GREEN POWERED FUTURE
MISSION

NOVEMBER 2021

JOINT ROADMAP OF GLOBAL INNOVATION PRIORITIES

DISCLAIMER

The Green Powered Future Mission members contributed to the development of this Roadmap through a process that involved a broad set of stakeholders that reached a high level of consensus. Please note that this Roadmap does not represent the views of any specific Green Powered Future Mission member country, entity or organisation or their members or the governments they represent. This Roadmap is intended to support and inform policymakers worldwide about the huge challenges and great opportunities related to the energy systems transformation and decarbonisation. However, the Roadmap does not constitute professional advice on any specific issue or situation. Green Powered Future Mission members make no representation or warranty, express or implied, in respect of the report Roadmap's contents (including its completeness or accuracy) and the members shall not be responsible for any use of, or reliance on, the Roadmap.

EXECUTIVE SUMMARY

Emissions from the power sector need to fall dramatically in the next decade to achieve global climate goals. This leads power systems worldwide to face unprecedented challenges, including how to achieve **mass-scale integration of variable renewable energies** (VRE), such as wind and solar. Despite being the lowest cost form of generation in many regions, VRE currently still meets a small fraction of current global energy demand. In part, this is due to challenges caused by their intermittent nature, which can jeopardise the security and reliability of power systems with the present level of flexibility. These challenges need to be overcome, since without a major acceleration in clean electricity innovation, we will not meet the net zero target by 2050.

The **Green Powered Future Mission** has the goal of demonstrating that power systems, regardless of geography or climates, can effectively integrate up to 100% VRE in their generation mix by 2030 while ensuring the system is cost-efficient, secure and resilient. The Mission is a 10-year endeavour which will accelerate innovation in clean energy by demonstrating innovative solutions to transform the present system. It is based on the model of a public-private partnership, an effective way to bring together the resources and the know-how that are needed to address innovations through the support of Mission Innovation (MI) member states, private sector companies and international organisations. The Green Powered Future Mission will lead the way in Research and Innovation (R&I) towards the global power system transformation to making the clean energy revolution happen in this decade.

This Mission, also leveraging synergies with other key initiatives, addresses the following three R&I pillars of energy systems transformation:

1. **Affordable and Reliable VRE:** reduce cost and increase efficiency, resilience and reliability of VRE technologies in various climates and system configurations.
2. **System Flexibility and Market Design:** develop the much-needed flexible solutions to meet network infrastructure needs, to be supported by regulation and innovative markets design.
3. **Data and Digitalisation for System Integration:** accelerate the digitalisation of energy systems through development of interoperable data exchange and effective system integration to unlock the full value of VRE.

The Mission has identified key **Tipping Points (TP)** against each pillar which need to be met to achieve its goal.

Affordable and Reliable VRE

TP1.1 - Novel cost-efficient PV technologies breaking the efficiency ceiling of 29%.

TP1.2 - Offshore wind technologies, including 10 to 20 MW wind turbines and offshore floating wind power plants, with efficiency and generation costs close to on-shore wind.

TP1.3 - Improve forecasting tools with error margins below 6% and a reliable estimation for up to 24 hours.

TP1.4 - Demonstration of VRE-based island and off-grid applications to provide electricity as well as heat, desalination and/or H2 production with up to 100% VRE

System Flexibility and Market Design

TP2.1 - Short-term flexibility adequacy for system stability through fast reserve, voltage regulation, frequency response and inertia services (full activation within 1 second and lasting for less than 15 minutes).

TP2.2 - Power system mid-term flexibility to cope with the natural variability of VRE, load/supply forecast errors and congenstion from minutes to several hours.

TP2.3 – Long-term flexibility to deal with low wind and solar energy availability lasting several days and involving a vast geographical area, coping with VRE seasonal variability.

Data and Digitalisation for System Integration

TP3.1 - Take up common international standards so that up to 100% of flexible devices will be compliant with the interoperability and data sharing principles developed in this Mission by 2030.

TP3.2 - Raise public and private sector confidence, so that the asset and network data relating to 60% of all electricity flows is shared or accessible using open standards.

TP3.3 - Increasing the level of coordination and speed of responsiveness across flexible assets which represent up to 100% of operational needs.

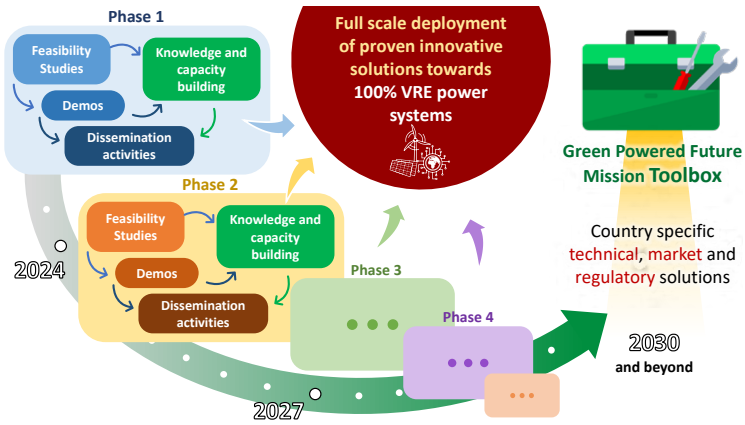
Mission Pillars' Tipping Points

This **roadmap identifies 17 R&I themes and the top 100 innovation priorities** and has been developed to work towards meeting these tipping points by 2030 and achieve the Mission goal.

To achieve these priorities, the Mission will support innovation through feasibility studies, pilots and large demonstrator set-up and validation. These activities will be complemented by knowledge sharing, capacity building, and dissemination activities, whilst ensuring technical, regulatory and market aspects are considered throughout. The Mission will capitalise on members' collaborative work and expertise to simultaneously tackle multiple innovation priorities and will cooperate with existing initiatives working towards a similar goal. In addition, the Green Powered Future Mission commits to support updating and informing climate policy and regulation, which will enable rapid progress towards achieving its goal. Given the global ambition of the Mission, ensuring replicability and scalability of the devised solutions is vital to ensure they function in a broad range of contexts and system conditions.

A Mission Action Plan is being developed which will outline the practical actions to address the identified innovation priorities. Simultaneously, the Mission has distilled the following key messages and calls upon governments, private sector companies, international organisations and the R&I community at large to work together to:

- **Share knowledge among countries** that face similar issues to boost innovative solutions, and recognise that while **innovation challenges are global,** optimal solutions may differ depending on local conditions and characteristics.
- Actively engage **energy system stakeholders** to develop and deploy innovative solutions that are increasingly complex, and which require the joint effort of different expertise/roles.
- Recognise that affordable and reliable **VRE integration, system flexibility and data are key:** most of the innovation priorities related to these aspects need to be tackled to have a significant impact. Besides **technology, business and market aspects** are also essential to enable effective uptake of innovative solutions.
- Validate innovative solutions by means **of real-scale demonstration** to effectively foster their deployment: suitable scalable pilots and large **demo projects** need to be designed and launched.
- Support novel photovoltaic, offshore wind, renewables integration, off-grid power systems, energy storage and system stability technologies to **enhance affordability and reliability of renewables** from a global viewpoint.
- **Support smart electricity networks,** enhanced system operation and tools involving the deployment of new technologies, market solutions and regulatory frameworks to enable integration of very high shares of VRE.
- **Support digitalisation as a key enabling factor which** will play a pivotal role in future energy systems.
- **Recognise that distribution electricity networks are essential** to host increasing amounts of distributed generation, especially from VRE and will play a vital central role in the energy transition.
- **Support storage, demand-side flexibility and EV smart charging initiatives** which will represent an increasingly important support to system flexibility and VRE uptake.
- Enable deep transformation through effective **system integration** which will underpin and unleash substantial sources for additional flexibility.
- Allow systems flexible operation through **digitalisation and enhanced system operations and tools** involving the deployment of new technologies, market solutions and regulatory frameworks.



