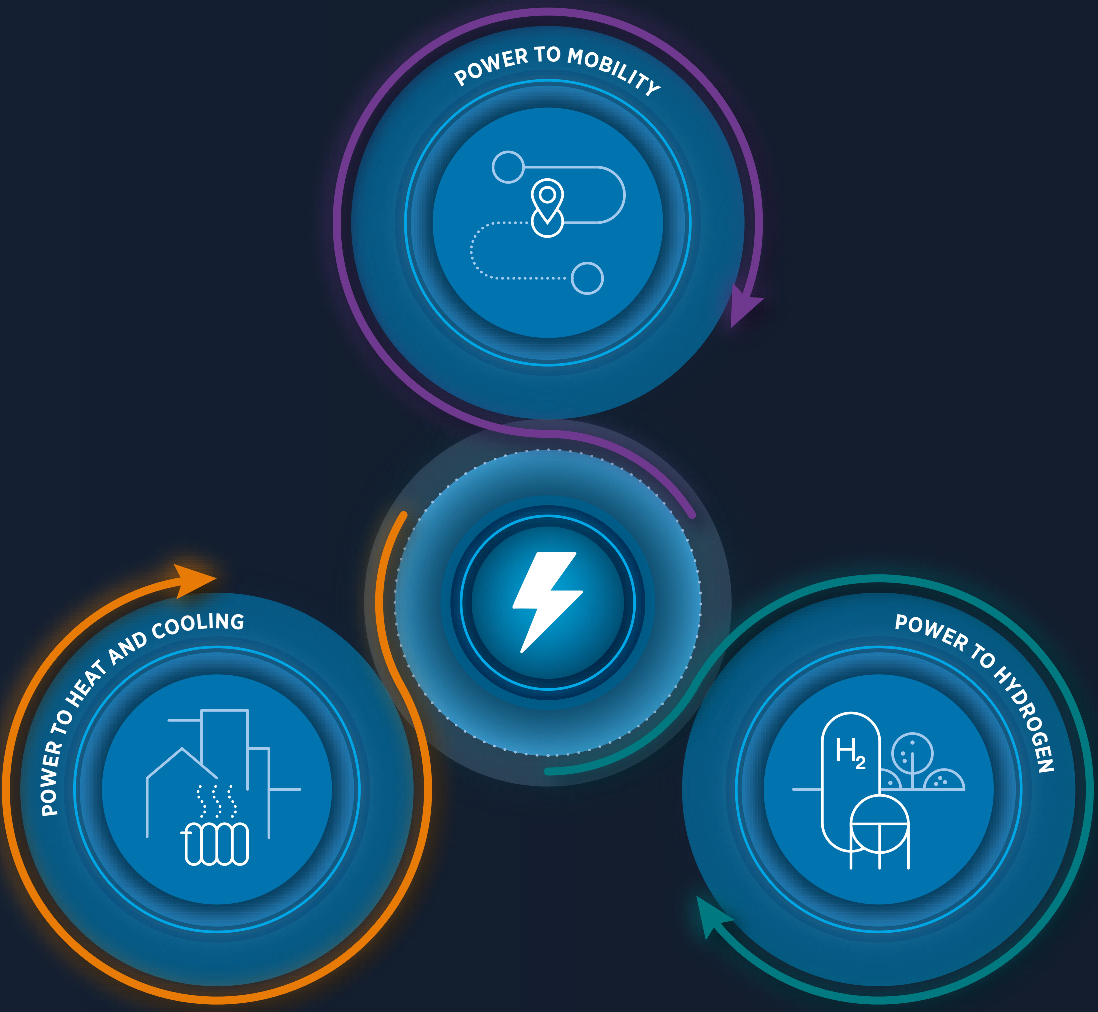
IRENA

International Renewable Energy Agency

INNOVATION LANDSCAPE FOR SMART ELECTRIFICATION

DECARBONISING END-USE SECTORS WITH RENEWABLE POWER



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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

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FOREWORD

Francesco La Camera

Director-General

International Renewable
Energy Agency

Recent global events have led to a new sense of urgency in the energy transition discourse, but it is clear that delivering a clean energy future in line with the collective commitment to limit global temperature increase to 1.5°C of pre-industrial levels will entail measures that reach far beyond renewable energy generation. A successful, inclusive energy transition that benefits all must also address aspects such as energy security, access, competitiveness, investment and social equity.

The 28th Conference of the Parties to the UNFCCC (COP28) will define concrete plans that governments should implement in the coming 2-3 years to significantly accelerate decarbonisation. To inform these zero-carbon pathways and translate them into concrete action, governments will require guidance as to the optimal mix of innovations for their specific national contexts. Innovation is therefore not only the driving force behind the ongoing transformation of the global energy system - it also holds the key to significantly accelerating its delivery to meet increasingly urgent climate objectives.

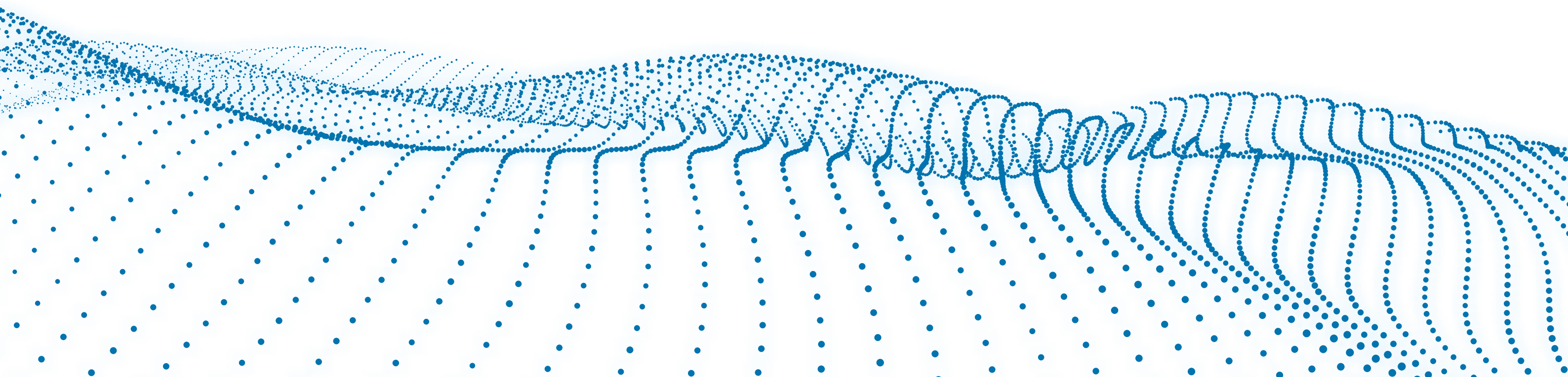
Global investment across all energy transition technologies reached a record high of USD 1.3 trillion in 2022; but this must quadruple in annual terms to meet the 1.5°C Scenario detailed in IRENA's *World Energy Transitions Outlook*. Investment will need to be channelled to a range of emerging technologies, such as energy storage and electrolysers for green hydrogen production, as sizeable stimulus packages are implemented in major economies – including the Inflation Reduction Act in the United States and the Net Zero Industry plan in the European Union. To a great extent, these initiatives and associated investments are the result of technological innovation, as well as innovations in policy, market design and financing instruments.

