage ride through and reactive control can also help stabilize the grid.

Offshore wind

The offshore wind energy sector is expected to grow, with the initial projects being planned off the coast of TN aiming to harness a potential of 35 GW. High and constant wind speed offshore gives offshore wind a higher plant load factor than land-based wind energy. Land-based turbines differ from offshore wind turbines in terms of the technologies used for their foundation and support structures. Although the advances made in blade design and the generator technology used in land-based turbines can be largely replicated for the offshore sector, the foundational and related aspects draw inspiration from the oil and gas industry and depend mostly on the depth of water. Offshore wind turbines tend to be larger in terms of capacity, with matching rotor diameters and hub heights. They are also designed with greater strength and durability to withstand harsh offshore conditions and have lower maintenance requirements. For the initial offshore wind projects, fixed platforms can be utilized due to the lower water depths at the locations where the projects are being planned. For deeper waters (50–1,000 m), floating platforms can be considered. Details on the different types of offshore wind platform are provided in Appendix B.

Small wind

Preliminary studies estimate the small wind potential in TN to be about 4 GW. The total installed capacity of SWTs in India in the year 2018–19 stood at 3.34 MW, of which TN had an installed capacity of 257 kW. Considering the favorable geographical location of the state and its reasonable wind resources, TN becomes a suitable candidate for the installation of SWTs (Kajol and Kumar 2021b), which have rated capacities within about 50 kW. Various designs and models of SWTs can be considered depending on the applications. Horizontal-axis SWTs can be considered for industrial applications, telecom towers, and small wind farms sited in large open areas, whereas vertical-axis SWTs and other innovative designs can be considered for rooftop and other space-constrained applications. The general aspects of SWTs are described in Appendix B.

Solar PV technologies

Solar energy technology systems broadly cover a wide range of technologies such as PV, concentrating solar power (CSP), and solar heating and cooling (SHC) technologies. The focus of this report, however, is limited to PV, because the planned capacity additions of the state primarily focus on solar PVs. The different types of PV cells and their classification are described in Appendix B.

Utility-scale solar farms in the TN primarily use first-generation technologies that offer efficiencies in the range of 14–18 percent and a land area of 3–5 acres per megawatt capacity of solar power (Government of Tamil Nadu 2012). Although more advanced technologies are available in the market, the large-scale manufacturing and incremental improvements associated with silicon-based technologies have led to a considerable drop in costs, leading to wider adoption. Among these technologies, the costs of monocrystalline modules have been dropping and are competitive with those of multicrystalline cells. Because monocrystalline cells are also more efficient than multicrystalline cells, they can be the preferred choice moving forward. It is likely that more recent projects, such as the Kamuthi Solar Power Project in Ramanathapuram district, commissioned in March 2017, utilizes solar cells with the same silicon-based technologies but with higher efficiencies than before (18–24 percent).

During discussions, experts pointed out that climate is an important factor in the degradation of modules, and hot climatic zones result in higher degradation and crack formation. Hence, climate-specific modules need to be deployed that take into consideration the climatology of TN. Internationally available modules and certification standards for hot conditions can be explored in this regard. Modules need to be checked for quality during manufacturing, upon arrival, after installation, and periodically during their operational life. This checking can help detect any manufacturing imperfections and degradation. These points regarding the use of climate-specific modules and quality checks can be considered while planning and executing solar projects in TN.

Grid integration remains significant for the large-scale uptake of solar power, and considerable advances have been made in technologies and solutions that help integrate solar PV into the grid. A summary of these technologies is provided in Appendix B. These technologies are readily available for supporting RE integration with the grid and need to be considered for large-scale solar farms.

Bioenergy

Bioenergy is a source of RE that is derived from plant- and algae-based organic matter (biomass) such as crop waste, forest residue, purpose-grown grasses, woody energy crops, microalgae, urban wood waste, and food waste (Office of Energy Efficiency & Renewable Energy n.d.). Heat and electricity can be generated from biomass directly through burning or bacterial decay. It can also be used after conversion to oil or gas substitutes and liquid biofuels. Liquid biofuels such as biodiesel and ethanol are commonly used transportation biofuels with lower carbon intensities. The various bioenergy generation technologies and processes are outlined in Appendix B. The different technologies available for bioenergy generation from different feedstocks need to be considered for community-level plants.

One of the advances in bioenergy technologies explores its uses as an energy carrier and for storing energy. The advances leverage the fact that bioenergy can be taken through various intermediates and processes to arrive at many different energy carriers. These carriers offer flexibilities such as short- and long-term energy storage, which can help integrate larger shares of VRE. Technologies are being developed that allow greater flexibility for bioenergy generation to operate in conjunction with other renewables such as wind and solar. This flexibility can be spatial and temporal or related to feedstock, operation, and end products. An explanation of this technology is provided in Appendix B. These technologies can be considered for the further bioenergy capacity additions the state has planned. Bioenergy technologies for energy storage and flexibility can be explored to manage the higher VRE that is expected to come into the grid.

Energy storage

The available technologies used for energy storage can be broadly classified into five different categories: mechanical, electrochemical, thermal, electrical, and chemical. Apart from electrochemical storage, most of the other options are still in the early stages of R&D or are currently too expensive for large-scale implementation. Appendix B provides an overview of the different types of options available under these categories and their principle of operation.

Multiple storage technologies are available in the market for commercial applications, and they can be explored for driving the energy transition in TN. Mechanical energy storage technologies such as PSH are already being used in the state. BESS technologies with higher maturity can be considered for grid-scale storage.

Decentralized energy storage options can also be explored for TN. Here, storage systems are installed at or near the point of consumption and are designed considering the energy demand profile of the end user. The end user can be an individual, community, commercial complex, and so on. The system is charged and discharged based on the availability and price of energy, and can be tailored to individual requirements. For example, the Indian Institute of Technology (IIT) Madras Research Park is a 110,000-square-meter commercial complex with an average daily electricity usage of 40 MWh. The complex has a 1 MW rooftop solar facility and is developing a wind and solar captive capacity of 4.1 MW to increase its renewable consumption to 90 percent. To facilitate this, the research park is developing a 2 MWh, 750 V DC Li-ion BESS system and a 2.45 MWh chilled-water storage system. This is expected to reduce the overall cost of energy and increase the share of renewables in the total energy consumption (Jhunjhunwala et. al 2022).

Hydrogen energy: Green hydrogen

Hydrogen, being an energy vector, is seen as an alternative that can be used for the storage and transport of energy. The hydrogen generated from certain renewable sources is termed green hydrogen. This hydrogen can then be directly used as a fuel for transportation or for other industries that require hydrogen as an input material. It can also be used in a fuel cell to generate electricity.[3] Globally, about 95 percent of hydrogen is produced through fossil fuels (which is unsustainable) and subsequently utilized primarily in the fertilizer and refinery segments. Hydrogen produced through steam methane reforming emits about 8–12 kg of CO_2 per kg (Cho et al. 2022). Hydrogen can also be produced from RE sources, in mainly two ways: The primary method utilizes biogas, a gaseous form of methane obtained from biomass; the secondary method uses electrolysis, which utilizes energy generated from renewable sources. This generated hydrogen is then termed green hydrogen. Details of the different methods of producing hydrogen are given in Appendix B. As of 2021, about 94 MT of hydrogen was produced globally (ETC 2018; IEA 2022), whereas achieving a zero-carbon economy requires global hydrogen production (either blue or green) to reach 425–650 MT by 2050 (ETC 2018).

Green hydrogen complements other renewable sources such as wind and solar by providing an effective mechanism for long-term and/or seasonal electricity storage at competitive costs. Green-hydrogen-based energy solutions can also solve the problem of storage and long-distance transport of RE. Green hydrogen can also offer solutions for decarbonizing otherwise difficult and intractable sectors such as freight, transport, shipping, chemicals, and iron and steel. Several pilot/demonstration projects have also explored green hydrogen as a fuel source for passenger and commercial vehicles with electric motors or internal combustion engines. This is significant for Tamil Nadu because it has industries such as cement and chemicals. The state also has a high share of VRE and is planning to add more wind and solar into the energy mix, necessitating energy storage options. Green hydrogen can be stored in liquid, gaseous, or solid form. The available storage options include liquid hydrogen, compressed hydrogen, geological storage, and material-based storage.

TRLs

The TRLs for many of the technological advances outlined above and in Appendix B are tabulated in Table 7.

Wind energy: Wind energy technologies are at high levels of technology maturity, where many of the solutions are commercial and competitive, requiring integration at scale to reach predictable stable growth. Certain floating offshore wind technologies are also seen to be at the commercial demonstration stage.

Solar energy: High technology maturity is observed for the most popular of solar PV technologies such as monocrystalline and multicrystalline technologies. Thin film PVs, although at a lower level of technological maturity, are undergoing commercial demonstrations.

Bioenergy: The maturity of the available bioenergy technologies varies significantly, with some of them in the concept stage and others entering early adoption and commercial operation in the relevant environments. This may be attributed to the various available technologies or processes that cater to combinations of input material, intermediaries, and conversion routes for bioenergy generation.

Table 7 | **TRLs of renewable technologies and their applications**

NEW CLEAN ENERGY TECHNOLOGY/ APPLICATION	TRL
Wind	
Onshore	9–10
Onshore (repowering)	9–10
Offshore (seabed fixed)	9–10
Offshore (floating)	8
Small wind	9
Solar	
Crystalline silicon	9–10
Multi-junction cell	9
Thin film PV	8
Organic thin film solar cell	5–6
Perovskite solar cell	4–5
Bioenergy	3–9
Energy storage	
Battery (Li-ion;	
grid scale or BTM)	9
Battery (redox flow)	8
Mechanical (PSH)	11
Mechanical (liquid air)	9
Mechanical (compressed air)	8
Thermal	4–6
Green hydrogen	
Alkaline	9–10
Polymer electrolyte membrane	9–10
Molten carbonate fuel cell	7–9
Solid oxide fuel cell	7–9

Notes: BTM = behind the meter; PSH = pumped storage hydropower; PV = photovoltaic; TRL = Technology Readiness Level.

The TRLs represent the indicative maturity of the technology and are not specific to Tamil Nadu. Their values are based on IEA data and stakeholder consultations.

Source: IEA n.d.

Energy storage: Except for thermal energy storage, which is still in the prototype stage, many of the other energy storage options are at high levels of technology maturity. PSH is a mature technology, whereas other forms of mechanical energy storage are in the demonstration and early adoption stage. The Li-ion battery for BESS for both grid scale and behind the meter (BTM) is in the early adoption stage, whereas redox flow batteries are in the demonstration stage.