Implementation "phases" towards the Mission's toolbox development

FOREWORD

To achieve global climate goals, emissions from the power sector need to fall dramatically in the next decade. At the same time, power systems worldwide face unprecedented challenges, key among them being the mass-scale integration of variable renewable energies (VRE), deep electrification of end uses, and achieving universal electricity access. While in many regions VRE are already the lowest cost form of generation, further and bold action is needed to achieve the necessary pace of deployment. The government's ambition to achieve net zero greenhouse gas emissions by 2050 is a "colossal challenge". According to IRENA scenarios[1], renewable energy sources must meet 86% of power demand by 2050 with almost two-thirds generated by VRE, such as wind and solar. Today the current global average VRE share is less than 10%[2].

Without a major acceleration in clean energy innovation, this target will not be achievable. However, the intermittent nature of VRE poses significant challenges to power systems to ensure the security and reliability of the energy supply. To maximise the integration of increasingly higher levels of distributed VRE, it is crucial that power systems are operated more flexibly to balance supply and demand while keeping the system costs low. Even though the technologies in use today can allow significant emissions reduction and flexibility, they are insufficient on their own to enable very high shares of VRE while maintaining the energy systems' security and resiliency.
The year 2021 marks the beginning of a key decade for this endeavour, and the 26th Conference of the Parties (COP26) of the United Nations Framework Convention on Climate Change is a pivotal point in raising the global climate ambitions and actions.
The Green Powered Future Mission, launched within Mission Innovation phase 2, developed this ***Joint Roadmap of Global Innovation Priorities*** drawing a pathway to guide large R&I investment, energy policy and international cooperation towards clean energy transition. This Roadmap identifies the top 100 global innovation priorities to be tackled to accelerate energy system modernisation and decarbonisation, spanning three main thematic areas (R&I Pillars): i) Affordable and reliable VRE, ii) System flexibility and market design, and iii) Data and digitalisation for system integration. Moreover, the ongoing energy transformation and the power systems of the future must be sustainable and fair in a broader sense, thus ensuring that all countries receive the financing and technological know-how to build their green energy futures.

This Roadmap is global in scope however, since innovative solutions need to be validated and implemented locally, R&I activities will rely on large-scale demonstrations, replicability studies and digital solutions to build a "toolbox" from which countries can pick and customise innovative solutions as appropriate to their own geography, system conditions and national strategies.
Power Mission R&D activities and demonstrators will provide confidence to regulators, innovators and the industry, that the power systems with high shares of VRE can guarantee a secure electricity supply when and where it is needed, by making the right tools and best practices available to all. As a result, the mission will boost the energy system transformation needed to reach global decarbonisation objectives.

It is important to underline that this Roadmap has been developed based on an extensive consultative process involving a broad set of stakeholders including MI member governments, power sector leaders (TSOs, DSOs, RTOs, technology providers, etc.) and international organisations.
Finally, we are eager to state that this Roadmap lays the basis for the Power Mission **Action Plan 2022 – 2024** which is meant to highlight and explicate the dedicated bold actions of Mission members, leading to full scale demonstrators to validate the proposed innovative solutions.

[1] IRENA, Global Renewables Outlook: Energy transformation 2050

[2] IEA, Net Zero by 2050: A Roadmap for the Global Energy Sector

Chapter 1

THE GREEN POWERED FUTURE MISSION

LAUNCHED AS ONE OF THE FIRST MISSIONS OF MI 2.0, THE GREEN POWERED FUTURE MISSION - THE **POWER MISSION** IN BRIEF - AIMS TO UNLOCK SMART AND FLEXIBLE POWER SYSTEMS WITH UP TO 100% VRE. THE POWER MISSION IS AN INTERNATIONAL COALITION OF 27 MEMBERS CO-LED BY CHINA, ITALY AND THE UK, THAT EMBRACES SEVERAL MI MEMBER COUNTRIES, INTERNATIONAL ORGANISATIONS AND PRIVATE SECTOR COMPANIES.

Scope and objectives

The Power Mission has the ambitious goal to demonstrate that power systems in different geographies and climates, can effectively **integrate up to 100% Variable Renewable Energies (VRE),** like wind and solar, in their generation mix by 2030, while maintaining the system as cost-efficient, secure and resilient. The Power Mission is a 10-year endeavour to demonstrate innovative solutions to transform the present system and is organised around three R&I pillars:

- Affordable and reliable VRE
- System flexibility and market design
- Data and digitalisation for system integration

The Power Mission's coalition

The Mission is driven by over 25 members from around the world, including MI2.0 member states, private sector companies and international organisations (see figure 1). Through their commitment, the Power Mission will lead the way in R&I towards global power system transformation and progress the clean energy revolution in this decade.

The Mission leverages the power of its public-private partnership as an effective way to bring together the resources and knowledge that are needed to address innovation barriers. Pooling resources, skills and expertise will bring benefits in terms of cost-efficiency, the scale of the impact, the ability to simultaneously tackle numerous challenges and a global perspective on challenges.

The first sprint towards COP26

Following the Joint Mission Statement announced at the Mission launch in June 2021 at CEM12/MI-6 **(link)**, the Power Mission members began building a set of key global innovation priorities and evidence-based pathways to achieve the Mission's goal within this decade. This work is at the base of this Roadmap and aimed to further develop and refine the structure and focus of the Mission to draw a cohesive picture of global innovation needs for the power system transformation.

Moreover, the Mission started to set up a governance structure by convening partners central committees and Pillar working groups meetings and workshops. Following the approval of a joint roadmap development strategy the individual pillars ran a series of national and international stakeholder engagement meetings and landscape studies on emerging technology trends to identify the global innovation needs required to fulfil the Mission goal of integrating up to 100% VRE into power systems around the world by 2030.

Figure 1: The Green Powered Future Mission members

Links and synergy with key initiatives

It is vital that the Mission is additive to the sector and works effectively with other key initiatives and stakeholders which share the common goal of efficient integration of high shares of VRE. To achieve this, the Power Mission has worked to the following main set of collaborative guiding principles:

- Leveraging available **best practices** and building on the experience of ongoing initiatives. Starting from the **existing knowledge** to better understand current barriers and the needed innovation priorities.
- Engaging **policymarkers** to understand how to best support decarbonization strategies.
- Involving **private sector and industry players** to be able to launch effective demo projects and foster future fast deployment of R&I solution.
- Linking with **international organisations** to ensure that the identified innovation priorities are inclusive and globally relevant to all.