Under the 1.5°C Scenario, electricity would become the energy carrier of the future – meeting more than 50% of global energy consumption, compared to 22% in 2020. It will be needed to electrify the transport and heating/cooling sectors, as well as to produce green hydrogen to decarbonise hard-to-electrify sectors such as fertiliser production, as well as chemical and synthetic fuel production for shipping and aviation. Meanwhile, holistic, smart electrification strategies will be required to deliver an effective structural transformation of the energy economy, allowing the electrification of transport, buildings and industry to facilitate an accelerated uptake of solar and wind power, while minimising the investments needed.

Many smart electrification solutions are already available and ready for commercialisation, with pioneering companies creating, trialling and deploying potentially transformative innovations. However, timely and focused government actions are essential to support innovation and integrate emerging solutions. In 2019, IRENA published its first innovation landscape report, that presented a toolbox of innovations that policymakers can use to integrate high shares of renewable energy in power systems while maintaining their affordability and reliability.

This 2023 edition of the report provides a new toolbox comprising 100 innovations that countries can embed in tailored national strategies to decarbonise end-use sectors. Decision-makers should adopt a systemic approach, combining innovations in technology and infrastructure with those in market design and regulation, system planning and operation, and business models. This requires careful consideration and understanding in order to identify and address obstacles to the process of coupling the power system with the end-use energy sector. Also, the unique factors that prevail in each national energy system must be taken into account when transferring knowledge, sharing experiences and replicating success stories.

The accelerating pace of innovation offers great promise for a sustainable low-carbon future powered by the adoption of renewable energy and smart electrification strategies. This innovation toolbox aims to provide key information on existing and emerging innovations that policymakers can draw upon to support end-use sector decarbonisation using renewables. IRENA stands ready to support countries by tailoring this innovation toolbox to their specific contexts in order to accelerate a just and fair energy transition that serves national energy policy objectives.



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ABBREVIATIONS

4GDH	fourth-generation district heating
5GDH	fifth-generation district heating
AC	alternating current
AEM	anion exchange membrane
AI	artificial intelligence
ALK	alkaline
BNEF	Bloomberg New Energy Finance
CAAS	charging as a service / cooling as a service
CCFD	carbon contract for difference
CO_2	carbon dioxide
DC	direct current
DER	distributed energy resources
DHC	district heating and cooling
DSO	distribution system operator
EJ	exajoule
E-MAAS	electric mobility as a service
EMEC	European Marine Energy Centre
ENTSO-E	European Network of Transmission System Operators for Electricity
ETS	Emission Trading System / Economic Transition Scenario
EU	European Union
EUR	euro
EV	electric vehicle
FPPA	flexible power purchase agreement
GW	gigawatt
H_2	hydrogen
HAAS	heat as a service
HPA	hydrogen purchase agreement
HTHP	high-temperature heat pumps
HYAI	Hydrogen Artificial Intelligence
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IOT	Internet of Things
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IPT	inductive power transfer
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
KM	kilometre
KG	kilogramme
KW	kilowatt
KWH	kilowatt hour
LOHC	liquid organic hydrogen carrier
m^3	cubic metre
MAAS	mobility as a service
MFRR	manual frequency restoration reserve
MT	million tonnes
MW	megawatt
MWH	megawatt hour
NEDO	New Energy and Industrial Technology Development Organization
P2P	power to power
PCM	phase-change material
PEM	polymer electrolyte membrane
PPA	power purchase agreement
PV	photovoltaic
RES	renewable energy source
SOEC	solid oxide electrolyser cell
TFEC	total final energy consumption
TES	thermal energy storage
TSO	transmission system operator
TWh	terawatt hour
USD	United States dollar
V1G	unidirectional smart charging
V2B	vehicle to building
V2G	vehicle to grid
V2H	vehicle to home
VRE	variable renewable energy

EXECUTIVE SUMMARY

Innovation is the engine powering the global energy transformation towards a carbon-neutral future. This transformation focuses on how we produce energy but also on how we consume it. Both supply and demand must be transformed together and in co-ordination for a faster and more effective decarbonisation of the entire system. On the supply side, wind and solar technologies have experienced rapid growth in recent years, making available large amounts of clean electricity in power systems. However, the demand side has not evolved in parallel and– until recently, society has consumed energy following traditional fossil fuel-based approaches. Today, the transport and heating sectors still largely rely on fossil fuels.

According to IRENA's 1.5°C Scenario, the share of direct electricity in total final energy consumption must increase from 22% in 2020 to 29% by 2030, and to 51% by 2050; this can be achieved with tremendous growth in electric-powered technologies, many of which are already available (IRENA, 2023). They include electric vehicles (EVs) and heat pumps, which can provide heat for buildings and many industrial processes. In addition, end-use sectors that are difficult to electrify directly can be decarbonised using "green" hydrogen produced by electricity generated from renewable energy, also known as indirect electrification.

With direct and indirect electrification, global electricity demand would triple by 2050, compared with 2020, under IRENA's 1.5°C Scenario (IRENA, 2023c). This brings challenges to the power system and increases the importance of energy efficiency measures. However, given the enormous benefits of electrification for decarbonising end-use sectors, governments around the world should not see smart electrification as a threat but rather as a major opportunity to accelerate economic growth, improve energy security, reduce the growing impacts of climate change and achieve other important sustainability goals. Yet, electrifying the consumption of energy is a complex task that goes beyond the adoption of technology solutions and requires the involvement of all stakeholders across the energy value chain, from the power sector to end-use sectors. This comprehensive approach is known as smart electrification.

Smart electrification is a cost-effective decarbonisation pathway for energy systems that is based on the electrification of energy end-use sectors via the incorporation of large shares of renewables in power systems and the unlocking of the flexibility of sources.

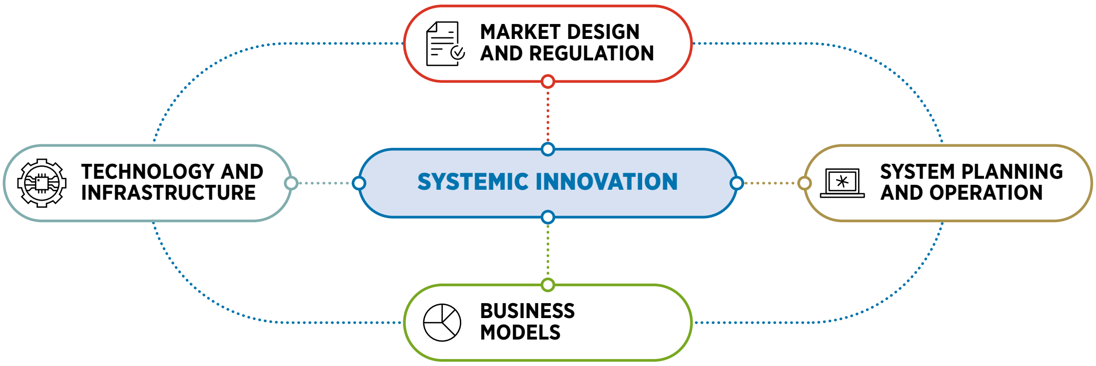
Smart electrification enables (1) power systems to accommodate new loads in a cost-efficient manner and creates (2) flexibility in power systems, which allows the integration of a larger share of renewables, making power systems more robust and resilient. For end uses, electrification is (3) the most cost-effective solution for decarbonising these sectors.