Green hydrogen: Fuel cell technologies for green hydrogen manufacturing are in the demonstration or early adoption stage. Electrolysis technologies such as alkaline fuel cells, polymer electrolyte membrane cells, and solid oxide fuel cells are at relatively higher levels of technological maturity than other technologies.

Key issues regarding the adoption of technologies

The key issues regarding the adoption of different technologies are summarized in Table 8 under the categories of technology barriers, economic barriers, commercialization barriers, policy, and others. These pertain to TN but in many cases are also applicable across states and evolved from stakeholder consultations, expert discussions, and the literature. Detailed explanations of the barriers pertaining to each technology are covered in Appendix C.

Table 8 | **Barriers to the adoption of different technologies**

	TECHNOLOGICAL	ECONOMIC	COMMERCIAL	POLICY RELATED	OTHERS
Wind	New materials for generator design in early stages, with associated higher costs and complexities	High investments needed for offshore wind	No demonstration projects in India for offshore wind and higher costs than in the solar sector	To facilitate repowering of wind, clarity needed on aspects such as land and turbine ownership, power evacuation, and disposal	Port infrastructure, skilling, and capacity building
Solar	New technologies with higher panel efficiencies are in the early stages of R&D	Higher installation, maintenance, and repair costs	In India, number of manufacturers of modules with new technologies, supply chains, and infrastructure are limited	Greater policy support required from state governments on aspects such as DREG	Improper installation and maintenance, and need for skilled workforce
Bioenergy	Variation in raw materials used as input	Increase in feed material cost when the demand picks up	Difficulties in managing community-level plants	Focus required on community-level plants to address feed quality and segregation	Availability of human resources for managing biogas plants
Energy storage	Early stages of R&D on large-scale storage of hydrogen; materials for thermal energy; chemical incompatibility and low conductivity	High capital costs	Limited pilot projects and supply chains; early stages of R&D	Focus on tariff regulation, business models, and financing	Limited training courses, awareness, and skilled workforce
Green hydrogen	Safe storage, transportation, and handling are needed due to its flammable nature	Capital-intensive production, higher cost than gray hydrogen	Need for more large-scale pilots and infrastructure-related constraints such as pipelines and filling stations	Clarity needed on the industrial categorization of green hydrogen and the associated tax implications	Availability of cheaper gray hydrogen and limited R&D

Notes: DREG = decentralized renewable energy generation.

It is also important to consider the environmental effects of existing and new renewable technologies, especially factors such as end-of-life waste disposal. The precise kind and degree of environmental effects vary depending on the technology employed, the area, and a variety of other factors. We may act to effectively avoid or reduce these effects during the clean energy transition by recognizing the existing and potential environmental risks associated with each technology. This is an active and growing area of research but is beyond the scope of this paper.

Source: Compilation from stakeholder consultations and the literature.

CONCLUSION

Offshore wind has an immediate installation potential of 35 GW off the coast of TN. Offshore wind technologies have been successfully deployed in other countries and have high TRLs. Domestic supply chains are limited, but experience from the mature onshore wind ecosystem can be used. Existing studies have reported data on suitable areas, wind resources, soil characteristics, water depth, currents, suitable turbines, the estimated levelized cost of electricity, and so on. The existing domestic manufacturing facilities must be expanded and local supply chains must be set up, which can help lower costs. Infrastructural upgrades and the use of larger turbines can be considered. The workforce will need to be imparted skilling and training. Due to the higher costs associated with offshore wind, a financial mechanism will need to be put in place.

There is about 834 MW of immediate repowering potential in TN, and a further 3,979 MW will need repowering by 2027. The required technologies are also available for repowering onshore wind farms, with a significant market potential for repowering turbines. This is possible because India has an active onshore wind industry, with original equipment manufacturers that produce the modern higher-capacity machines used for repowering. The policies promoting repowering need to address issues related to cost and revenue sharing in multiple-owner wind farms and land acquisition. The safe disposal of old wind turbine blades also needs to be considered, because these are typically made of glass-fiber-reinforced plastics. Comprehensive studies that identify the small wind potential across the state are limited. They do not provide the required certainty for setting up projects, because wind tends to be highly site specific.

The state is planning to add 20 GW of solar capacity by 2030. Policies and schemes promoting the installation of solar PV exist at both the central and state levels. However, promotion of new technologies in installations is limited in terms of funding allocation and policies. Companies need to be given opportunities to test out new technologies in a real-world setting. These opportunities can be created through demonstration projects that can also help developers assess the viability of new technologies and compare them with existing technologies. Thus, these policies need to be streamlined.

The market for battery-based energy storage systems is expected to grow significantly, fueled by the higher shares of VRE. Related technologies are also mature and are being validated in actual operational environments. Battery energy technologies are already being commercially deployed, with the most popular options achieving price reductions and economies of scale. The popularity of electric vehicles has nurtured supply chains for BESS, which can be explored to stabilize the grid for VRE-rich states such as TN, due to their capability of quick ramping. Battery energy storage can also be considered for long-term storage along with options such as green hydrogen. Currently, most of the training programs are limited to solar and bioenergy, and greater focus is required on capacity building and skilling to develop and maintain energy storage projects.

Green hydrogen is another up-and-coming sector where the required technologies are being validated in the laboratory and tested in a practical setting. Further assessment is required before incorporating green hydrogen in hard-to-abate sectors, owing to the low TRLs of the associated technologies. The infrastructure needed for large-scale adoption of hydrogen as an energy vector needs to be developed: pipes, distribution networks, and storage facilities, along with more demonstration projects. Greater clarity is required on the industrial categorization and tax implications of green hydrogen.

Many of the technologies outlined here are largely proven in the Indian context and are prime candidates for further deployment. However, stakeholder support is essential to facilitate the development of the markets and related ecosystems. Support is also needed to formulate policies and regulations. It is clear that various new technologies exist that can help accelerate the energy transition, and these need to be carefully considered moving forward.

APPENDIX A: IEA TECHNOLOGY READINESS LEVEL FRAMEWORK

The Technology Readiness Level framework used in this working paper uses the extended classification followed by the International Energy Agency (IEA). The scale provides a common framework that can be applied to technologies in order to assess and compare their maturity. The framework developed by the IEA uses 11 levels to define the maturity of a technology. Table A-1 explains each TRL in the framework.

Table A-1 | **The technology readiness levels**

STAGE	TRL	DETAILS	
Concept	1	Initial idea	Basic principles have been defined
	2	Application formulated	Concept and application of solution have been formulated
	3	Concept needs validation	Solution needs to be prototyped and applied
Small prototype	4	Early prototype	Prototype proven in test conditions
Large prototype	5	Large prototype	Components proven in conditions to be deployed
	6	Full prototype at scale	Prototype proven at scale in conditions to be deployed
Demonstration	7	Pre-commercial demonstration	Solution working in expected conditions
	8	First-of-a-kind commercial	Commercial demonstration, full-scale deployment in final form
Early adoption	9	Commercial operation in relevant environment	Solution is commercially available, needs evolutionary improvement to stay competitive
	10	Integration needed at scale	Solution is commercial and competitive but needs further integration efforts
Mature	11	Proof of stability reached	Predictable growth

Source: IEA 2021a.

APPENDIX B: STAKEHOLDER MAPPING

At each stage of technology development, the associated stakeholder has to address a set of responsibilities, the execution of which is key for the technology's successful and timely deployment. In the early stages of technological development, government support is essential to encourage and fund new technologies. As the technology progresses, funding further development involves private sector participation. Basic research and applied research are carried out in government laboratories and academic institutions. The technology is further developed and prototyped, and commercialization initiatives require the participation of small, medium, and large businesses (Hensen et al. 2015).

Hence, a stakeholder mapping to identify the various central and state government agencies, academic and research institutes, industries, and other organizations is essential. This is required for a broad understanding of who will be involved in the technology development or commercialization process corresponding to the maturity of the technology (see Table B-1).

Table B-1 | **The stakeholder matrix**

TECHNOLOGY	MINISTRY/STATE GOVERNMENT	ACADEMIC INSTITUTES/AGENCIES	OTHER STAKEHOLDERS
Onshore Wind (repowering)	▪ Ministry of New and Renewable Energy (MNRE) ▪ Tamil Nadu Energy Development Agency (TEDA) ▪ Tamil Nadu Generation and Distribution Corporation Limited (TANGEDCO)	▪ National Institute of Wind Energy (NIWE) ▪ Indian Institute of Technology (IIT) Madras	Wind farm owner, WTG manufacturers
Offshore Wind	▪ MNRE ▪ TEDA	NIWE	▪ CSTEP, DNV GL, WISE, GWEC, FOWIND ▪ Wind turbine manufacturers
Solar	▪ MNRE ▪ TEDA	SECI	Utilities and industries
Bioenergy	▪ MNRE ▪ TEDA	SSS-NIEB	Sugar industries
Energy Storage	▪ MNRE ▪ TEDA	▪ IIT Madras ▪ IESA ▪ NITI Aayog	▪ Utilities ▪ C&I consumers
Solar Thermal Energy	▪ MNRE ▪ TEDA	SECI	C&I consumers
Green Hydrogen	▪ MNRE ▪ TEDA ▪ MoPNG ▪ MST ▪ MoRTH	▪ NITI Aayog ▪ IITs/IISc	▪ Hard-to-abate sectors ▪ Transport sector ▪ Electrical storage ▪ Sector-specific ministries

Notes: C&I = Commercial and industrial; CSTEP = Centre for Study of Science, Technology and Policy; FOWIND = Facilitating Offshore Wind in India; GWEC = Global Wind Energy Council; IESA = India Energy Storage Alliance; IISc = Indian Institute of Science; MoPNG = Ministry of Petroleum and Natural Gas; MoRTH = Ministry of Road Transport and Highways; MST = Ministry of Science and Technology; SECI = Solar Energy Corporation of India; SSS-NIBE = Sardar Swaran Singh National Institute of Bioenergy; WISE = World Institute of Sustainable Energy; WTG = wind turbine generator.

An indicative list of stakeholders involved (not exhaustive).

Sources: Literature review, stakeholder consultations.

APPENDIX C: AVAILABLE AND UPCOMING TECHNOLOGY DEVELOPMENTS

C.1 Wind

Developments in wind technology can be categorized under advances in blade design, blade manufacturing, generator design, wind profiling, wind farm operations and maintenance (O&M), electronics, and computing. Figure C-1 gives a detailed explanation of these advances.

Table C-1 shows some of the technological advances in this sector, together with the resulting improvements they can offer to the wind sector.