Based on the above principles, the Power Mission will leverage synergies with existing initiatives, building bridges towards the other MI2.0 launched Missions, and will establish partnerships with other international initiatives and with key industry associations. Effective collaboration will rely on appointed liaison persons and by setting up of periodic meetings aimed to foster information and knowledge exchange. The foreseen collaboration with key global initiatives will also enable the promotion of strong synergy and complementarities in terms of clean energy challenges not directly covered by the Power Mission. The main initiatives which this Mission has already established or will seek to leverage synergies and effective collaboration on mutually interesting topics are reported in the following.

MI2.0 Missions (www.mission-innovation.net)

Mission Innovation, as a global initiative to catalyse action and investment in clean energy research, development and demonstration, launched its second phase (MI2.0) in June 2021, with a first wave of three Missions. Perfectly in line with the Mission Innovation approach, these three Missions bring together governments, public authorities, corporates, investors and academia in public-private partnerships to enable affordable clean energy innovation worldwide through action-oriented cooperation.

Clean Hydrogen Mission

This mission aims to increase the cost-competitiveness of clean hydrogen by reducing end-to-end costs and is committed to deliver at least 100 large-scale integrated hydrogen valleys worldwide. Clean hydrogen has the potential to decarbonize hard to abate sectors, such as industry and heat, which are responsible for two thirds of global emissions and help unlock the full potential of renewable energy.

The Mission is building a dynamic and ambitious alliance between countries, businesses, investors and research institutes to accelerate innovation on clean hydrogen. This includes international collaboration on research, development, and innovation to further develop hydrogen valleys and accelerate building a global clean hydrogen economy. A superordinate cooperation between the Power Mission and the Clean Hydrogen Mission is therefore essential in order to sustainably leverage and utilise synergies of the hydrogen valleys. Hydrogen valleys and flagship projects with a power sector focus will be a main collaboration subject in the future between the two Missions to stimulate knowledge exchange and best practices among Mission Innovation, countries, organisations and international cooperation towards a global clean hydrogen economy.

Zero-Emission Shipping Mission

This Mission has set a clear target for ships capable of running on well-to-wake zero-emission fuels to make up at least 5% of the global deep-sea fleet measured by fuel consumption by 2030, with an additional target to see at least 200 of these ships primarily use such fuels across the main deep sea shipping routes. To achieve this ahead of 2030, the Shipping Mission works across the energy and maritime value chains, with a focus on creating synergies and accelerating progress in the areas of ships, fuels and fuel infrastructure at

ports. Some of these fuels will be produced through electrochemical conversion pathways with electricity produced from renewable resources to ensure that they emit zero-emissions throughout their entire lifecycle. In connection with this work on electro-fuels, collaboration between the Zero-Emissions Shipping and Green Powered Future Missions is key to reach critical scale of electro-fuels production and lowering their cost.

International Smart Grid Action Network (ISGAN) www.iea-isgan.org

Established as both an IEA TCP and a CEM initiative, ISGAN is an international platform of grid experts. With its 26 member's countries and the European Commission represented by a broad set of stakeholders, ISGAN supports high-level government priorities and action for the accelerated development and deployment of smarter and cleaner electricity grids around the world. Dialogue on how to effectively collaborate with ISGAN is well-advanced and will build on the good track record of the past ISGAN-MI IC1 smart grids activities. There are wide-ranging and significant mutual benefits to derive from this potential collaboration, spanning from networking of research laboratories and tools, and experts' training to building a common framework of key concepts for the future energy system. Relevant topics include (but are not limited to) flexibility, resilience, and a consumer-centric vision for end users' empowerment and digitalised services. Both initiatives are committed to collaborate for their mutual benefits by leveraging their respective work and using their extensive professional, governments, regulators and academics research networks to advance the different pathways towards cleaner electricity grids.

Global Power System Transformation (G-PST) Consortium www.globalpst.org

This initiative shares with the Power Mission the goal of accelerating the transition to low emission and low cost, secure, and reliable power systems. Considering the different stakeholders involved in the Power Mission and G-PST both the initiatives can benefit from a reciprocal exchange of information and strategic views. In particular, the G-PST, under Pillar 1, is advancing six key collaborative research programmes including inverter design, stability tools and methods, control room of the future, planning, restoration and black start, and services. G-PST will work with the Power Mission to identify common areas where knowledge exchange, cross-learning, and coordinated broad outreach and stakeholder education, can inform and support both programmes.

International Energy Agency (IEA) Digital Demand-Driven Electricity Networks (3DEN) Initiative – IEA 3DEN

Accelerating progress on power system decarbonisation, clean electrification, enhanced resilience, security and flexibility is central to clean energy transitions. International collaboration and actions taken to drive clean energy innovation are crucial. Digitalisation is set to play an increasingly important role in enhancing efficiency, optimising systems, and creating new opportunities.

The IEA is conducting analysis and developing evidence-based actionable policy guidance to support national and international efforts in this area through the Digital Demand Driven Electricity Networks (3DEN) initiative. Supported by the Italian Ministry for Ecological Transition, 3DEN is an opportunity for the IEA and the broader international energy community to explore how digital technologies can support the development of much cleaner and more resilient power systems, especially in terms of enabling effective use of distributed energy resources. The project will provide analysis and policy guidance spanning regulatory innovation, new business models, opportunities to scale-up investments and technology deployment and utilisation. Innovation, research and development are of high priority, and the 3DEN initiative highly welcome the development of this roadmap, aimed at mobilising investments in R&D activities and also at implementing large-scale demonstration projects. The fruitful cooperation and exchange initiated between the IEA and Mission Innovation under the Green Powered Future Mission has been highly appreciated in order to promote cleaner and more innovative power systems.

European Technology & Innovation Platform (ETIP) on Smart Networks for Energy Transition (SNET) www.etip-snet.eu

European Technology & Innovation Platforms (ETIPs) have been created by the European Commission in the framework of the Strategic Energy Technology Plan (SET Plan) by bringing together a multitude of experts from a wide array of stakeholders across the entire energy sector. The ETIP Smart Networks for Energy Transition (SNET) role is to guide Research, Development & Innovation to support Europe's energy transition. MI collaboration should gain leverage from the European thrust of being at the forefront in the decarbonisation process, namely on increasing RES penetration, grid-secure operation with massive VRE deployment, efficient sector integration, as well as advanced planning methodologies for new repurposed infrastructures.