Smart electrification with renewables creates a virtuous cycle. Electrification drives new uses and markets for renewables. This, in turn, accelerates the switch to electricity for end uses, creating even more flexibility and driving further growth of renewables and technological innovation. In this context, innovation can reduce costs and create additional investment and business opportunities; transform the policy arena; and accelerate the virtuous cycle. Therefore, innovation is the foundation for a global energy revolution and for the rollout of effective smart electrification strategies.

However, any innovation that is meant to contribute to the decarbonisation of future energy systems will not succeed if implemented in isolation. Innovative solutions, built upon combinations of individual innovations, should bring together the necessary elements to deliver a transformative impact on the way societies consume energy today. Therefore, these innovative solutions go beyond technology-based solutions and include innovations in market design and regulation, system planning and operation, and business models. Innovative solutions will consequently emerge from the complementarities of advances across multiple components of energy systems, leveraging the synergies of these innovations in a process called *systemic innovation.* Systemic innovation is essential to achieve an effective structural transformation of the energy economy and includes innovations in:

- **Technology and infrastructure**, which play key roles in facilitating the electrification of end-use sectors, and related infrastructure.
- **Market design and regulation**, including new market structures and changes in the regulatory framework to incentivise and shape the electrification of end-use sectors and encourage smart electrification.
- **System planning and operation**, including innovative ways of planning the coupling of the power sector with the end-use sector and operating systems to maximise the integration of renewable power generation and minimise the extra load on power systems.
- **Business models** that create the business case for new services, making power systems more flexible and accelerating the electrification of end-uses.

FIGURE S.1 | Systemic innovation



This innovation landscape includes 100 key innovations that can play a role in transforming and decarbonising the energy use sector following smart electrification strategies.

It draws from a review of hundreds of innovative solutions that are emerging worldwide from start-ups, large companies, regulators and system operators, and that contribute to the smart electrification of mobility, heating and cooling, and hydrogen production.

TABLE S.1 | One hundred smart electrification innovations across three categories

100 INNOVATIONS

FOR SMART ELECTRIFICATION OF END-USE SECTORS

POWER TO MOBILITY

TECHNOLOGY AND INFRASTRUCTURE

- **1** EV model evolution
- **2** EV battery
- **3** Battery recycling technology
- **4** Diversity and ubiquity of charging points
- **5** Wireless charging
- **6** Overhead charging
- **7** Portable charging stations
- **8** V2G systems
- **9** Digitalisation for energy management and smart charging
- **10** Blockchain-enabled transactions
- **11** Smart distribution transformers
- **12** Smart meters and submeters

MARKET DESIGN AND REGULATION

- **13** Dynamic tariffs
- **14** Smart charging: local flexibility provision
- **15** Smart charging: system flexibility provision
- **16** “Right to plug” regulation
- **17** Streamline permitting procedures for charging infrastructure
- **18** Standardisation and interoperability
- **19** V2G grid connection code

SYSTEM PLANNING AND OPERATION

- **20** Cross-sectoral co-operation and integrated planning
- **21** Including EV load in power system planning
- **22** Grid data transparency
- **23** Clean highway corridors
- **24** Operational flexibility in power systems to integrate EVs
- **25** Management of flexible EV load to integrate VRE
- **26** Management of flexible EV load to defer grid upgrades
- **27** EV as a resilience solution

BUSINESS MODELS

- **28** EV aggregators
- **29** EV load peak shaving using DERs
- **30** Battery second life
- **31** EV charging as a service
- **32** Electric mobility as a service
- **33** Ownership and operation of public charging stations
- **35** A single bill for EV charging at home and on the go
- **35** Battery swapping

POWER TO HEAT AND COOLING

TECHNOLOGY AND INFRASTRUCTURE

- **1** Low-temperature heat pumps
- **2** Hybrid heat pumps
- **3** High-temperature heat pumps
- **4** Waste heat-to-power technologies
- **5** High-temperature electricity-based applications for industry
- **6** Low-temperature thermal energy storage
- **7** Medium- and high-temperature thermal energy storage
- **8** Fourth-generation DHC
- **9** Fifth-generation DHC
- **10** IoT for smart electrification
- **11** AI for forecasting heating and cooling demand
- **12** Blockchain-enabled transactions
- **13** Digitalisation as flexibility enabler

MARKET DESIGN AND REGULATION

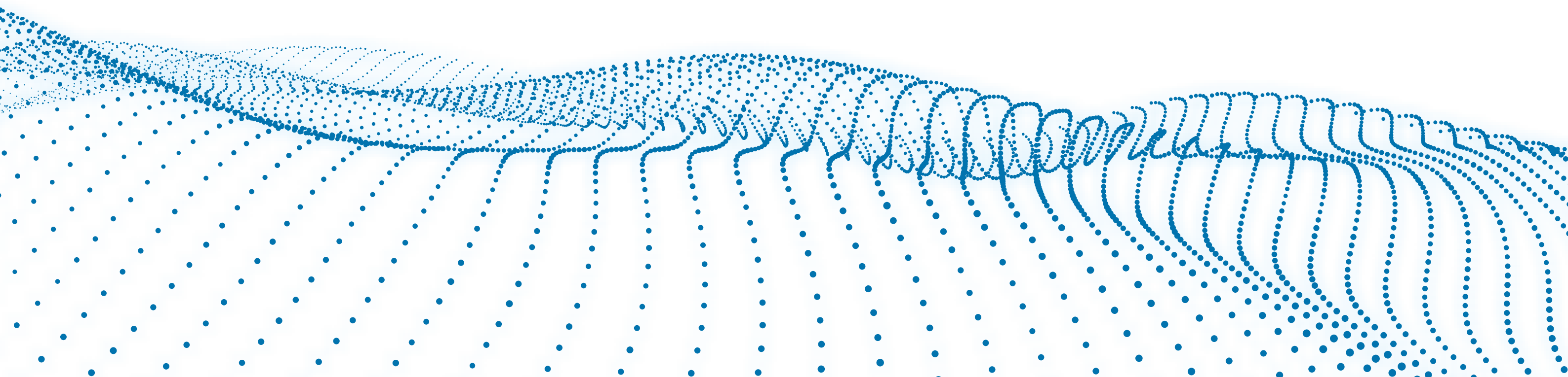
- **14** Dynamic tariffs
- **15** Thermal load flexibility
- **16** Flexible power purchase agreements
- **17** Standards and certifications for improved predictability of heat pump operation
- **18** Energy efficiency programmes for buildings and industries
- **19** Building codes for power-to-heat solutions
- **20** Streamline permitting procedures and regulations for thermal infrastructure