Offshore wind

Different types of foundations are used for offshore wind turbines depending on the water depth. Floating wind diverges from the conventional fixed platform to cater to deeper waters and is expected to play a significant role in the future offshore wind energy market for offshore sites with water depths between 50 and 1,000 m. The typical concrete foundations used in land-based wind turbines are unviable for offshore applications. Although multiple floating wind turbine designs exist, they are yet to be deployed commercially. This is expected to change in the future, because floating turbine capital costs are expected to drop sharply.

Figure C-1 | **Areas of technological advances in the wind sector**

Blade design and manufacturing
Wind turbine blades are designed for optimal aerodynamics and structural strength. Computational methods and simulations are used extensively for designing blades with high aerodynamic efficiency. Advances in manufacturing technologies are used to design high-strength blades with a single integrated structure, which makes it unnecessary to glue surfaces together. The ensuing structure will have minimal weak points and prevent cracking and water ingress, enhancing the operational life of the turbines.

Generator design and manufacturing
Developments in wind turbine generator technology include incremental improvements to existing subcomponents that enable machines with improved efficiency and fewer components to be produced. Such generators are advanced direct-drive permanent magnet generators and are typically direct drive, designed for better reliability, and use lower quantities of rare earth materials, reducing the overall generation cost. Other advances explore the viability of superconducting materials (high or low temperature), which can reduce the size and weight of the machines by about 50%. The challenge lies in the higher cost of windings (because they require more splices to achieve the desired length) and the use of cryogenics for cooling.

Wind profiling
Developments in wind power forecasts and dispatch have helped optimally coordinate wind power and apply wind power in peak load shifting. This has enabled online wind power capacity assessment, wind power day-ahead, intraday scheduling adjustments, and wind power grid integration performance evaluation. During operation, it is possible to incorporate wind power into start-up arrangements and apply rolling optimization to thermal power plan start-ups to maximize accommodation of fluctuating wind power within its operation range and ensure system operational safety.

Electronics and computing
Advances in computing and digitalization have helped minimize losses, stabilize energy generation, and supply power to the grid with less fluctuations. This has also helped coordinate and integrate generation from different sources (by shifting between them) to optimize efficiency and ensure stable power supply. Advances in electronics and the Internet of Things (IoT) are used to monitor wind turbine operating parameters in real time. These technologies help regulate the current and support the turbine during start-up, providing ride-through capability. This type of technology is also used for predictive maintenance, which helps operations and maintenance (O&M) service providers maintain the wind farm.

Source: Literature reviews and stakeholder consultations.

Table C-1 | **Advances in the wind energy sector and corresponding improvements**

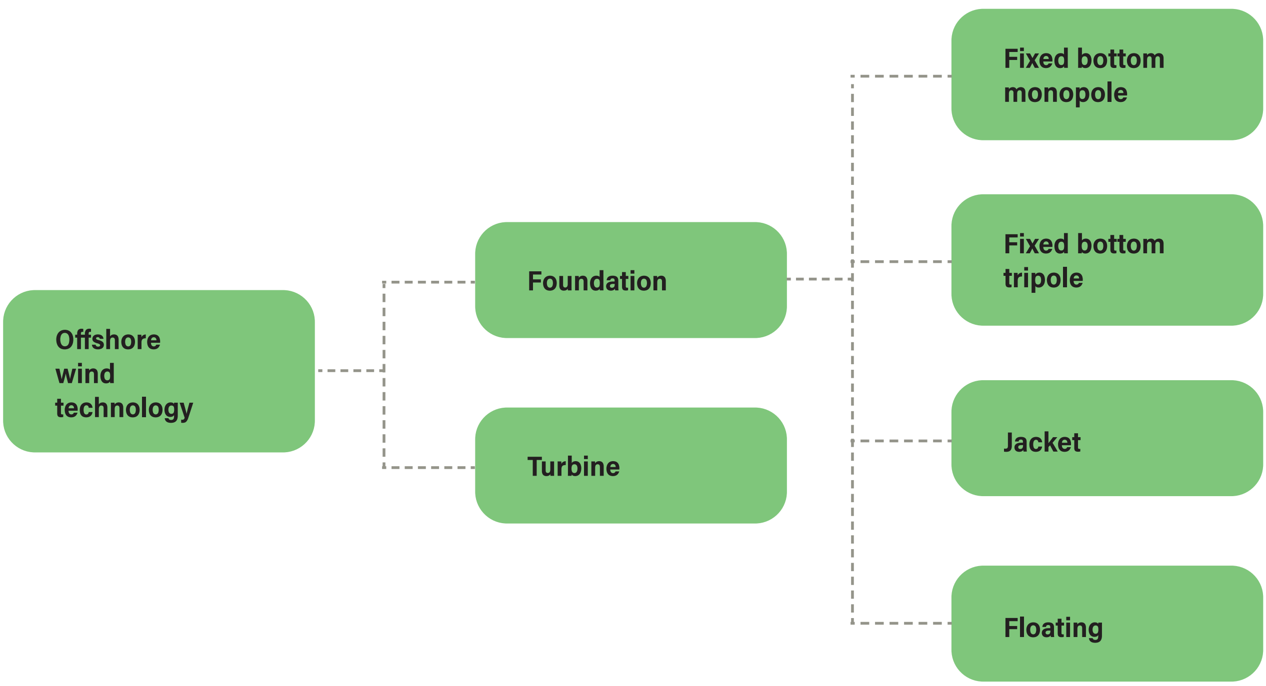
AREA	TECHNOLOGY	IMPROVEMENT
Blade design	Computational techniques for wind-regime-specific aerodynamic design and shape optimization	Higher aerodynamic efficiency and energy yield
Blade manufacturing	New composite materials with automated and machine-assisted manufacturing	High-strength blades, longer blades for modern machines
Generator design	Incremental improvements to generator subcomponents and use of new materials	Higher operational efficiencies, lower weight, and fewer parts
Wind profiling	Use of information technology and best practices in computing, such as IoT and cloud computing	Online wind power capacity assessment, wind power day-ahead, and intraday scheduling adjustments
Wind farm O&M	IoT, cloud computing, artificial intelligence, and drone surveys	Predictive maintenance, longer life, better performance, and safety
Electronics and computing	Data acquisition system using cloud computing and IoT, high-performance computing	Real-time data monitoring and power regulation, ride-through capability, and evaluation of grid integration performance

Notes: IoT = Internet of Things; O&M = operations and maintenance.

Sources: Literature reviews, expert opinions, and stakeholder consultations.

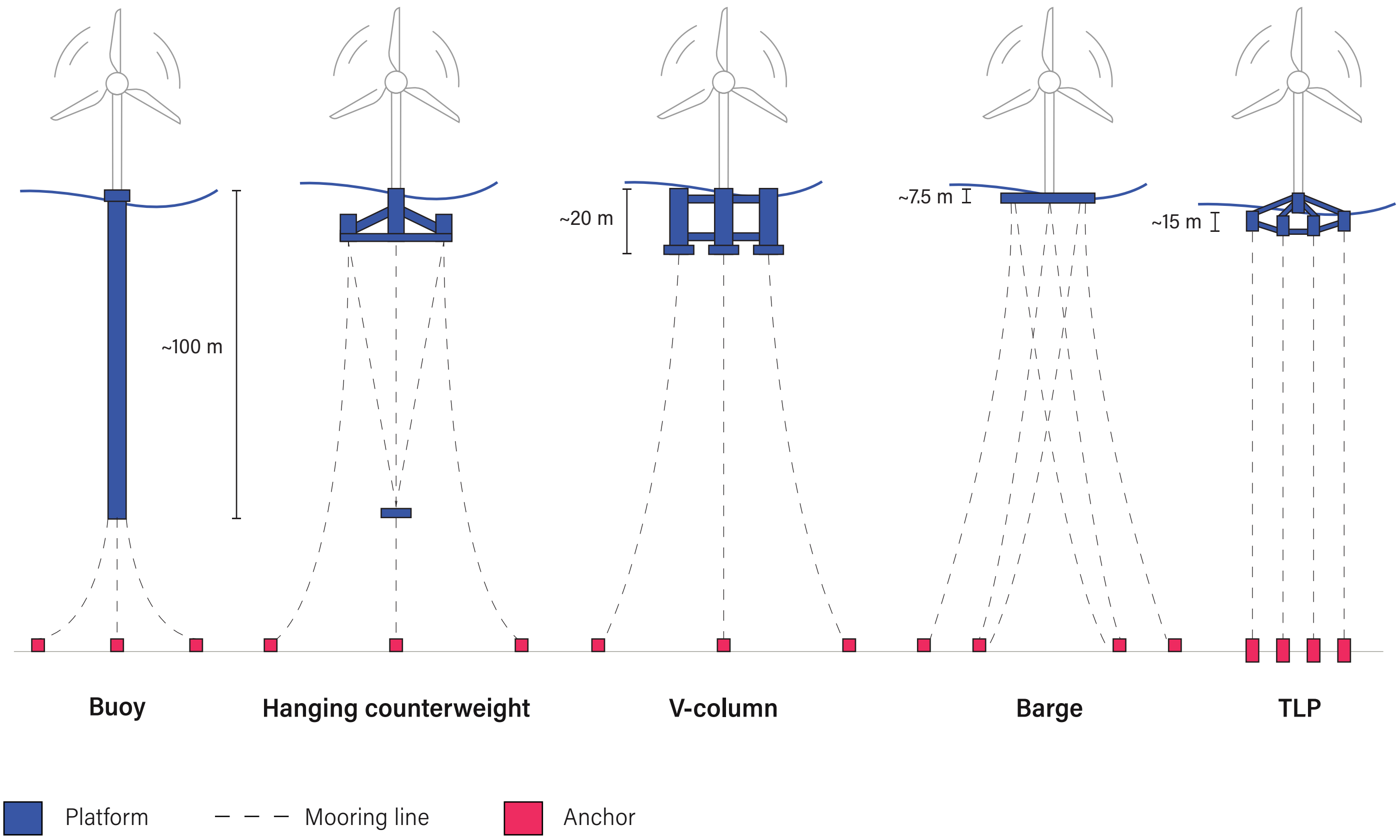
Figure C-2 shows a schematic of the developments in offshore wind technology. Figure C-3 presents information on the different types of foundation being developed for floating wind turbines.

Figure C-2 | **Developments in offshore wind technology and different types of foundations**



Sources: Literature reviews, expert opinions, and stakeholder consultations.