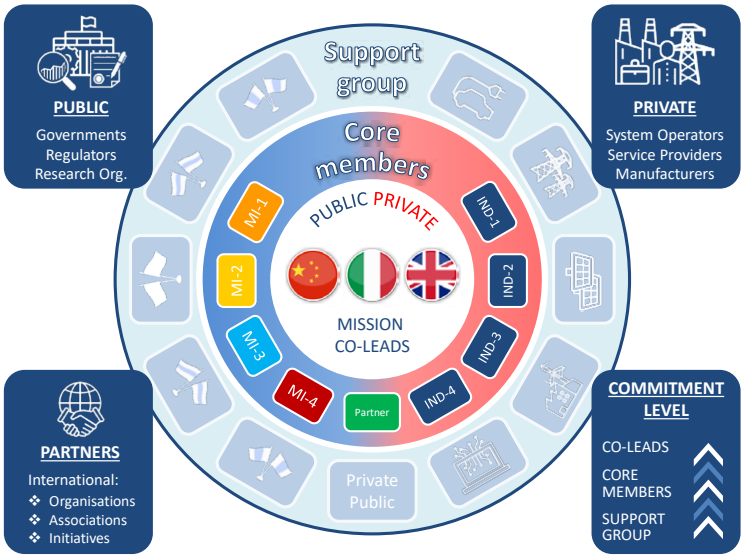


Figure 2: The Power Mission as a public-private partnership

Chapter 2

THREE R&I PILLARS TOWARDS 100% VRE SYSTEMS

THE GREEN POWERED FUTURE MISSION IS ORGANISED AROUND THREE R&I PILLARS AND HAS IDENTIFIED 10 TIPPING POINTS TO BE REACHED TO PROVIDE CONFIDENCE TO GOVERNMENTS, INDUSTRY AND SYSTEM OPERATORS THAT POWER SYSTEMS CAN BE RUN WITH UP TO 100% VRE.

The R&I Pillars and tipping points at a glance

Enabling the efficient integration of very high shares of VRE requires a systemic approach to re-thinking the design, operation and planning of energy systems from a technical and economic perspective. The Power Mission, with the support of experts from around the world, identified the most critical problems that need to be solved and the changes that need to occur by 2030 to achieve the Mission's goal. As a result, the Power Mission identified **3 R&I Pillars**, representing key focus areas of energy systems, and **10 Tipping Points (TP)** that need to be reached by 2030 to provide confidence to governments, industry and system operators that power systems can be run with up to 100% VRE in their generation mix, whilst maintaining cost-efficiency, security and resiliency.

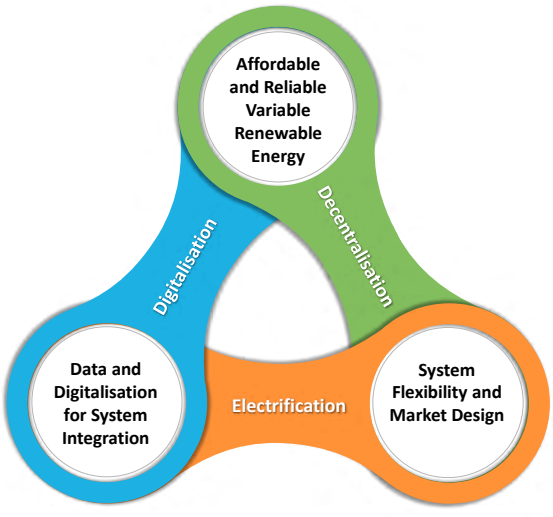


Figure 3: The three cooperative Mission's R&I pillars

Pillar 1

Affordable and Reliable VRE

Led by China, this pillar aims to reduce cost and increase efficiency, resilience, and reliability of VRE technologies in various climates and system configurations. The Tipping Points to support these efforts are:

- TP1.1 - **Novel PV technologies** breaking the efficiency ceiling of 29%, and PV cell and systems able to provide high-efficiency, low-cost and high reliability of electricity in different climates and in extreme weather events.
- TP1.2 – **Offshore wind technologies** including 10 to 20 MW wind turbines and offshore floating wind power plants. Bring their efficiency and generation costs close to onshore wind to enable wide deployment in coastline, islands, offshore platforms, etc.
- TP1.3 - **Improve forecasting** tools with error margins below 6% and a reliable estimation 24 hours ahead of the productivity of PV and wind power units.
- TP1.4 - **Demonstration of VRE-based island and off-grid** applications to provide electricity as well as heat, desalination and/or H2 production with up to 100% VRE. Demonstrating new technologies and hardware for high-efficiency grid-integration and grid-support of PV and wind.

Pillar 2

System Flexibility and Market Design

Led by Italy, this pillar is devoted to the enhancement of system flexibility[3], developing the needed solutions whilst considering relevant market and regulatory implications. As VRE shares increase, systems further electrify, and dispatchable fossil fuel plants are retired; the ability of the system to provide the needed flexibility is challenged, as reported by several analysis such as by IRENA at this **link**. To overcome this, the Mission's R&D activities will identify, develop, and validate innovative solutions to address technical and non-technical barriers, to reach the following tipping points:

- TP2.1 - **Short-term flexibility adequacy** for system stability through fast reserve, frequency response, voltage regulation and inertia services (full activation within 1 second and lasting for less than 15 minutes) to cope with the short-term VRE variability and sudden large imbalances caused by contingencies.
- TP2.2 - **Power system mid-term flexibility** to cope with the natural variability of VRE and load/supply forecast errors and grid congestion criticalities from minutes to several hours.
- TP2.3 – **Long-term flexibility** to deal with low wind and solar energy availability lasting several days and involving a vast geographical area, coping with VRE seasonal variability.

Pillar 3

Data and Digitalisation for System Integration

Led by the UK, this pillar will deal with digitalisation that has the potential to revolutionise the energy sector. It can optimise the use of networks and generation sources, support the coupling of different energy vectors and foster a faster electrification of end uses adding up flexibility from the demand side. By 2030, this Mission will accelerate the digitalisation of energy systems, by supporting globally applicable, flexible and adaptive architectures for interoperable data exchange and effective system integration that can unlock the full value of renewables. Tipping points to be reached are:

- TP3.1 – **Standards for Interoperability:** enough innovators and providers of smart technology take up common international standards so that up to 100% of flexible devices will be compliant with the interoperability and data sharing principles developed in this Mission by 2030.
- TP3.2 – **Secure and resilient digital energy systems:** the 2030 power system will be secure enough such that the procedures introduced will raise public and private sector confidence, so that the asset and network data relating to 60% of all electricity flows is shared or accessible using open standards.

[3] **Flexibility** is defined as *the ability of a power system to manage the variability and uncertainty of demand and supply reliably and cost-effectively across all relevant timescales, from ensuring power system stability to supporting long-term security of supply.*

- TP3.3 – **Integrated solutions:** Improving operational control and contingency planning by increasing the level of coordination and speed of responsiveness across flexible assets providing balancing or ancillary services which represent up to 100% of operational needs through the integration of platforms and sectors (vectors) supported through this Mission.

Barriers to Achieving the Tipping Points

Current progress towards achieving these tipping points is too slow. Through a comprehensive landscape study, the Power Mission has identified the barriers preventing the acceleration required to achieve these by 2030. These barriers have been categorised across the 3 R&I pillars and are summarised below.

Pillar 1 – Affordable and Reliable VRE

- Slow development of **new wind turbine models** with reduced weight able to operate under complex conditions.
- Lack of commercialisation of **floating offshore wind technology** to reach the huge amount of the world's offshore wind resource that lies in deep waters.
- Challenges ensuring **solar PV performance under specific climates and extreme weather conditions**
- **Degradation of PV panels** in harsh environments
- Challenges in designing **floating solar PV** which can operate effectively, and a lack of mooring specialists engaged in the sector.
- A lack of accurate **forecasting of VRE generation patterns** to allow reliable energy dispatching thus reducing the amount of system operating reserves required.