SYSTEM PLANNING AND OPERATION

- **21** Holistic planning for cities
- **22** Heat and cold mapping
- **23** Coupling cooling loads with solar generation
- **24** Smart operation with thermal inertia
- **25** Smart operation with seasonal thermal storage
- **26** Smart operation of industrial heating
- **27** Combining heating and cooling demands in district systems

BUSINESS MODELS

- **28** Aggregators
- **29** DERs for heating and cooling demands
- **30** Heating and cooling as a service
- **31** Waste heat recovery from data centres
- **32** Eco-industrial parks and waste heat recovery from industrial processes
- **33** Circular energy flows in cities – Booster heat pumps
- **34** Community-owned district heating and cooling
- **35** Community-owned power-to-heat assets



POWER TO HYDROGEN

TECHNOLOGY AND INFRASTRUCTURE

- **1** Pressurised ALK electrolyser
- **2** PEM electrolyser
- **3** SOEC electrolyser
- **4** AEM electrolyser
- **5** Compressed hydrogen storage
- **6** Liquefied hydrogen storage
- **7** Hydrogen-ready equipment
- **8** Digital backbone for green hydrogen production
- **9** Hydrogen leakage detection

MARKET DESIGN AND REGULATION

- **10** Additionality principle
- **11** Renewable PPAs for green hydrogen
- **12** Cost-effective electricity tariffs
- **13** Electrolysers as grid service providers
- **14** Certificates
- **15** Hydrogen purchase agreements
- **16** Carbon contracts for difference
- **17** Regulatory framework for hydrogen network
- **18** Streamline permitting for electrolyser projects
- **19** Quality infrastructure for green hydrogen
- **20** Regulatory sandboxes

SYSTEM PLANNING AND OPERATION

- **21** Electricity TSOs including hydrogen facilities in their planning
- **22** Co-locating electrolysers with renewable generators (onshore and offshore)
- **23** Smart hydrogen storage operation and P2P routes
- **24** Long-term hydrogen storage
- **25** Co-operation between electricity and gas network operators

BUSINESS MODELS

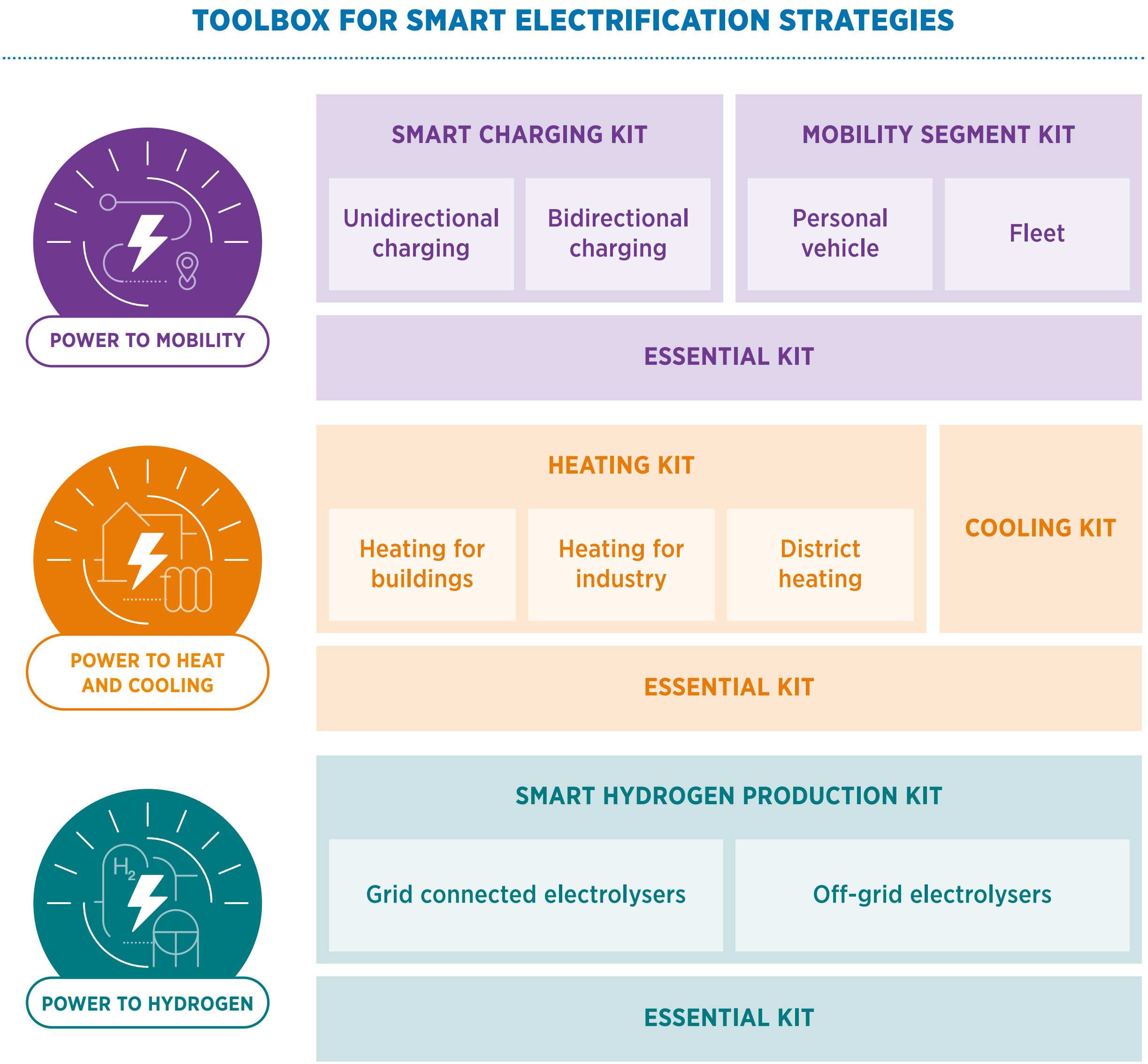
- **26** Local hydrogen demand
- **27** Hydrogen trade
- **28** Hydrogen industrial hub
- **29** Revenues from flexibility provided to the power system
- **30** Sale of electrolysis by-products (oxygen and heat)

AEM = anion exchange membrane; AI = artificial intelligence; ALK = alkaline; DER = distributed energy resources; DHC = district heating and cooling; EV = electric vehicle; IoT = Internet of Things; PEM = polymer electrolyte membrane; PPA = power purchase agreement; P2P = power-to-power; SOEC= solid oxide electrolyser cell; TSO = transmission system operator; VRE = variable renewable energy; V2G = vehicle to grid.