Figure C-3 | **Foundations under development for use in floating offshore wind turbines**



Notes: TLP = tension leg platform.
An indicative representation. Not to scale.

Small wind

Table C-2 shows the general aspects of small wind turbines (SWTs), including their definition, subclassifications, application, usage, components, types, and aspects of construction. SWTs are supported by towers, which include either a self-supporting (free-standing) tower or a guyed tower, supported with wires. The advanced forms include tilt-down towers, which are more resilient to extreme weather events.

C.2 Solar

Solar energy systems can be divided into solar photovoltaics (PV), concentrating solar power (CSP), and solar heating and cooling systems. These systems can be further subclassified, depending on the method used. Figure C-4 shows the different types of solar energy systems and their classification. Solar PVs use different chemistries for electricity generation. These chemistries can be classified into first-, second , and third-generation PVs, depending on the chemistry used. Figure C-5 gives the classification details.

Table C-3 gives the typical efficiencies of first-, second-, and third-generation solar PV cells and modules. Table C-4 presents details of the first-generation technologies. Table C-5 gives the key aspects of emerging technologies using crystalline silicon such as tandem and multi-junction high-efficiency PVs and bifacial passive emitter and rear contact (PERC) technology.

Futuristic developments in solar PV technologies include integrated PV (vehicles, roads, etc.), which addresses the viability of integrating PV into different surfaces. Other advances from the application point of view include floating solar, hybrid systems, and agro-PV. Another technology being explored is duplex solar panels that generate electricity and heat water simultaneously; they are used mainly for residential applications.

Grid integration remains significant for the large-scale uptake of solar power, and considerable advances have been made in technologies and solutions that help integrate solar PV into the grid. Table C-6 summarizes these technologies.

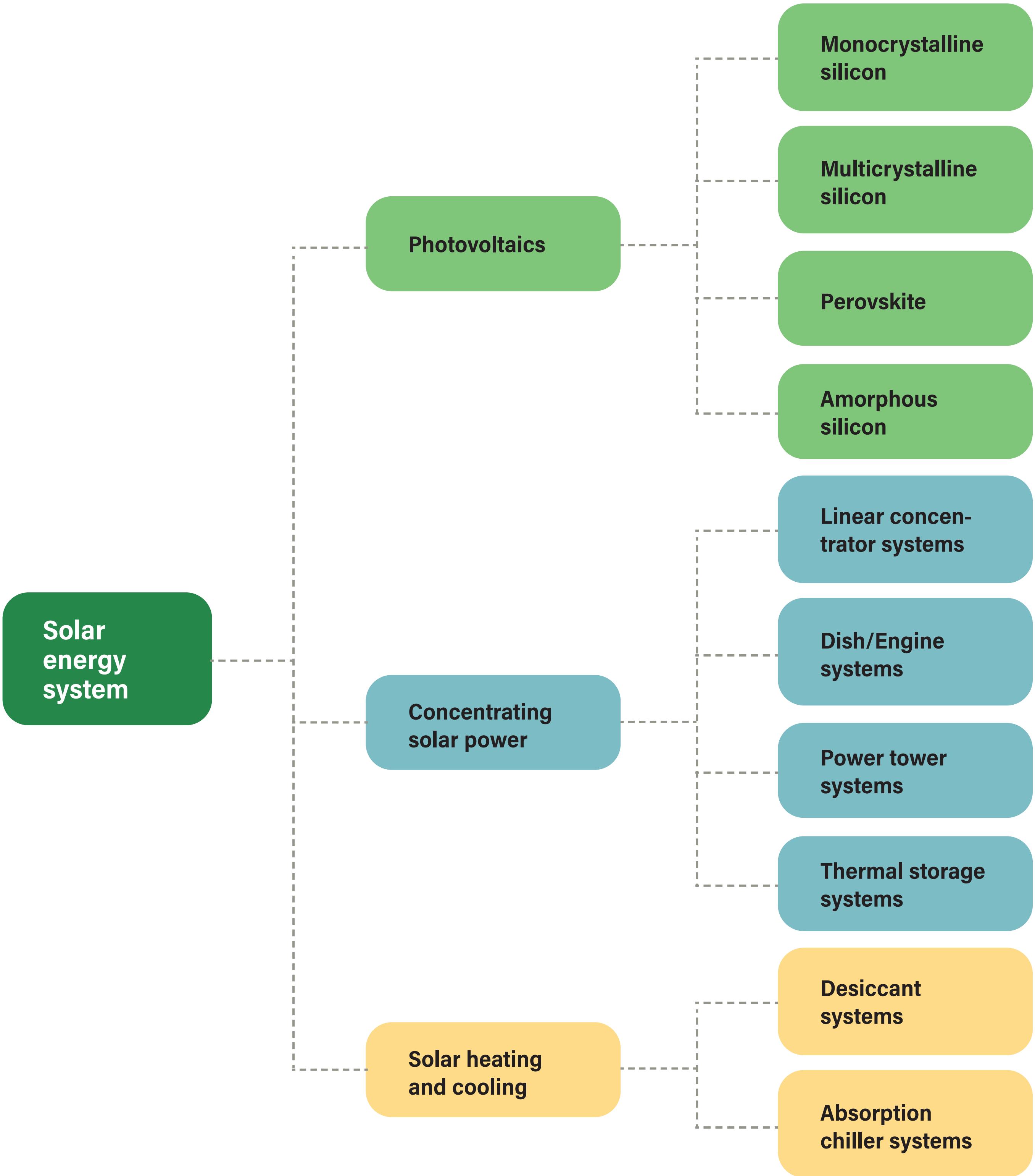
Table C-2 | **General aspects of SWTs**

	DETAILS
Definition IEC 61400-2-2013	▪ Rotor swept area ≤ 200 sq. m ▪ Voltages below 1,000 V AC or 1,500 V DC ▪ Both on-grid and off-grid applications
Subclassifications (based on capacity)	▪ Pico (<1 kW) ▪ Micro (1–7 kW) ▪ Mini (7–50 kW)
Applications	▪ Electricity generation: Residential, rural, industrial applications, telecom towers, seagoing vessels, coastal areas, offshore platforms ▪ Mechanical power: Water pumping, grinding grain
Usage	▪ Off-grid or stand-alone systems ▪ On-grid or grid-connected systems ▪ Can be used in hybrid mode in combination with other clean energy technologies such as solar PV
Components	▪ Turbine (rotor assembly, generator, and tail) ▪ Tower ▪ Electronics
Types/classification	▪ Based on capacities: Mini, micro, pico ▪ Based on the axis of rotation: Horizontal, vertical ▪ Based on rotor placement with respect to the oncoming wind: Upwind, downwind ▪ Based on the type of force that causes rotation: Lift, drag
Turbine construction	▪ Wood ▪ Glass-fiber-reinforced plastics (GFRP) ▪ Carbon-fiber reinforced plastics (CFRP) ▪ GFRP+CFRP
Overspeed protection	Furling: Moves the plane of rotation of the rotor away from the oncoming wind

Notes: PV = photovoltaics; SWT = small wind turbine.

Sources: IEC n.d.; NIWE n.d.; Wood 2013.

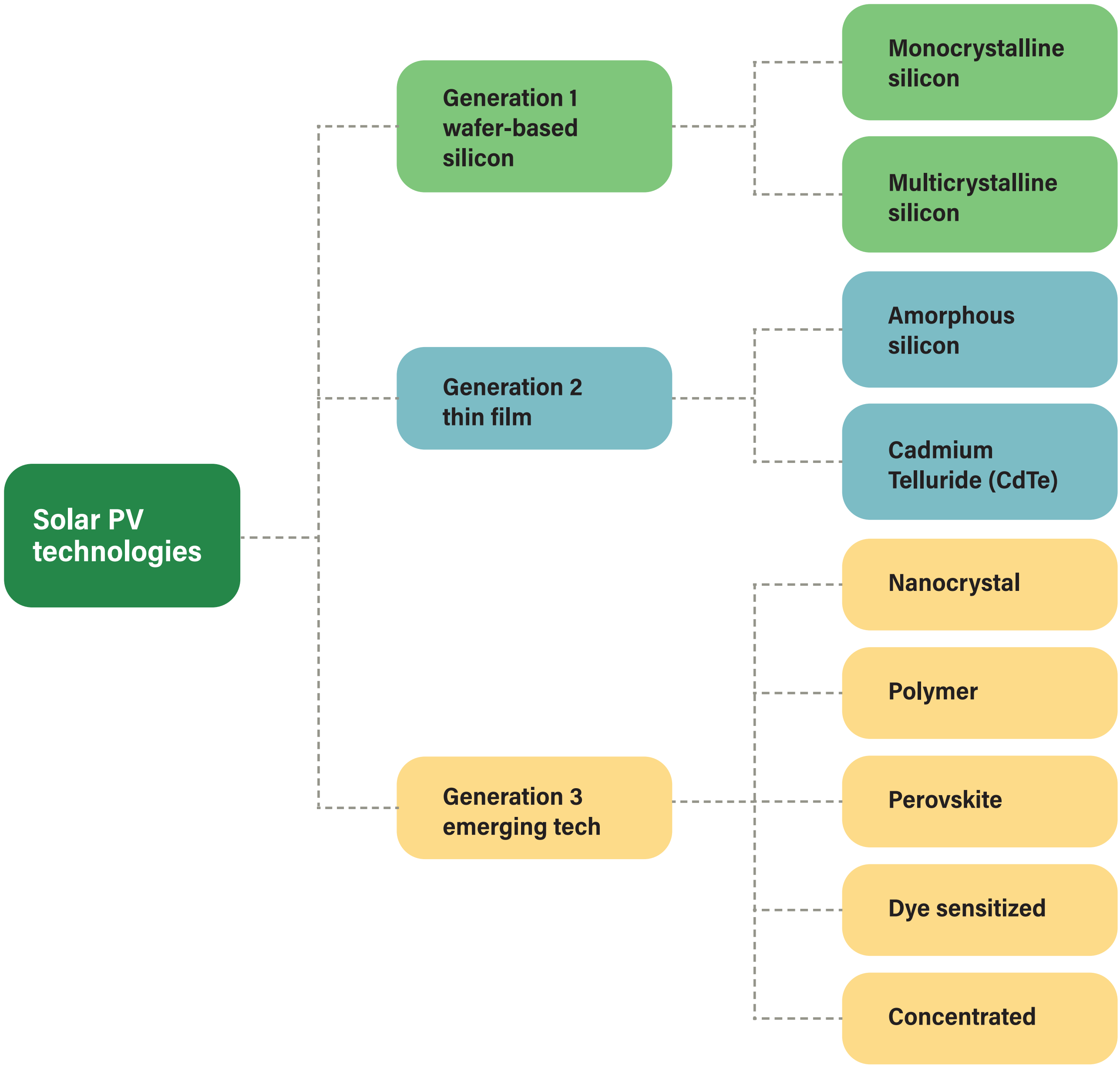
Figure C-4 | **Categorization of solar energy systems**



Notes: PV = photovoltaics.