Pillar 2 – System Flexibility and Market Design

- Potential instability of **inverter-based power systems** with high shares of VRE.
- Unavailability of **common digital and cyber-secure data sharing tools and control platforms** to allow system operators to deal with high number of resources.
- **Regulatory frameworks and market rules** stifling flexibility markets and preventing wider participation of new actors (VRE assets owners, aggregators, end users, etc.).
- A lack of **co-operation among distribution and transmission system operators** in managing the different flexibility sources.

Pillar 3 – Data and Digitalisation for System Integration

- Lack of **digital interconnectivity** within the energy sector preventing innovation in novel data-enabled business models.
- Inadequate levels of **data collection, visibility, access, and interoperability.**
- **Poor availability and use of energy system data** due to fragmented and siloed datasets.
- Little expertise available on how to manage **large sets of energy data.**
- Limited understanding on how to implement digital tools and innovations (e.g. big data analytics, machine learning, AI), including how the digital infrastructure converges with the physical infrastructure.
- Slow to evolve **policies and regulations** which would allow for a redefining of the market design and governance structures to ensure an open, adaptable and agile data-enabled innovation ecosystem.

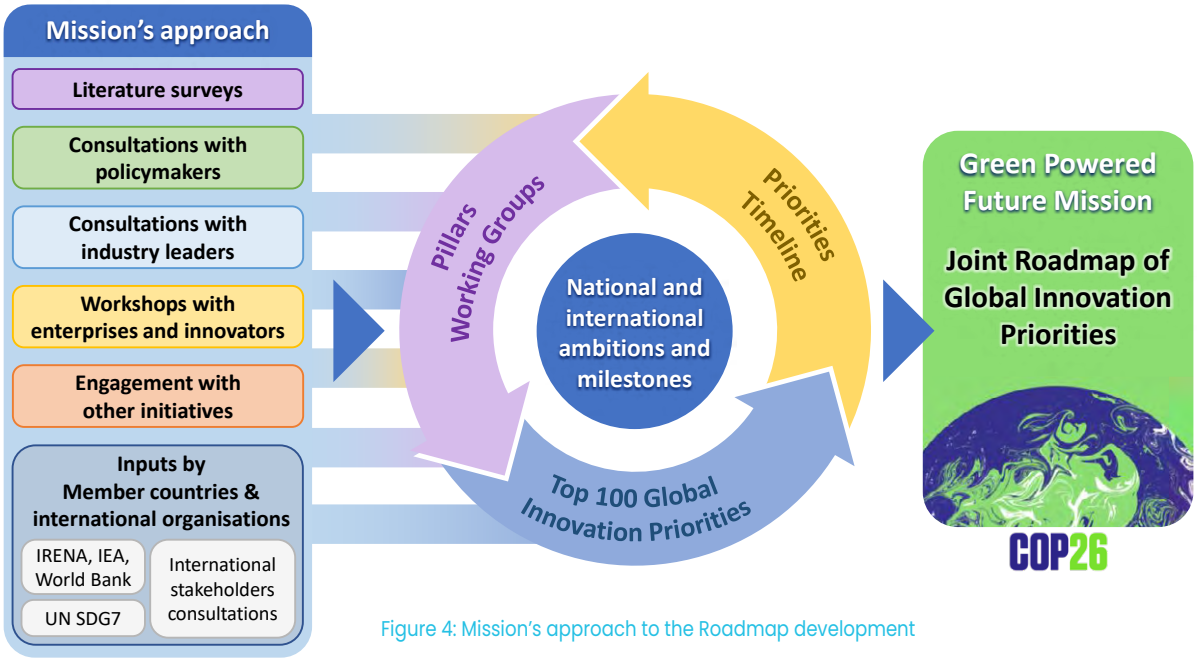


Figure 4: Mission's approach to the Roadmap development

Chapter 3

THE ROADMAP: GLOBAL INNOVATION PRIORITIES AND MAIN ACTIONS

THE GREEN POWERED FUTURE MISSION ROADMAP SETS OUT THE TOP 100 GLOBAL INNOVATION PRIORITIES TO BE ADDRESSED TO ACHIEVE THE MISSION'S GOAL. EACH PRIORITY HAS BEEN RANKED, IN TERMS OF URGENCY AND IMPORTANCE, TO GUIDE THE MISSION'S UPCOMING ACTIONS. THIS ROADMAP WILL ACT AS THE GUIDE TO THE DEVELOPMENT OF THE MISSION ACTION PLAN WHICH WILL DETAIL THIS DECADE'S KEY MISSION ACTIVITIES.

Introduction

To achieve the 10-year Mission goal, this roadmap defines 17 R&I themes and the top 100 Innovation Priorities. These are not only the breakthrough technological needs to reach the tipping points but are fundamental R&I advancements that need to be tackled through collaborative research, demonstration and knowledge sharing.
To deliver the roadmap, a multi-phase implementation method will be adopted consisting of a feasibility phase, a pilot and a demonstrator phase followed by knowledge dissemination and best practice sharing.

Ranking the innovation priorities

Given the decade-long Mission mandate, and the number of global innovation priorities identified, the Power Mission has ranked the priorities by recognising the relative urgency and importance of each. This will allow the Power Mission to focus resources effectively to systematically work towards the Mission's goal. Through a series of workshops, consultations and surveys with stakeholders across the globe, the following aspects of each priority was assessed:

- **Importance and impact:** how important is the priority in terms of its potential depth and breadth of impact towards achieving the tipping points.
- **Urgency:** how critical is the priority to solving a present barrier which needs to be overcome to achieve the tipping points which would otherwise be impossible given current initiatives.
- **Interdependency:** which priorities need to be completed for subsequent priorities to be implemented.
- **Pilot projects and demonstrators:** which priorities require the completion of pilot projects or demonstrators to be properly addressed, and the availability of stakeholders to launch these.

In the following infographics, the 17 **R&I themes** (left-hand side labels) and their related innvovation priorities are reported: the "Higher priority" innovations have the strongest urgency, the highest technical maturity and are expected to make a breakthrough in the first 3 years of the Mission implementation. The technology maturity and urgency of a medium priority innovation are categorised as "mid-priority", where a breakthrough is expected in 4-6 years. The "lower priority" innovations can be recognised as the ones in their early stage of R&D, which in the long-term will advance and be deployed in 6-10 years
Moreover, the interest of the Mission stakeholders to deliver demonstrators in selective priorities is indicated with:

- a "gear" icon if a demo project is foreseen for the innovation priority.
- a "star" icon if a demo project has been indicated as "nice to have".