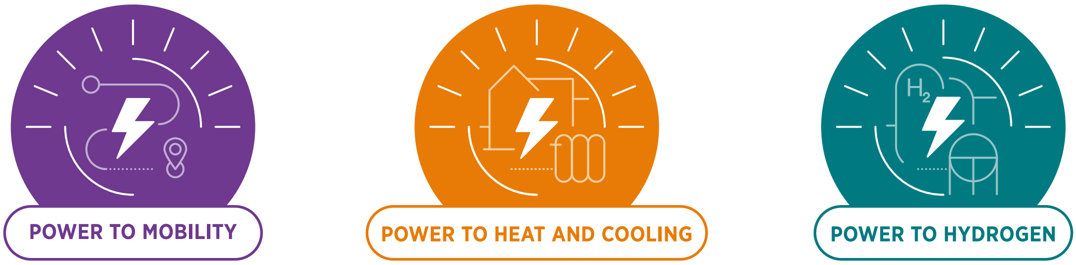
A "one-size-fits-all" solution for smart electrification does not exist. Optimal strategies and implementation of innovations will vary between countries and to account for system-specific attributes, including both the technical and economic aspects of a given power system and end-use sector, and social and cultural dimensions.

This work goes beyond an overview of promising innovations. It also provides guidance on how these innovation toolboxes can be used to build smart electrification strategies. To do so, innovations are grouped in “kits” that can complement one another. The kits are defined for the three end-use sectors based on the strategy’s ambition. First, the essential kit incorporates the innovations that are fundamental to start the transition to electrification. Next, more specific kits are defined to build on top of the essential kit, according to needs and objectives in each context.

FIGURE S.2 | Toolbox for smart electrification strategies



This report is organised into three sections:

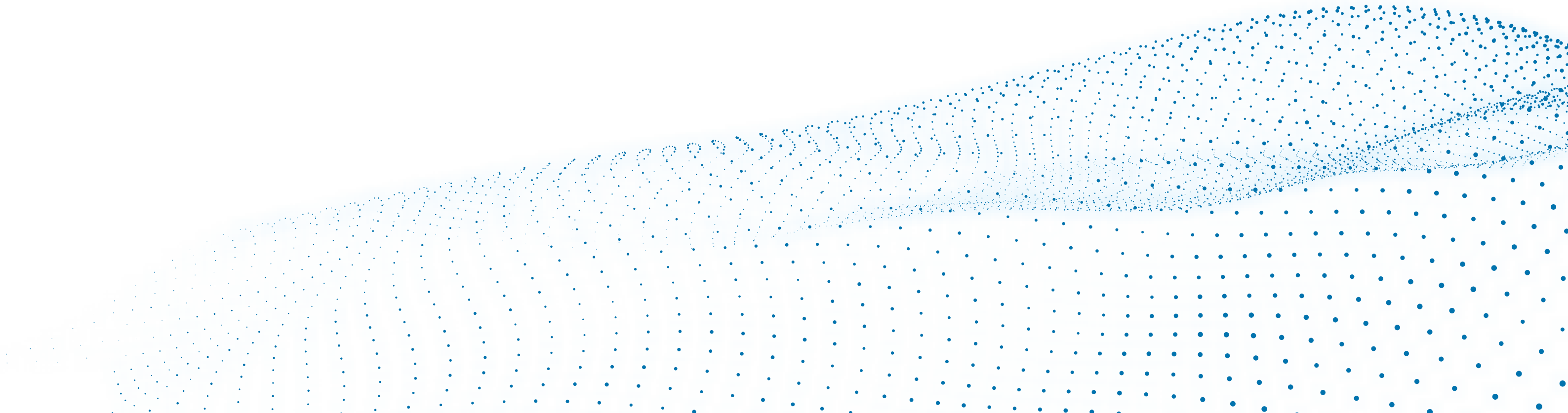


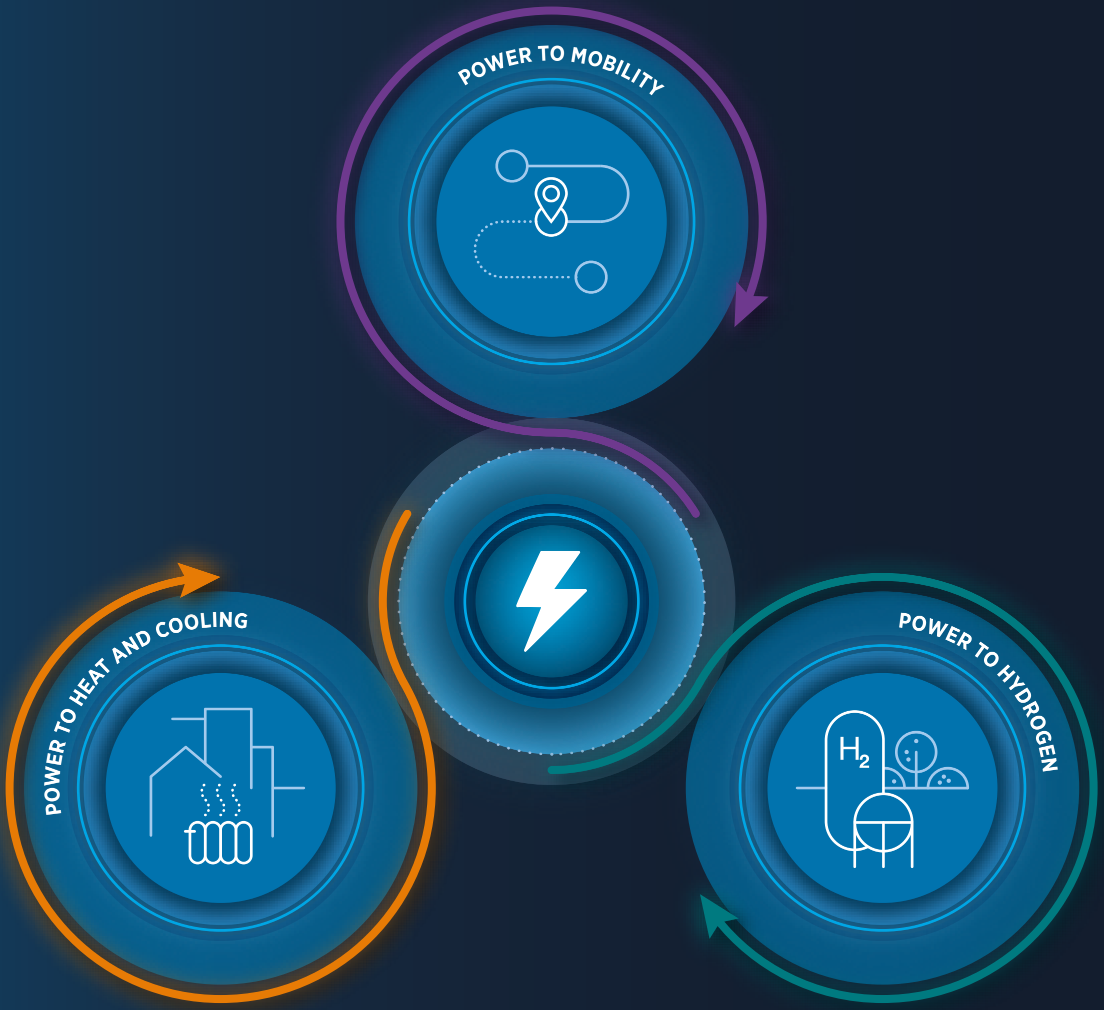
Each section follows the same structure:

- **Status and pace of progress of electrification of end-use sector**
  This section provides a quick overview of where the sector is today in the electrification process, which path could lead to decarbonisation goals, and the importance of a smart electrification approach. It also summarises the main challenges and identifies the blind spots that are often overlooked and hinder the deployment of smart electrification strategies.