Sources: Literature reviews, expert opinions, and stakeholder consultations.

Figure C-5 | **Categorization of solar PV technologies**



Note: PV = Photovoltaics.
Sources: Literature reviews, expert opinions, and stakeholder consultations.

Table C-3 | **Solar PV efficiency comparison**

GENERATION/TYPE	SOLAR PV TECHNOLOGY	EFFICIENCY (%)
First (crystalline silicon)	Si monocrystalline cell	26.7
	Si monocrystalline module	24.4
	Si multicrystalline cell	22.3
	Si multicrystalline module	19.9
Second (thin film)	CIGS cell	23.4
	CIGS module	19.2
	CdTe cell	21.0
	CdTe module	19.0
Third (emerging technologies)	Perovskite cell	21.61
	Perovskite module	6.1

Notes: CdTE = cadmium telluride; CIGS = copper indium gallium (di)selenide; PV = photovoltaics.

Sources: Fraunhofer Institute of Solar Energy Systems, ISE 2023.

Table C-4 | **Information on first-generation technologies**

CLASSIFICATION	TECHNOLOGY	DETAILS
First generation	Single/monocrystalline silicon or poly/multicrystalline silicon solar cells	▪ Oldest technology ▪ High power efficiency (<30%) ▪ 90% of global PV market ▪ Monocrystalline dominates the market with a growing market share ▪ Monocrystalline has higher efficiency than multicrystalline ▪ Price difference between monocrystalline and multicrystalline is dropping, and price parity is expected to be reached in the near future ▪ Cost of monocrystalline modules saw a decline from $1 per watt in 2012 to $0.2 per watt in 2020

Notes: PV = photovoltaics.

Sources: Literature review, expert opinions, and stakeholder consultations.

Table C-5 | **Emerging technologies incorporating crystalline silicon**

TYPE[a]	DETAILS
Tandem and multi-junction high-efficiency PVs	Target efficiencies are greater than 30%
Bifacial passive emitter and rear contact (PERC) technology	▪ Higher power outputs with lower unit costs; expected to gain predominance in the near future ▪ Bifacial solar cells can harvest energy from both surfaces (front and rear), and their higher efficiency can augment the power output by 10–30%

Notes: PV = photovoltaics.

a. At the time of this writing, they have not reached commercial maturity (market competition driving widespread deployment and bankable grade asset class with known standards and performance) or price parity for large-scale deployment.

Sources: Literature review, expert opinions, and stakeholder consultations.

Table C-6 | **Technologies for successful integration of solar power into the grid**

TECHNOLOGY	DETAILS
Output and weather forecasting	Utilizes numerical computations and algorithms and large amounts of data
Operation monitoring and closed-loop control	Used to continuously improve or modify the input of large photovoltaic power stations
Rolling optimization of day-ahead and intraday scheduling of high-penetration photovoltaic power grids	Rolling optimization is used for recurrent problems where the immediate decision must depend upon upcoming ones and is achieved through forecasts updated at each optimization step
Active and reactive power output regulation	▪ Used to resolve issues related to momentary output fluctuations using automatic and smooth regulation of the active and reactive power output ▪ Active power is the real power that continuously flows from a source to the load in an electric circuit, whereas reactive power is imaginary power that moves from the load to the source ▪ Some solar inverters provide reactive power support to the grid even during non-solar hours
Hierarchical control system (HCS)	An HCS has devices; the governing software is arranged in a hierarchical tree and has the ability to integrate a comprehensive energy management system
Maximum power point tracking (MPPT)	Improves efficiency by swiveling solar panels around so that they always face the sun using tracking systems and algorithms

Source: Literature review.

C.3 Bioenergy

The generation of bioenergy can be categorized into traditional and modern methods based on the type of biomass and process used. Traditional methods involve the combustion of biomass in the form of wood, animal waste, and charcoal. Modern methods use biogas from anaerobic digestion of residues, biofuels, bio-refineries, and so on (IRENA n.d.).

Technologies used to convert biomass to heat, power, or fuels are divided into thermochemical and biochemical types. Thermochemical conversion involves combustion, gasification, and pyrolysis, whereas biochemical conversion uses aerobic and anaerobic methods. Feedstock is often converted to an intermediate biomaterial before the energy generation process. The variety of feedstock involved necessitates the development of specific technologies for the conversion. This specificity makes it difficult to generalize technology across feedstock and accelerate technological progress and commercialization. Few technologies are ready for commercialization; most are in the prototype and demonstration stages. Figure C-6 summarizes the multiple methods for converting feedstock to bioenergy.

When considering the processes for producing biofuels from biomass alone, the associated technologies can be categorized into the first, second, third, and fourth generation, depending on the type of input material used (see Table C-7).

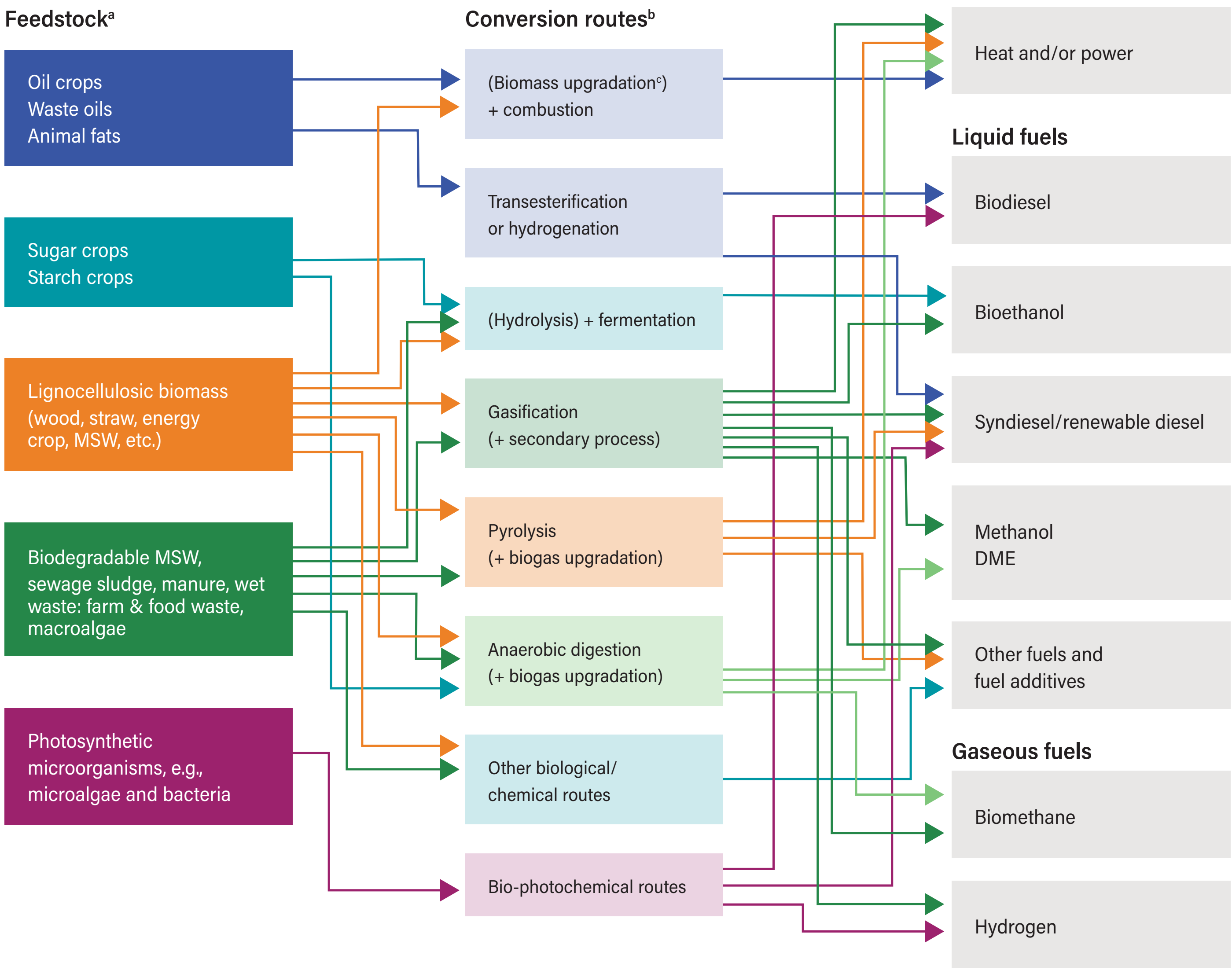
The efficiencies and production costs vary and depend on the type of process used for energy generation. Biofuel feedstock, which includes crop residues, forestry residues, used cooking oil, municipal solid waste, and energy crops, is considered sustainable because it is not fossil fuel based and is also not from food plants.

To advance the technology, R&D is being done on developing low-energy processes for producing biofuels and biochemicals using emerging technologies such as membrane filtration. This can achieve higher production quantities with lower costs (IEA 2021b). Early stage projects are also being deployed using bioenergy with carbon capture and storage (BECCS) technologies where CO_2 is captured from biogenic processes such as biofuel/biohydrogen production and stored (IEA n.d.).

Other advances involve producing energy carriers from feedstock and feature two main types of flexibility: short term and long term. Short-term flexibility balances and stabilizes the grid, whereas long-term flexibility involves seasonal storage and transportation (see Figure C-7).

Figure C-7 shows that biomass is initially converted to intermediaries such as biogas or pyrolysis oils, which are generally difficult to transport and store over long distances and time frames, limiting flexibility. However, technologies can be used in which hydrogen produced from renewable sources can be reacted with biogas or other intermediaries to produce liquid fuels, stabilized oils, pellets, chips, and so on, which can then be more easily stored, transported, or used to address variable generation, improving the flexibility. The process may also use carbon capture technologies.

Figure C-6 | **Different process and routes for the generation of bioenergy from feedstock**



Notes: DME = dimethyl ether; MSW = municipal solid waste.

a. Parts of each feedstock can also be used in other routes. b. Each route also gives coproducts. c. Biomass upgrading includes any one of the densification processes (pelletization, pyrolysis, torrefaction, etc.)