The descriptions of the innovation priorities reported in the following infographics are available at this **link.**

Pillar 1 - Affordable and reliable VRE

- **TP 1.1** Novel PV technologies
- **TP 1.2** Offshore wind technologies
- **TP 1.3** Improve forecasting tools
- **TP 1.4** Off-grid VRE-based systems
- **TP 2.1** Short-term flexibility
- **TP 2.2** Mid-term flexibility
- **TP 2.3** Long-term flexibility
- **TP 3.1** Standards for Interoperability
- **TP 3.2** Secure & digitalised energy system
- **TP 3.3** Integrated platforms

	Higher priority (within 3 years)	Mid priority (next 4-6 years)	Lower priority (next 7-10 years)	Contribution to Tipping Points
Novel Photovoltaic	**1.1.1** High efficiency PV cells and modules			
	1.1.2 Affordable and customisable building-integrated PV			
	1.1.3 Reliability evaluation of PV modules and systems			
	1.1.4 Floating PV technologies			
	1.1.5 Software and database for PV systems			
	1.1.6 Recycling and eco-design of PV cells and modules			
	1.1.7 Agri-PV technologies			
	1.1.8 PV ecosystem to enable sustainable development			
	1.1.9 Climate change impact on solar resource			
Offshore Wind Power	**1.2.1** Intelligent control, operation and maintenance of offshore wind farms			
	1.2.2 Floating offshore wind turbines			
	1.2.3 Very-large offshore wind turbines			
	1.2.4 Modelling, simulation and analysis of offshore wind farms			
	1.2.5 Built-for-purpose offshore wind			
	1.2.6 Wind turbines recycling and end-of-life management			
Integrated Renewable Energy	**1.3.1** IRE technologies with Power-to-X			
	1.3.2 Large-scale IRE generation for improving system reliability and stability			
	1.3.3 Distributed IRE generation at grid edge			
	1.3.4 Enhanced granularity and intelligent forecasting method for high share VRE generation			
	1.3.5 New control architectures, modelling and energy management of IRE			

Demo projects Nice to have demo

Pillar 1 - Affordable and reliable VRE

- **TP 1.1** Novel PV technologies
- **TP 1.2** Offshore wind technologies
- **TP 1.3** Improve forecasting tools
- **TP 1.4** Off-grid VRE-based systems
- **TP 2.1** Short-term flexibility
- **TP 2.2** Mid-term flexibility
- **TP 2.3** Long-term flexibility
- **TP 3.1** Standards for Interoperability
- **TP 3.2** Secure & digitalised energy system
- **TP 3.3** Integrated platforms

	Higher priority (within 3 years)	Mid priority (next 4-6 years)	Lower priority (next 7-10 years)	Contribution to Tipping Points
Off-grid systems		**1.4.1** Isolated power systems with high share VRE ★		
		1.4.2 Remote microgrids ⚙		
		1.4.3 Integration of off-grid systems for electricity, heating/cooling, and transport ⚙		
		1.4.4 Small- to medium-size wind turbines for remote applications		
Energy Storage supply chain, recycle and reuse	**1.5.1** Analysis of batteries life cycle and monitor, test and recycle of batteries			
	1.5.2 Recycling and reuse batteries design ★			
	1.5.3 Innovation in energy storage technologies ★			
	1.5.4 Driving cost-reduction across the battery supply chain			
		1.5.5 Novel high-performance methods for battery evaluation		
	1.5.6 Safety assessment of electrochemical storage			
			1.5.7 Smart sensors for batteries	
		1.5.8 Energy storage technologies, demo and applications, economic analysis ⚙		
Technologies for System Stability	**1.6.1** Grid-forming devices applied to solar PV and wind			
	1.6.2 Grid-supporting technologies from inverter-based resources ★			
		1.6.3 MVDC/LVDC-based renewables systems for enhancing stability and efficiency ★		
			1.6.4 Stability evaluation and enhancement strategies for grid integration of VRE	

⚙ **Demo projects** ★ **Nice to have demo**

Pillar 2 - System flexibility and market design

- **TP 1.1** Novel PV technologies
- **TP 1.2** Offshore wind technologies
- **TP 1.3** Improve forecasting tools
- **TP 1.4** Off-grid VRE-based systems
- **TP 2.1** Short-term flexibility
- **TP 2.2** Mid-term flexibility
- **TP 2.3** Long-term flexibility
- **TP 3.1** Standards for Interoperability
- **TP 3.2** Secure & digitalised energy system
- **TP 3.3** Integrated platforms

	Higher priority (within 3 years)	Mid priority (next 4-6 years)	Lower priority (next 7-10 years)	Contribution to Tipping Points
Flexible Generation	**2.1.1** VRE flexibility provision and contribution to generation capacity			
	2.1.2 Further exploitation of hydropower and pumped hydro flexibility			
	2.1.3 Low carbon flexible generation enhancement			
Grid Flexibility	**2.2.1** Innovative components and dynamic line rating			
	2.2.2 Technologies and controls for multi-terminal HVDC interconnections			
	2.2.3 Power electronics devices for grid flexibility			
	2.2.4 Enhanced control rooms and automated decision systems			
	2.2.5 New and automated protection schemes for converter-based systems			
System Stability and Flexible Operations	**2.3.1** System stability assessment considering high VRE penetration			
	2.3.2 Enhanced TSO-DSO coordination platform for flexibility markets optimisation			
	2.3.3 Innovative frequency and non-frequency ancillary services specifications			
	2.3.4 Tools and solutions for DSO flexibility management			
	2.3.5 DSOs and TSOs enhanced grid and DER observability			
	2.3.6 Solutions to mitigate short circuit power reduction			
	2.3.7 Black start capabilities assessment of VRE-based systems			
	2.3.8 Early identification of system critical situations			
	2.3.9 Optimized balancing procedures considering demand-side flexibility			
	2.3.10 Building blocks of delivering flexibility services			
Energy Storage Integration	**2.4.1** Need and requirements assessment for storage systems new services			
	2.4.2 Aggregation of behind the meter batteries for flexibility services			
	2.4.3 Utility scale storage systems for innovative flexibility services			
	2.4.4 Assessment of energy management for multi-service energy storage systems			
	2.4.5 Tools for optimal energy storage technology selection and sizing			
	2.4.6 Identification of main barriers hindering storage systems mass deployment			
			2.4.7 Fuel Cells and Fuel Cell-Battery Hybrid systems integration	