- **Toolbox for smart electrification strategy**
  This section includes the guidelines for implementation. Using the innovation toolbox, it illustrates how smart electrification strategies can be developed for different context specificities and needs.

- **Innovation landscape for smart electrification of end-use sector**
  This section lists and describes the key innovations for each dimension and explains why it is important. It also includes examples of how the innovation has been implemented.




POWER TO MOBILITY
POWER TO HEAT AND COOLING
POWER TO HYDROGEN
H2

INTRODUCTION

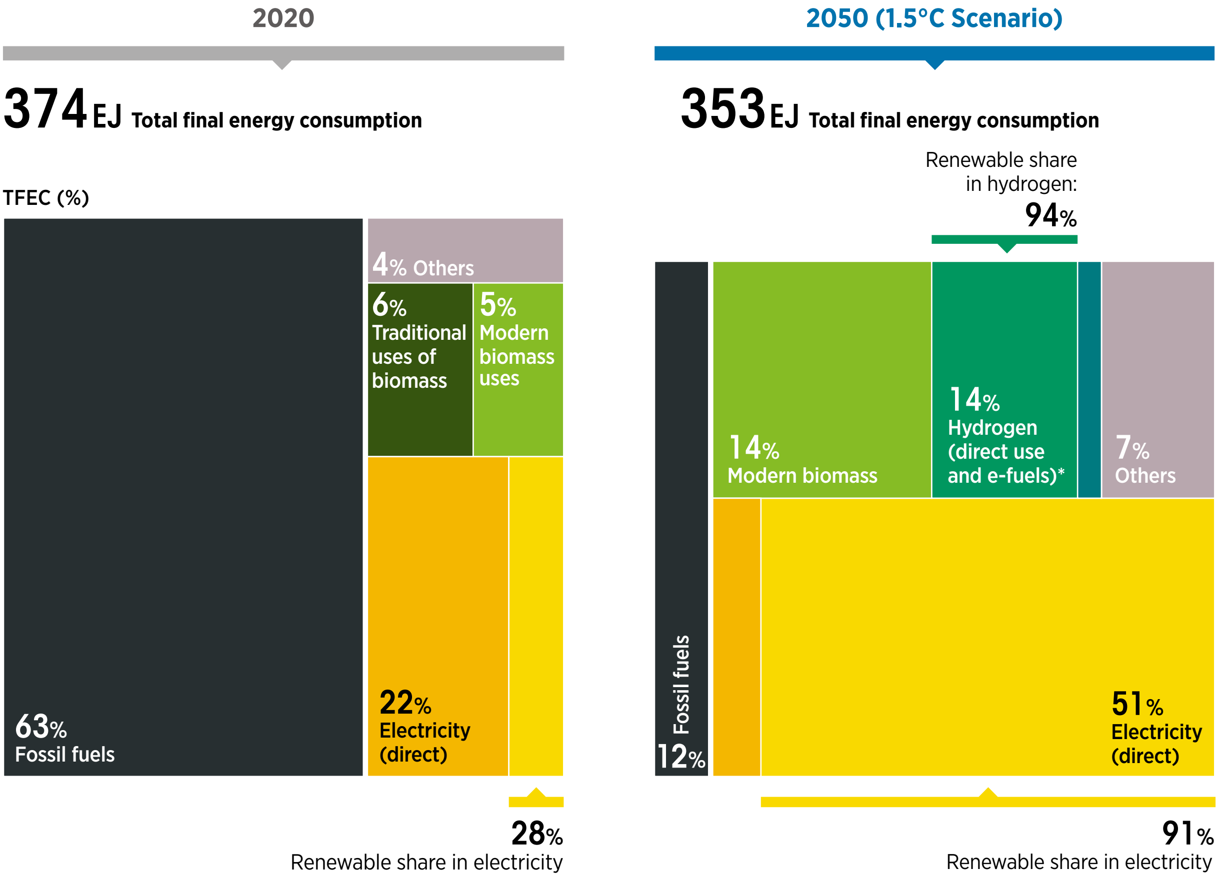
Systemic innovation is needed to achieve smart electrification of end-use sectors

The world has already begun a historic shift towards cleaner sources of energy. Rapid reductions in the cost of solar and wind technologies have led to widespread adoption of these technologies, which are now dominating the global market for new power generation capacity.

But the pace of change must accelerate if we are to meet sustainability and climate goals. We need an even faster expansion of renewables, along with a smarter, much more flexible electricity grid. Equally important is the need for significant increases in the range of products and processes that run on clean electricity in major end-use sectors, notably industry, buildings and transport.

Because the electrification of end uses enables the use of efficient technologies, widespread electrification – combined with efficiency measures – will decrease total global energy consumption. In IRENA's analysis, meeting the goals of the 2015 Paris Agreement on Climate Change will require the share of electricity in the energy mix to rise from 22% in 2020 to 51% in 2050, as shown in Figure I.1.

FIGURE I.1 | Final energy mix in 2018 and 2050



Source: (IRENA, 2023).

But the electrification of end uses alone is not enough. Electrification must be done in a “smart” way, both by interconnecting the power sector with other energy sectors, such as heat and mobility, and by enabling flexible sources across all energy sectors. Electric vehicles, for example, not only cut greenhouse gas emissions dramatically, they can also feed electricity to the grid, reducing the need to build additional generation capacity. Smart electrification, through sector coupling, flexibility and energy efficiency, thus prevents a higher electricity load for the power system and is a tremendously powerful tool for decarbonising the energy sector, including end uses.

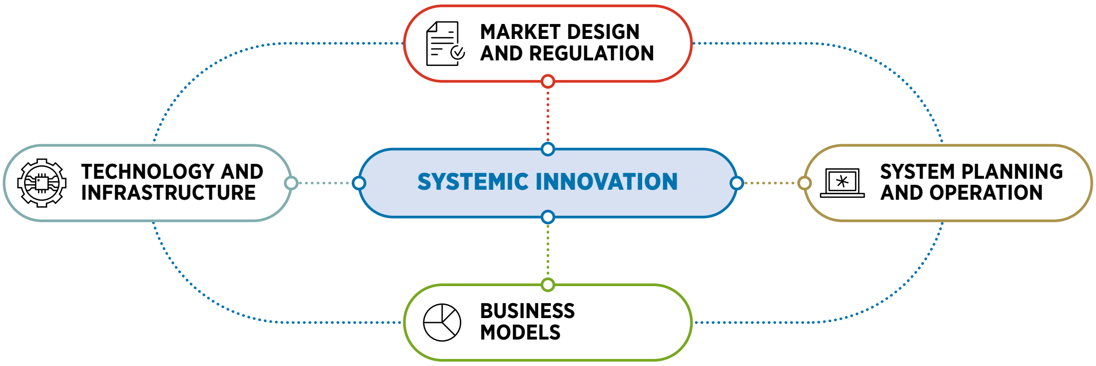
Smart electrification enables the power system to accommodate new loads in a cost-efficient manner. It also builds flexibility into the power system, thereby permitting the integration of a higher share of renewables and making the power system more robust and resilient. Smart electrification is the most cost-effective solution for decarbonising major end uses such as transport and heating.