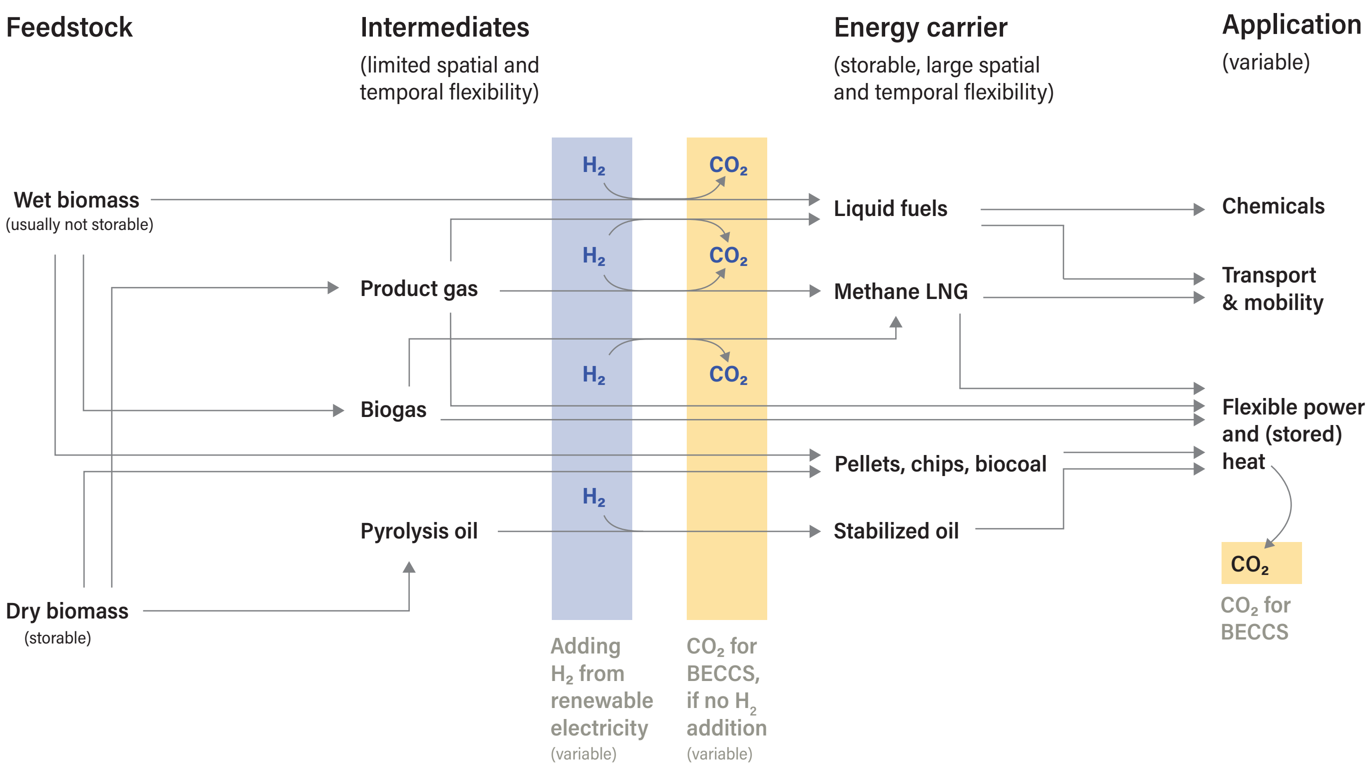
Source: ERP n.d.

Table C-7 | **Biofuel generation technologies**

CLASSIFICATION	PARTICULARS
First generation	These technologies produce hydrocarbons from edible products such as sugar-based ethanol and vegetable-oil-based biodiesel
Second generation	These technologies use non-edible-product-based fuels such as animal fat
Third generation	These technologies use engineered energy crops such as algae to generate biofuels
Fourth generation	These technologies use the second- and third-generation technologies along with carbon dioxide capture

Sources: Literature review, expert opinions, and stakeholder consultations.

Figure C-7 | **Processes for flexibility in biomass-related energy conversions**



Notes: BECCS = bioenergy with carbon capture and storage; CO_2 = carbon dioxide; H_2 = hydrogen; LNG = liquefied natural gas.

Source: IEA Bioenergy 2021.

Among the different biomass types, solid biomass is still the most popular option worldwide for energy generation. This is especially true in countries with a high per capita forest area and important wood processing industries. Countries with low forest biomass potential are seen to rely on solid biomass imports (IEA Bioenergy 2021). Other than solid biomass, the use of biogas/biomethane, liquid biofuels, and renewable waste is also relevant. It is seen that biogas is mainly used directly for combined heat and power (CHP) generation. In most countries, biogas usage for energy generation is about 1–5 percent of their natural gas usage (IEA Bioenergy 2021). The use of municipal solid waste (MSW) as feed material is gaining popularity in countries with better waste management and effective collection systems. There are also linkages between the quantity of MSW used for energy generation in a country, their waste management advances, and the phasing out of landfills (IEA Bioenergy 2021).

Biofuels and bioenergy are the dominant RE sources for the heat and transportation sectors globally. Liquid biofuels are also increasingly used for transportation. Biofuels account for 2–5 percent of the total fuel consumption by vehicles, with fossil fuels accounting for the rest. Biodiesel and bioethanol are dominant in the global transportation market, and their use is expected to increase with their application to heavy duty transport. The market trend is leaning toward the use of advanced and drop-in biofuels (IEA Bioenergy 2021). Drop-in biofuels, which are renewable hydrocarbon biofuels produced from biomass sources, are chemically similar to petroleum-based fuels.

C.4 Energy storage

Energy storage technologies can be broadly classified into mechanical, electrochemical, thermal, electrical, and chemical. Table C-8 summarizes the types of technology used and the principle of operation.

Electrochemical storage options utilize different battery chemistries to store energy. Table C-9 summarizes the different battery technologies and the key aspects of each type of battery chemistry. Table C-10 compares electrochemical and mechanical storage technologies.

Thermal energy storage (TES) technology stocks thermal energy by heating or cooling a storage medium. The stored energy can be used later for applications such as heating, cooling, and power generation. TES technology can be classified by the medium used, such as sensible heat, latent heat, and thermochemical storage. Figure C-8 shows the different TES storage mediums and their subclassifications, and Table C-11 details the key aspects of each of the TES mediums.

Electrical storage technologies such as supercapacitors and superconducting magnetic energy storage (SMES) devices can release large quantities of energy in very small time spans (high energy release in short bursts). This technology is slowly entering the market and can be used for power quality control.

Table C-8 | **Different categories of energy storage**

CLASSIFICATION	TYPES	PRINCIPLE
Mechanical	Pumped hydro energy storage (PHES)	Stores electrical energy as the potential energy of water
	Compressed air energy storage (CAES)	Converts electrical energy into compressed air
	Flywheel energy storage	Stores electrical energy as the rotational energy in a heavy mass
Electrochemical	Lead acid batteries and advanced lead acid (lead carbon, bipolar lead acid)	Uses chemical compounds to store and release electricity
	Lithium batteries (LCO, LMO, LFP, NMC, LTO, NCA)	
	Sodium batteries: NaS, $NaNiCl_2$	
	Zinc batteries: zinc-air, Zn–MnO_2	
	Flow batteries: zinc bromide, vanadium redox	Chemical energy is stored in varying types of flowing liquid electrolytes
Thermal	Sensible thermal storage: molten salt, chilled water	Excess thermal energy collected for later use
	Latent thermal energy: ice storage, phase change materials	
	Thermochemical storage	

Table C-8 | **Different categories of energy storage (cont'd)**

CLASSIFICATION	TYPES	PRINCIPLE
Electric	Supercapacitors and superconducting magnetic energy storage (SMES)	Stores electricity in electric
Chemical	Power-to-power (fuel cells, etc.)	Typically utilizes electrolysis of water to produce hydrogen as a storage medium that can subsequently be converted to energy
	Power-to-gas	Typically utilizes electrolysis of water to produce hydrogen as a storage medium that can subsequently be converted to energy

Notes: LCO = lithium cobalt oxide; LFP = lithium iron phosphate; LMO = lithium manganese oxide; $NaNiCl_2$ = sodium–nickel chloride; NaS = sodium–sulfur; NCA = nickel-cobalt-alumina; NMC = nickel manganese cobalt oxide; Zn–MnO_2 = zinc–manganese dioxide.

Sources: Compilation from literature reviews; ISGF 2019.

Table C-9 | **Summary of battery chemistries**

TYPE	PARTICULARS
Lead acid and advanced lead acid batteries	▪ One of the most widely used battery chemistries worldwide ▪ Recent advances in lead acid batteries include longer life and improved charging-discharging capabilities, and incorporate bipolar plates and recyclable materials ▪ Suitable for storing energy, which can then be used for frequency regulation of solar farms
Lithium-ion batteries	▪ Here, carbon forms the anode, lithium oxide forms the cathode, and lithium salt is used as the electrolyte ▪ Li-ion batteries have attracted tremendous interest over the last few years because they are suitable for application in electronic devices and electric vehicles ▪ Their use in electronic devices had led to their mass production, resulting in a sharp decline in prices; annual global manufacturing capacity is greater than 100 GWh (Global Data 2020) ▪ Lithium chemistries offer higher energy densities and faster reaction times, which has resulted in uptake in large-scale grid storage
Sodium batteries	▪ Available in two chemistries: sodium–sulfur and sodium–nickel chloride ▪ Made from abundant, low-cost, and non-toxic chemistries but operate at high temperatures (>300°C) ▪ Suitable for frequency regulation, renewable energy time shift, and transmission congestion relief
Zinc- based batteries	▪ Offer low-cost and non-toxic storage solutions ▪ Combine zinc with different chemistries; are expected to become an alternative to lithium-ion batteries once the technology is fully developed ▪ Currently in the early stages of development
Flow batteries	▪ Store energy in electrolytes ▪ Different chemistries of flow batteries at different stages of commercialization: vanadium redox, zinc-iron, and zinc-bromine (326 MW of grid-connected flow batteries up to 2018)

Notes: GWh = gigawatt-hour; MW = megawatt.