Demo projects **Nice to have demo**

Pillar 2 - System flexibility and market design

- **TP 1.1** Novel PV technologies
- **TP 1.2** Offshore wind technologies
- **TP 1.3** Improve forecasting tools
- **TP 1.4** Off-grid VRE-based systems
- **TP 2.1** Short-term flexibility
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- **TP 3.1** Standards for Interoperability
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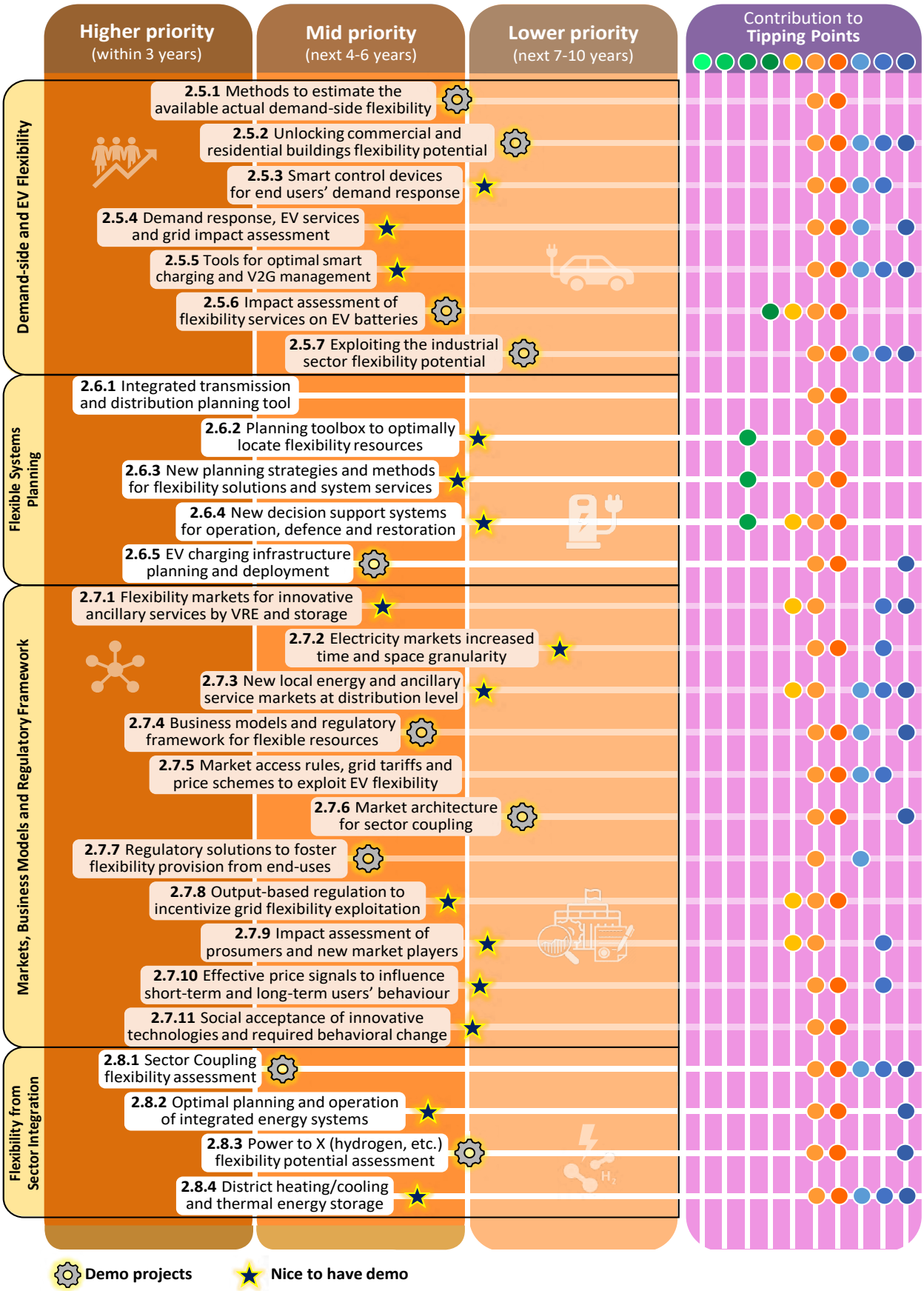
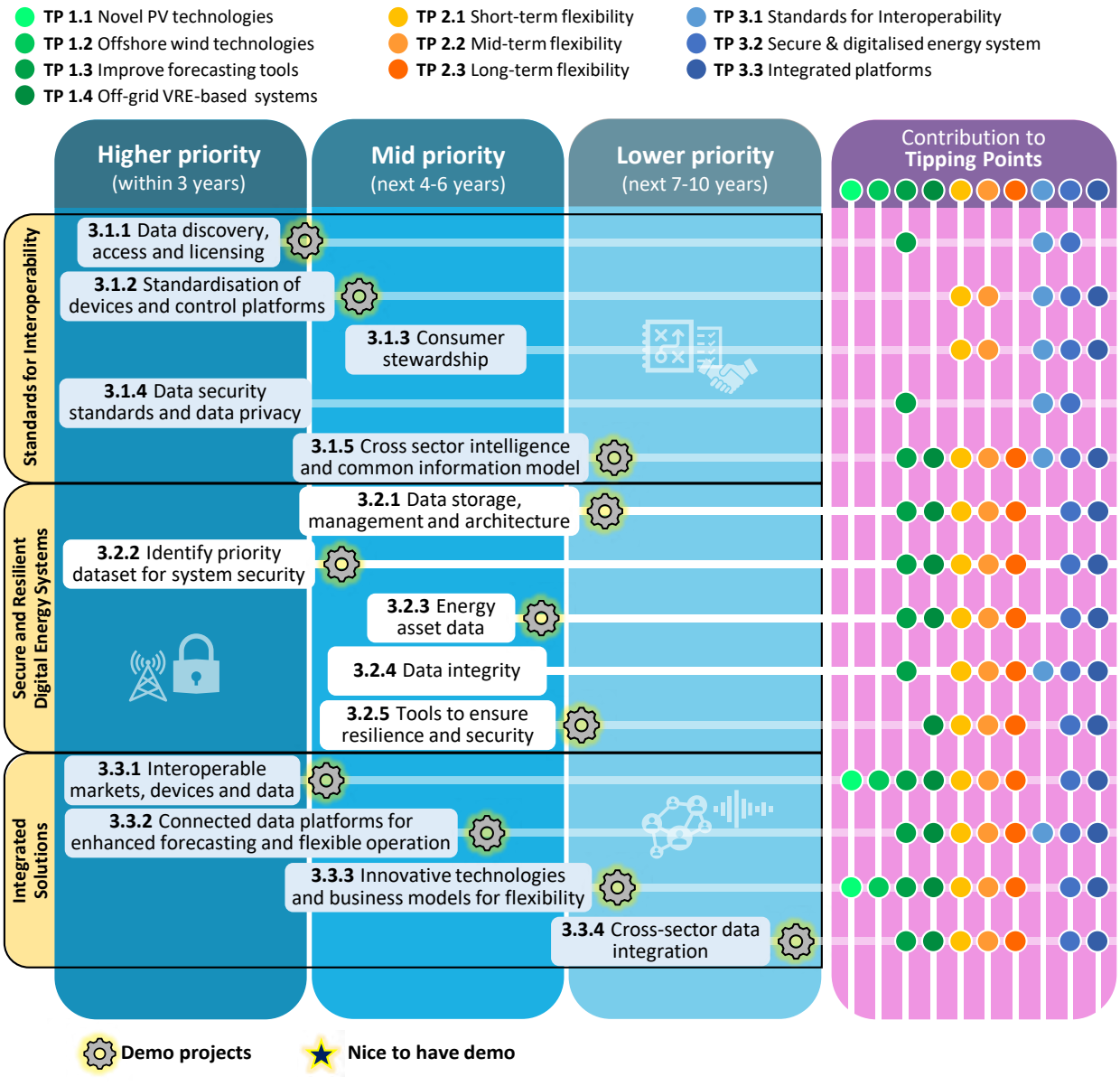


Pillar 3 - Data and Digitalisation for System Integration



Implementing the Roadmap: The Mission Action Plan

Whilst this Roadmap sets out the priorities of the Green Powered Future Mission, the next steps will be to develop a detailed action plan which considers the resources required to deliver the Mission's goal. Demonstrations of innovative solutions will form an important part of the Green Powered Future Mission, as reflected in the roadmap. To deliver these successfully, different "phases" of implementation, each one involving feasibility studies, demonstrators set up and validation, knowledge and capacity building, and dissemination activities, will form the approach to systematically implementing the Mission's priorities. This approach will take best advantage of the resources and expertise brought by the Power Mission members allowing different innovation priorities to be tackled at the same time. Simultaneously, technical, regulatory and market aspects will be considered to ensure they keep up with the pace of innovation required.