Moreover, smart electrification with renewables creates a virtuous cycle. Electrification drives new uses and markets for renewables. That, in turn, accelerates the switch to electricity for end uses, creating even more flexibility and driving further growth in the use of renewables and continued technological innovation. Growth and innovation also cut costs and create additional opportunities for investment and business.

Innovation is the foundation for smart electrification and the global energy transformation. Most innovations cannot be implemented in isolation, nor are they limited to technology-based solutions. Along with innovation in technology and infrastructure, innovations are also needed in market design and regulation, system planning and operation, and business models. Innovative solutions will consequently emerge from the complementarities of advances across multiple components of energy systems and leveraging the synergies of these innovations in a process called *systemic innovation.*

The 100 key innovations identified in this report are spread across four dimensions: (1) technology and infrastructure, (2) market design and regulation, (3) system planning and operation, and (4) business models (Figure I.2). It is only by matching and leveraging synergies in innovations in all parts of the power system and end-use sectors and including all relevant actors and stakeholders that successful solutions can be implemented on the ground.

FIGURE I.2 | Dimensions of systemic innovation



Smart electrification cannot be pre-packaged. Optimal strategies for power system design and the application of innovation will vary among countries and their specific attributes, including both the technical and economic aspects of a given power system and its social and cultural context.

Electricity will be the main energy carrier in future energy systems

Achieving the Paris Agreement goal of limiting the increase in the global average temperature to 1.5°C relative to pre-industrial levels is the unifying principle behind IRENA's 1.5°C Scenario. To achieve that scenario, the share of electricity in total final energy consumption (TFEC) will have to grow from 21% in 2019 to 29% by 2030, and to 51% by 2050; this can be achieved through tremendous growth in technologies that operate on electricity, many of which are already available (IRENA, 2023). These include electric vehicles (EVs) and heat pumps, which provide heat for buildings and many industrial processes. In addition, end uses that are difficult to electrify directly, such as other industrial processes, can be electrified and decarbonised indirectly with "green" hydrogen produced using renewably generated electricity.

By 2050, global electricity demand is set to be 3 times what it was in 2020, posing challenges for power systems and raising the importance of energy efficiency. However, given the enormous benefits of electrification and decarbonisation, governments around the world should not see rapid, smart electrification as a threat or onerous task but rather as a golden opportunity to accelerate economic growth, improve energy security (Box I.1), reduce the growing impacts of climate change and achieve other important sustainability goals.

Table I.1 summarises the levels of electrification needed to reach the Paris Agreement targets.

TABLE I.1 | Electrification progress towards 2050 based on IRENA's 1.5°C Scenario

	Recent years	2030	2050
Share of direct electricity in total final energy consumption	22% (1)	29%	51%
Share of electricity in transport sector TFEC (%)	1% (2)	7%	52%
Share of electricity in the buildings sector (in TFEC terms)	34% (3)	53%	73%
Share of electricity in industry (TFEC)	20% (4)	25%	27%
Electric and plug-in hydrid light passenger vehicles stock (millions)	10 (5)	359	2 182
Passenger electric cars on the road (millions)	10.5 (6)	360	2 180
Electric vehicle chargers (millions)	1 (7)	372	2 300

	Recent years	2030	2050
Heat pumps in industry (in millions)	<1 (8)	35	80
Heat pumps in buildings (in millions)	58 (9)	447	793
Investment needed in heat pumps (USD billion/year)	64 (10)	237	230
Clean hydrogen production[b] (million tonnes per year)	0.7 (11)	125	523
Investment needs in clean hydrogen and derivitives infrastructure (including electrolysers, feedstock and infrastructure) (USD billion/year)	1.1 (12)	100	170
Industrial consumption of clean hydrogen (EJ)	0	14.4	40

Source: (IRENA, 2023b).

Notes: 1. 2020; 2. 2020; 3. 2020; 4. 2020; 5. 2020; 6. 2022; 7. 2020; 8. 2020; 9. 2020; 10. 2022; 11. 2021 - clean hydrogen here refers to the combination of hydrogen produced by electrolysis powered by renewables (green hydrogen) and hydrogen produced from natural gas in combination with carbon capture and storage (blue hydrogen); 12. 2022.

BOX I.1 | Electrification and energy security in Europe

The onset of the crisis in Ukraine in February 2022 triggered a severe energy crisis in Europe. Not only did the price of natural gas from Russia soar, but electricity prices also climbed steeply because of the still high use of gas to generate power. As a result, European industries, which are highly reliant on natural gas, are losing competitiveness, and energy bills for European citizens have soared dramatically.

This energy crisis is revealing the need for Europe to accelerate its energy transition. In addition to lessening the impacts of climate change, resilient and more secure energy systems will ensure stability, competitiveness, affordability and sustainability. Integrating high shares of renewables in the power system and using the resulting clean electricity to fuel end uses will decrease the dependence on gas that helped cause the current crisis. The current energy crisis in Europe may ultimately be an accelerator for the much-needed energy transition.

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Innovation landscape for smart electrification of end-use sectors

This report presents a landscape of innovations to help policy makers formulate smart electrification strategies. As noted, it includes 100 key innovations for both direct and indirect electrification of end uses (Figure I.3 and Table I.2). The innovations were selected based on analysis of hundreds of real-world projects in consultation with more than 150 external experts from across the world. The report also provides a list of important topics often overlooked when developing smart electrification strategies.

The report is divided into three parts corresponding to three main power to X routes for smart electrification:

- **Power to mobility** maps 35 key innovations for smart electrification of the transport sector.
- **Power to heat or cooling** maps 35 key innovations for smart electrification of the heating and cooling sector across three segments: buildings, industry, and district heating and cooling.
- **Power to hydrogen** maps 30 key innovations for smart indirect electrification to produce green hydrogen with renewable electricity via electrolysis. This section is limited to green hydrogen production and infrastructure and does not cover further uses and processing of hydrogen.

Each of the avenues illustrated in Figure I.3 includes guidelines on how to implement key innovations.