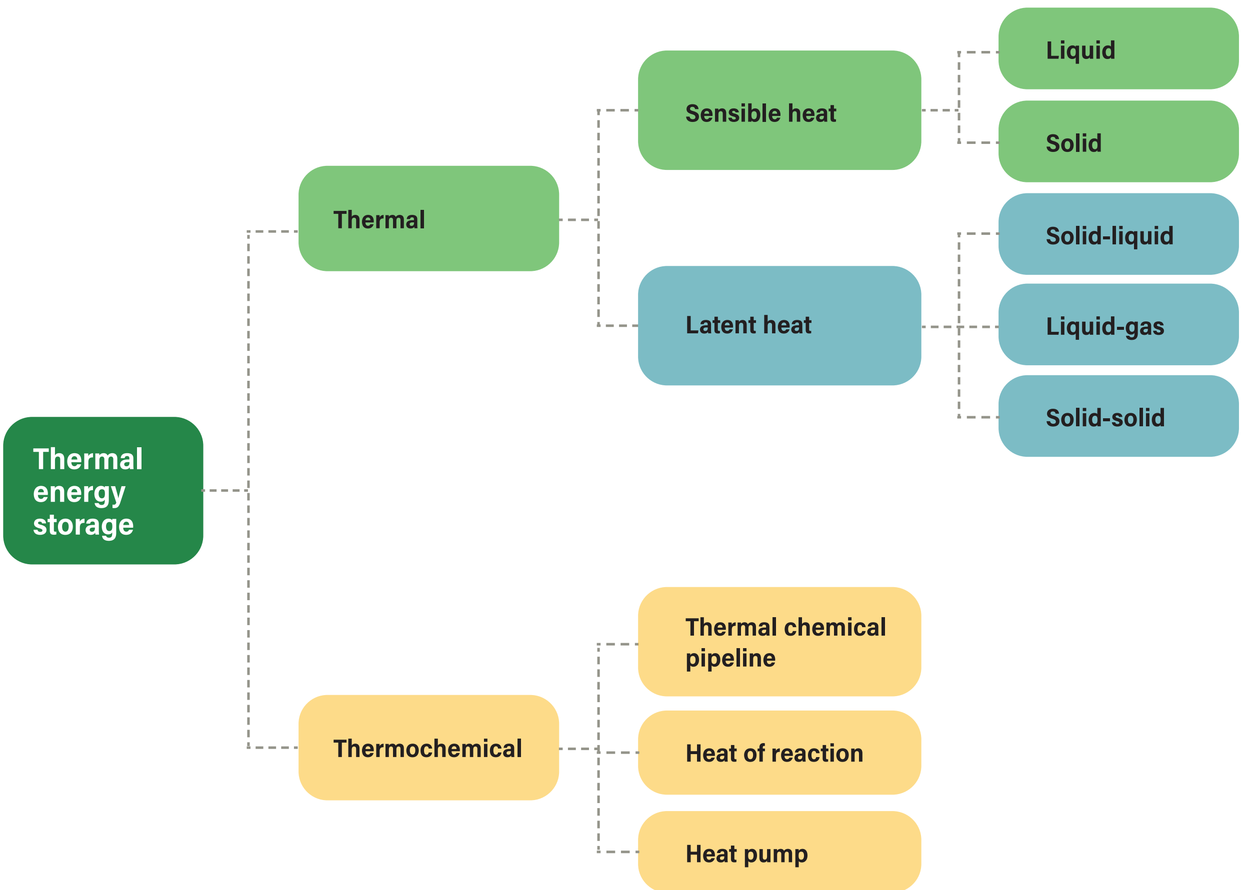
Sources: Compilation from literature reviews; ISGF 2019.

Table C-10 | **Comparison of battery and mechanical storage options**

CLASSIFICATION	TYPES	ROUND TRIP DC-DC ENERGY EFFICIENCY (%)	DISCHARGE DURATION (HR)	CONSTRUCTION AND DEVELOPMENT TIME (YEARS)	OPERATING COST	SPACE REQUIRED (ESTIMATED)	NUMBER OF CYCLES	MATURITY
Mechanical	Pumped hydro energy storage (PHES)	70–80	6–20	5–15	Low	Large	10,000+	Mature
	Compressed air energy storage (CAES)	50–65	4–10	3–10	High	Moderate	10,000+	Moderate
	Flywheel	60–80	0.25–4	1–2	Low	Small	100,000	Early to Moderate
Electro-chemical	Lead acid batteries	70–85	2–6	0.5–1	High	Large	500–2,000	Mature
	Lithium batteries	85–95	0.25–4+	0.5– 1	Low	Small	2,000–10,000+	Commercial
	Sodium batteries	70–80	6–8	0.5–1.5	Moderate	Moderate	3,000–5,000	Commercial
	Flow batteries	60–75	4–12	0.5–1.5	Moderate	Moderate	5,000–8,000+	Early to moderate

Source: ISGF 2019.

Figure C-8 | **Different types of thermal energy storage medium**



Source: Compilation from literature reviews.

Table C-11 | **Specification of different energy storage options**

TYPE	DETAILS
Sensible heat storage	▪ Simplest method based on storing thermal energy by heating or cooling a liquid or a solid storage medium (e.g., water, sand, molten salts, or rocks), with water being the easiest available option ▪ The amount of heat stored depends on the specific heat of the medium, the temperature change, and the quantity of the storage material ▪ Utilizes heat capacity and a change in the temperature of the storage medium during the charging and discharging; it is low cost and uses non-toxic materials
Latent heat storage	▪ Relies on storage of energy in materials that undergo a phase change (solid–solid, solid–liquid, liquid–gas) ▪ Energy absorbed by the material to accomplish a phase change is termed the latent heat of vaporization/fusion ▪ The transition between the phases stores and releases energy, and constitutes the charging and discharging cycles
Thermochemical storage	▪ Uses reversible chemical reactions that absorb and release heat energy ▪ Mostly in the early stages of R&D

Sources: Compilation from literature reviews; ISGF 2019.

C.5 Hydrogen energy: Green hydrogen

Hydrogen can be produced from fossil fuels and renewable sources. Figure C-9 outlines the methods of production from both these options. Table C-12 presents information about green hydrogen and the key aspects of its production from steam methane reforming, biomass, and electrolysis of water. Table C-13 gives details about hydrogen production, the associated color coding, and emission characteristics.

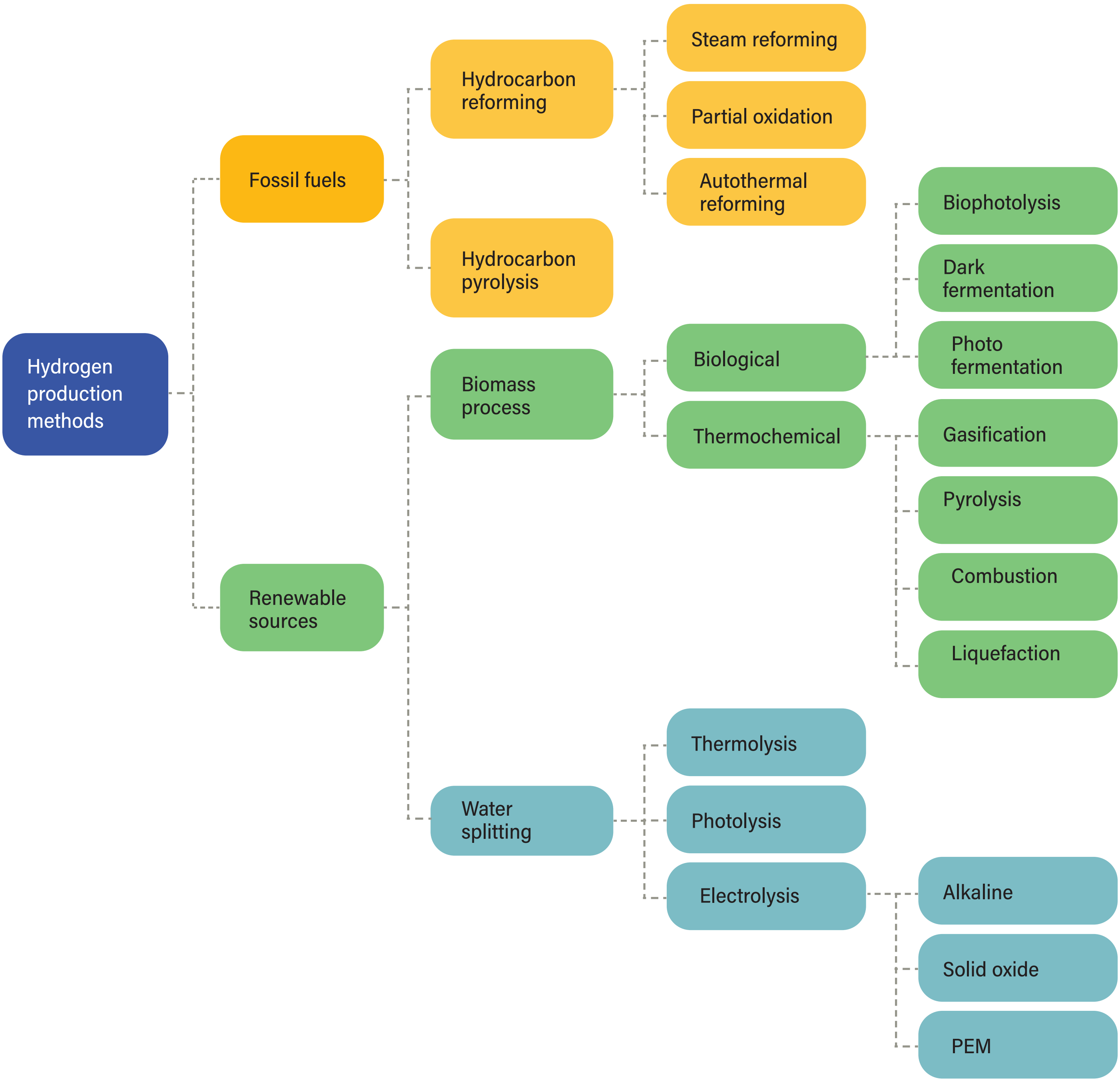
Green hydrogen is primarily produced by the electrolysis of water using energy from renewable sources. Electrolysis is an electrochemical process that splits water into hydrogen and oxygen. In the case of green hydrogen, excess or underutilized renewable energy is utilized. There are broadly three main electrolysis technologies in use: alkaline fuel cell (AFC), polymer electrolyte membrane (PEM), and solid oxide electrolysis (SOE). At present, the commercial availability of electrolyzers is limited to alkaline and PEM technologies. Table C-14 gives the specifications and operating parameters of different electrolysis technologies.