The Mission Action Plan will also consider the importance of embedding replicability and scalability in order to develop pilot projects suitable for the replication of innovative solutions in a broad range of contexts and system conditions.

Moreover, additionality will be the preferred approach, increasing the impact of existing initiatives which already target priorities through existing pilot schemes or grid modernisation initiatives.

The Power Mission members have already expressed strong interest across the list of innovation priorities and are ready and committed to developing and delivering on the Mission Action Plan by validating innovative solutions in the specific indicated R&I areas, and by providing policy and technology recommendations for the activities not targeted by demo projects.

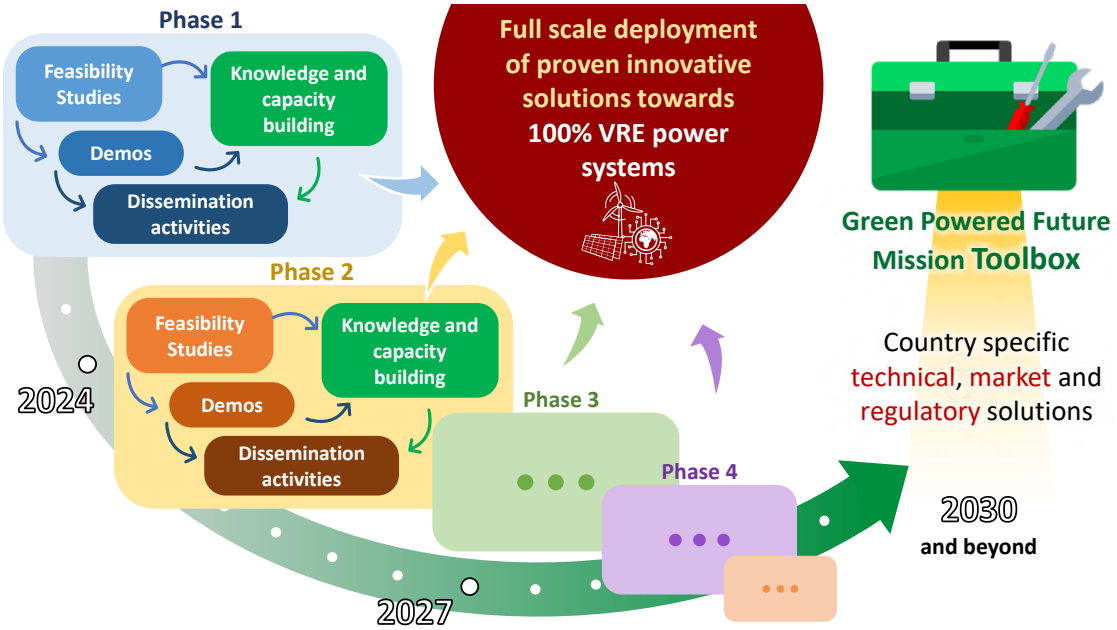


Figure 5: Implementation "phases" towards the Mission's toolbox development

KEY MESSAGES AND THE WAY FORWARD

THIS ROADMAP IDENTIFIES THE MOST RELEVANT R&I THEMES AND RELATED GLOBAL INNOVATION PRIORITIES TO BE TACKLED TO ACHIEVE UP TO 100% VRE POWER SYSTEMS. THE PRIORITIES HAVE BEEN RANKED IN TERMS OF URGENCY AND IMPACT, INDICATING THE GREEN POWERED FUTURE MISSION'S COALITION STRATEGY AND COMMITMENT FOR THIS DECADE.

This Roadmap, developed through the efforts of all the Power Mission members, identifies the most relevant R&I efforts needed for the achievement of the Mission goal. This document is a tangible and actionable output of the first sprint of the Mission and will serve as a base to further detail the Mission activities towards the 2022-2024 Action Plan.

Key messages

- System innovation challenges are global, solutions can differ depending on local conditions and power system characteristics. Effective knowledge sharing among countries that face similar issues and present similar conditions will boost innovation deployment.
- Active engagement of all energy system stakeholders is essential to develop and deploy innovative solutions that are increasingly complex and require a joint effort of different expertise.
- System flexibility, digitalisation and data are key: there are several innovation priorities related to these aspects and they all need to be tackled to have a significant impact.
- Besides technology, business and market aspects such as new business models and market design are also essential to enable effective uptake of innovative solutions.
- Field and real-scale testing is necessary to effectively foster the deployment of innovative solutions: suitable demo projects need to be designed, launched and validated. Power Mission members are committed to support the achievement of the Mission goal especially through the launch of demo projects involving different innovation priorities.
- The deployment of affordable and reliable VRE, considering various climates and environments, as well as innovation on PV, offshore wind, storage and their system integration is an essential factor.
- The integration of high shares of VRE requires enhanced system operation and tools involving the deployment of new technologies, market solutions and regulatory frameworks.
- Digitalisation is a key enabling factor and will play an increasingly pivotal role in future energy systems.
- Storage, flexibility from demand-side and EV smart charging will represent an increasingly important support to system flexibility and VRE uptake.
- Effective system integration will underpin deep transformation of the overall energy system and unleash substantial opportunities for additional flexibility, essential to accommodate higher penetration of VRE.
- Distribution networks that are hosting increasing levels of VRE are in the frontline in addressing system challenges.

The way forward

Besides the incorporation of a large number of inputs received from public and private sector stakeholders as well as from international organisations, what characterises this Roadmap is the identification of the innovation that Mission's members are committed to tackle by supporting large and well-tergeted demonstration projects. The actionable dimension is extremely important for the definition of the Mission **Action Plan 2022-2024** that the Power Mission is developing and that will report in detail the practical key actions to be implemented in order to reach the Mission's ambitious goal.

MISSION INNOVATION

Green Powered Future Mission Coalition

China *- Ministry of Science and Technology (MOST)*
Italy *- Minister for Ecological Transition (MITE)*
United Kingdom *- Department for Business, Energy and Industrial Strategy (BEIS)*

Australia *– Department of Industry, Science, Energy and Resources (DISER)*
India *– Department of Science and Technology (DST)*
Saudi Arabia *– Ministry of Energy*
IRENA – International Renewable Energy Agency
World Bank Group
Alperia SpA, Italy
Areti SpA, Italy
Enel Global Infrastructure & Networks, Italy
National Grid Group, United Kingdom
Icebreaker One, United Kingdom
LONGi Green Energy Technology Co., Ltd., China
Xinjiang Goldwind Science Technology Co., Ltd., China

Austria *– Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK)*
Brazil *– Energy Research Office (EPE)*
Canada *– Natural Resources Canada/Ressources Naturelles Canada (NRCan/RNCan)*
European Commission *– Directorate-General for Research & Innovation*
Germany *– Federal Ministry for Economic Affairs and Energy (BMWI)*
Japan *– Ministry of Economy, Trade and Industry (METI)*
Netherlands *– Ministry of Economic Affairs and Climate Policy (MINEZK)*
Republic of Korea *– Ministry of Trade, Industry and Energy (MOTIE)*
IEA – International Energy Agency
Energy Networks Association (ENA), United Kingdom
Gestore dei servizi energetici (GSE), Italy
BSI Group, United Kingdom

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GREEN POWERED FUTURE MISSION