Table C-12 | **Methods of hydrogen production**

METHOD	DETAILS
Steam methane reforming	Well-known, commercially available process for hydrogen production using natural gas as a primary fuel
Biomass	▪ Renewable and easily available source of energy for hydrogen production ▪ Gasification is, however, likely to emerge as the most economical and sustainable process to produce hydrogen from biomass
Electrolysis	▪ Most discussed and near commercially viable option, available for hydrogen production ▪ Three main types of water electrolysis processes: alkaline, acidic (membrane-based), and high-temperature ceramics (solid oxides) ▪ Alkaline is a more mature technology compared to acidic (PEM), and ceramic electrolysis is still in the R&D stage

Source: Compilation from literature reviews.

Figure C-9 | **Methods of hydrogen production**



Source: Compilation from literature reviews.

Table C-13 | **Hydrogen production, color coding, and emissions**

METHOD	COLOR	EMISSIONS	DETAILS
Steam methane reforming from natural gas	Gray	High	Accounts for most of the hydrogen produced across the world
Steam methane reforming with CCUS	Blue	Medium	▪ Proven technology with numerous demonstration plants awaiting scaling ▪ Limited pilot plants in India
Electrolysis of water using renewable electricity	Green[a]	Nil	▪ Reliable method of green hydrogen production ▪ Currently being deployed as pilot projects

Notes: CCUS = carbon capture, utilization, and storage.
a. Nascent technologies such as biomass gasification may be a viable path for green hydrogen production in India because there is no net carbon emission; when coupled with CCUS, it may even have a carbon-negative potential.

Source: Compilation from literature reviews.

Table C-14 | **Specification of electrolysis technologies**

	OPERATING TEMPERATURE (°C)	ELECTRICAL EFFICIENCY (%)	MATURITY	COST	LIFETIME (HR)
Alkaline fuel cell (AFC)	80–90	60–70	High	Low	5,000–10,000
Polymer electrolyte membrane (PEM)	>120	60 (Pure H_2)	High	High	<15,000
Solid oxide fuel cell (SOFC)	600–900	60	Medium	High	30,000–40,000
Phosphoric acid fuel cell (PAFC)	150–200	40	Low	High	<5,000
Molten carbonate fuel cell (MCFC)	600–700	50	Low	High	10,000–20,000

Source: Guo et al. 2019.

APPENDIX D: BARRIERS TO THE ADOPTION OF DIFFERENT TECHNOLOGIES

The issues pertaining to the adoption of different technologies are detailed below (Sections D-1 to D-5) under the categories of technological barriers, economic barriers, commercialization barriers, policy barriers, and others. These details, which evolved from stakeholder consultations, expert discussions, and literature reviews, pertain to TN but in many cases are also applicable across states.

D.1 Wind

Figure D-1 | **Barriers pertaining to wind energy**

Technological

The use of superconducting material in generator design is in the early stages of research. The design of HTSCGs involves higher costs because the windings require more splices to achieve the desired length. Although this issue is mitigated in the case of LTSCGs, the need for cryogenic cooling adds complexities to the design. Hence, these technologies cannot be immediately commercialized.

Economic

The investments needed for offshore wind projects are high and depend on factors such as the depth of the water and distance from the coastline.

Commercialization

Most of the research institutions and manufacturers exploring these technologies are based outside India. Market development and technological maturity can help these companies set up a domestic manufacturing base. An exception is onshore wind, for which an active manufacturing ecosystem already exists in Tamil Nadu. For repowering and offshore wind, there are currently no independent large-scale demonstration projects available in the state, despite competitive capital costs and the high efficiency of the operating commercial units. Costs associated with transportation, supply chains, maintenance, and operating performance are higher than those in the solar PV sector, which also hinders optimum commercialization.

Policy

The issues hampering large-scale repowering initiatives concern ownership, offtake arrangements, evacuation, disposal, and regulation. Tackling these challenges would require policy and regulatory interventions, coupled with institutional support from nodal agencies. Long-term policy coupled with an incentive mechanism is critical to the success of repowering initiatives.

Others

In the case of offshore wind, India needs to overcome the key challenges of port infrastructure and high initial investment. Skilling and capacity-building initiatives that could train the workforce of existing industries (maritime engineering, O&G, etc.) to handle offshore wind projects would promote smooth operations and maintenance.

Notes: HTSCG = high temperature superconductor generator; LTSCG = low temperature superconductor generator; O&G = oil and gas; PV = photovoltaics.

Sources: Literature reviews, expert opinions, and stakeholder consultations.

D.2 Solar

Figure D-2 | **Barriers pertaining to solar energy**

Technological

Multiple technologies can offer higher cell and panel efficiencies, but many of them are in the early stages of research and have low Technology Readiness Levels. This also makes them more expensive.

Economic

The new solar PV technologies have higher initial and installation costs than the existing solar PV module types. The maintenance and repair costs also tend to be high. Currently, the supply chains and required infrastructure are also limited for these newer-technology solar PVs.

Commercialization

Manufacturing of new solar PV technologies is currently limited. Most of the high-efficiency technologies are in the early stages of research and lack maturity. Effective industry–academia collaboration is needed to push the outcomes of the research into the market.

Policy

Greater support is required from the state government in terms of timely regulations, grants, and financial support. More clarity required on the use of solar energy for DREG applications. Inconsistencies between central and state-level policies, if any, would need to be addressed.

Others

Lack of knowledge about solar technologies leads planners to not recommend PV for new buildings; it also results in improper usage and maintenance. Workers skilled in solar-specific technologies are also lacking.

Notes: DREG = decentralized renewable energy generation; PV = photovoltaics.

Sources: Literature reviews, expert opinions, and stakeholder consultations.

D.3 Bioenergy

Figure D-3 | **Barriers pertaining to bioenergy**

Technological

A major problem with bioenergy is that the raw materials have different properties, necessitating matching technologies. The composition of the feed materials will always be variable, and solutions need to be developed for their management.

Economic

To manage the economics of bioenergy systems, it is essential that the feed be obtained free of cost, often with a negative feed price, where people are paid to remove the agricultural by-product that then serves as the feed. However, it is seen that when technologies are developed to generate energy from a type of feed, the feed that was initially free begins to be sold at a price, making bioenergy production unviable.

Commercialization

The difficulty in managing community-level plants due to the variable nature of the feed material collected leads to suboptimal plant performance.

Policy

Policy interventions need to focus on smaller community-level plants that face challenges stemming from feed quality, segregation, and collection of biowaste. The larger plants, which do not need policy support because they are able to generate energy efficiently due to feed stock uniformity, generally tend to be successful.

Others

Managing a biogas plant is more difficult than managing other renewable options. Labor is needed to prepare the feed fuels. For instance, it is now difficult to find people to prepare the feed for the biogas plant.

Sources: Literature reviews, expert opinions, and stakeholder consultations.

D.4 Energy storage

Figure D-4 | **Barriers pertaining to energy storage**

Technological

The overarching technical challenges associated with using hydrogen as a storage medium—the large-scale storage of hydrogen for transportation, industrial processes, and power generation—need to be addressed. Thermal energy storage systems have, up to now, not been used for power-to-heat conversion and process heating in industries. This is mainly due to the technical and commercial challenges associated with the process. The required materials, components, and devices required for thermal energy storage are in the nascent stages in India. The key challenges hampering the large-scale availability of thermal storage options include problems with chemical incompatibility and low thermal conductivity. The materials required for thermal energy storage systems are currently below a Technology Readiness Level of 4.

Economic

High capital cost and a risky market situation compared to conventional power consumption are the financial challenges that have to be overcome before energy storage can be deployed across India.

Commercialization

Research on thermal energy storage materials, commercialization through domestic market development, supply chain strengthening, and capacity building are crucial for wider adoption.

Policy

Further, state-wide deployment of energy storage systems will require a conducive policy environment built upon supportive regulations, favorable tariff policies, innovative business models, and facilitative financing schemes.

Others

Workforce upskilling and the creation of awareness about different energy storage technologies are needed. Courses in Industrial Training Institutes (ITIs) and vocational courses through the National Institute of Open Schooling (NIOS) are available that focus on other renewable sectors, but courses related to energy storage are limited.

Sources: Literature reviews, expert opinions, and stakeholder consultations.

D.5 Hydrogen energy: Green hydrogen

Figure D-5 | **Barriers related to hydrogen energy**

Technological

Hydrogen is a flammable fuel with backfire and pre-ignition tendencies. Standards and regulations are necessary to ensure safety during transportation and handling. Comprehensive regulations and standards are required that define standard procedures over the entire lifecycle. The lack of codes and standards has repeatedly been identified as a major institutional barrier to the deployment of hydrogen technologies.

Economic

Production of green hydrogen is a capital-intensive process. The cost of green hydrogen and ancillary systems is high, especially in comparison with that of conventional gray hydrogen systems. Low-cost materials and components for hydrogen storage systems and low-cost, high-volume manufacturing methods are required to bring down the cost of green hydrogen.

Commercialization

Globally, several research projects, pilots, and hydrogen facilities have been developed across countries for pushing the hydrogen economy. In India, the focus needs to be on large-scale pilots and demonstrations. Only a handful of pilots, led by private players, are currently in the pipeline. As the production of hydrogen increases, infrastructure-related constraints will also need to be addressed. Large-scale hydrogen production will require a network of industrial-size underground pipes and filling stations spread across the country. The preinstalled natural gas pipeline in Tamil Nadu could be considered for this purpose.

Policy

The Green Hydrogen Policy notified by the Ministry of Power in February 2022 facilitated the production of green hydrogen and provided incentives, such as open access to renewable resources and waivers on transmission charges, to stakeholders. The policy also facilitates the export of green hydrogen. However, more clarity is needed on the industrial categorization of green hydrogen from the standpoint of the directions laid down by the Central Pollution Control Board. There is also no clarity on the tax implication of green hydrogen.

Others

The availability of cheaper gray hydrogen and the limited research being carried out in this sector need to be addressed to attract larger investments. Technical and trade regulations also have hindered the development of the hydrogen industry in some cases.

Sources: Literature reviews, expert opinions, and stakeholder consultations.

ENDNOTES

1. Repowering is the process of replacing aging or old wind turbines with newer, more efficient, and higher-capacity machines. This leads to better utilization of the wind resource at a location, higher capacity utilization factors, and consequently higher energy generation.
2. A"ton" in this paper denotes the metric ton (i.e., the tonne).
3. A standard fuel cell consists of an anode, a cathode, and an electrolyte. At the anode, the hydrogen molecule undergoes an oxidation reaction to form positively charged hydrogen ions. These ions then move through the electrolyte toward the cathode. Simultaneously, the ejected electrons of the hydrogen molecule flow toward the cathode through an external circuit, producing a direct current.

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ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

Our challenge
Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our vision
We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our approach
COUNT IT
We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT
We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT
We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.