FIGURE I.3 | Direct and indirect avenues for smart electrification

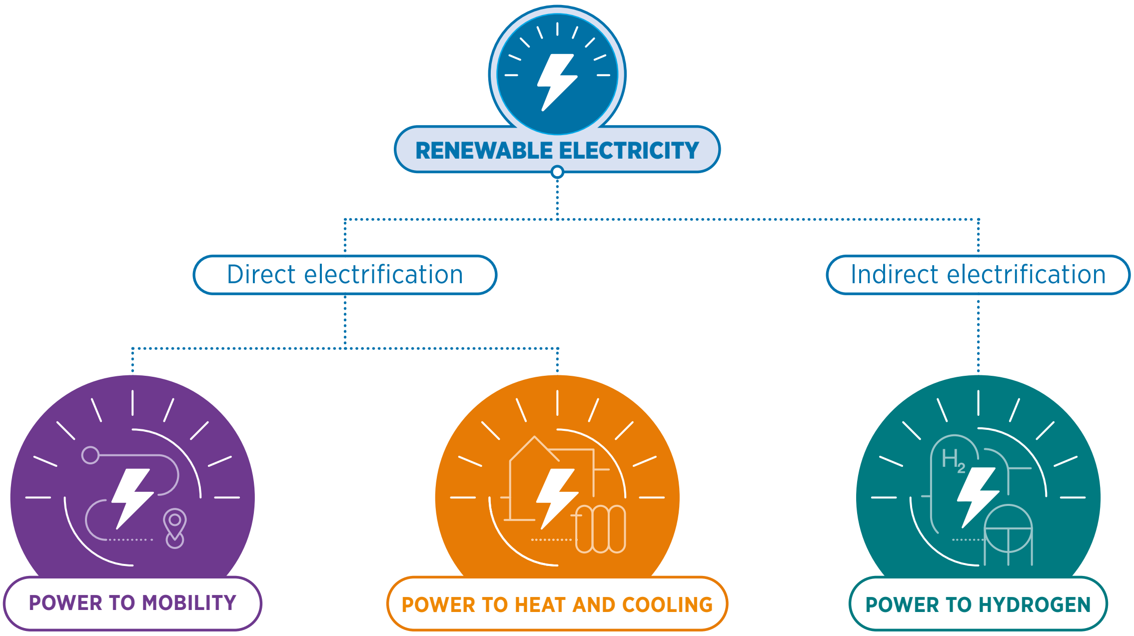


TABLE I.2 | **A hundred innovations for smart electrification of end uses spread across the four dimensions of systemic innovation**

POWER TO MOBILITY

35 INNOVATIONS

TECHNOLOGY AND INFRASTRUCTURE

- **1** EV model evolution
- **2** EV battery
- **3** Battery recycling technology
- **4** Diversity and ubiquity of charging points
- **5** Wireless charging
- **6** Overhead charging
- **7** Portable charging stations
- **8** V2G systems
- **9** Digitalisation for energy management and smart charging
- **10** Blockchain-enabled transactions
- **11** Smart distribution transformers
- **12** Smart meters and submeters

MARKET DESIGN AND REGULATION

- **13** Dynamic tariffs
- **14** Smart charging: local flexibility provision
- **15** Smart charging: system flexibility provision
- **16** “Right to plug” regulation
- **17** Streamlining permitting procedures for charging infrastructure
- **18** Standardisation and interoperability
- **19** V2G grid connection code

SYSTEM PLANNING AND OPERATION

- **20** Cross-sectoral co-operation and integrated planning
- **21** Including EV load in power system planning
- **22** Grid data transparency
- **23** Clean highway corridors
- **24** Operational flexibility in power systems to integrate EVs
- **25** Management of flexible EV load to integrate VRE
- **26** Management of flexible EV load to defer grid upgrades
- **27** EV as a resilience solution

BUSINESS MODELS

- **28** EV aggregators
- **29** EV load peak shaving using DERs
- **30** Battery second life
- **31** EV charging as a service
- **32** Electric mobility as a service
- **33** Ownership and operation of public charging stations
- **35** A single bill for EV charging at home and on the go
- **35** Battery swapping

Notes: AEM = anion exchange membrane; AI = artificial intelligence; ALK = alkaline; DER = distributed energy resources; DHC = district heating and cooling; EV = electric vehicle; IoT = Internet of Things; PEM = polymer electrolyte membrane; PPA = power purchase agreement; P2P = power-to-power; SOEC= solid oxide electrolyser cell; TES = thermal energy storage; TSO = transmission system operator; VRE = variable renewable energy; V2G = vehicle to grid.

POWER TO HEAT AND COOLING

35 INNOVATIONS

TECHNOLOGY AND INFRASTRUCTURE

- **1** Low-temperature heat pumps
- **2** Hybrid heat pumps
- **3** High-temperature heat pumps
- **4** Waste heat-to-power technologies
- **5** Medium- and high-temperature electricity-based applications for industry
- **6** Low-temperature TES
- **7** High-temperature TES
- **8** Fourth-generation DHC
- **9** Fifth-generation DHC
- **10** IoT for smart electrification
- **11** AI for forecasting heating and cooling demand
- **12** Blockchain-enabled transactions
- **13** Digitalisation as a flexibility enabler

MARKET DESIGN AND REGULATION

- **14** Dynamic tariffs
- **15** Thermal load flexibility
- **16** Flexible PPAs
- **17** Standards and certifications for improved predictability of heat pump operation
- **18** Energy efficiency programmes for buildings and industries
- **19** Building codes for power-to-heat solutions
- **20** Streamlining permitting procedures and regulations for thermal infrastructure

SYSTEM PLANNING AND OPERATION

- **21** Holistic planning for cities
- **22** Heat and cold mapping
- **23** Coupling cooling loads with solar generation
- **24** Smart operation with thermal inertia
- **25** Smart operation with seasonal thermal storage
- **26** Smart operation of industrial heating
- **27** Combining heating and cooling demand in district systems

BUSINESS MODELS

- **28** Aggregators
- **29** DERs for heating and cooling demands
- **30** Heating and cooling as a service
- **31** Waste heat recovery from data centres
- **32** Eco-industrial parks and waste heat recovery from industrial processes
- **33** Circular energy flows in cities – booster heat pumps
- **34** Community-owned district heating and cooling
- **35** Community-owned power-to-heat assets

Notes: AEM = anion exchange membrane; AI = artificial intelligence; ALK = alkaline; DER = distributed energy resources; DHC = district heating and cooling; EV = electric vehicle; IoT = Internet of Things; PEM = polymer electrolyte membrane; PPA = power purchase agreement; P2P = power-to-power; SOEC= solid oxide electrolyser cell; TES = thermal energy storage; TSO = transmission system operator; VRE = variable renewable energy; V2G = vehicle to grid.

POWER TO HYDROGEN

30 INNOVATIONS

TECHNOLOGY AND INFRASTRUCTURE

- **1** Pressurised ALK electrolyser
- **2** PEM electrolyser
- **3** SOEC electrolyser
- **4** AEM electrolyser
- **5** Compressed hydrogen storage
- **6** Liquefied hydrogen storage
- **7** Hydrogen-ready equipment
- **8** Digital backbone for green hydrogen production
- **9** Hydrogen leakage detection

MARKET DESIGN AND REGULATION

- **10** Additionality principle
- **11** Renewable PPAs for green hydrogen
- **12** Cost-effective electricity tariffs
- **13** Electrolysers as grid service providers
- **14** Certificates
- **15** Hydrogen purchase agreements
- **16** Carbon contracts for difference
- **17** Regulatory framework for hydrogen network
- **18** Streamlining permitting for electrolyser projects
- **19** Quality infrastructure for green hydrogen
- **20** Regulatory sandboxes

SYSTEM PLANNING AND OPERATION

- **21** Electricity TSOs including hydrogen facilities in their planning
- **22** Co-locating electrolysers with renewable generators (onshore and offshore)
- **23** Smart hydrogen storage operation and P2P routes
- **24** Long-term hydrogen storage
- **25** Co-operation between electricity and gas network operators

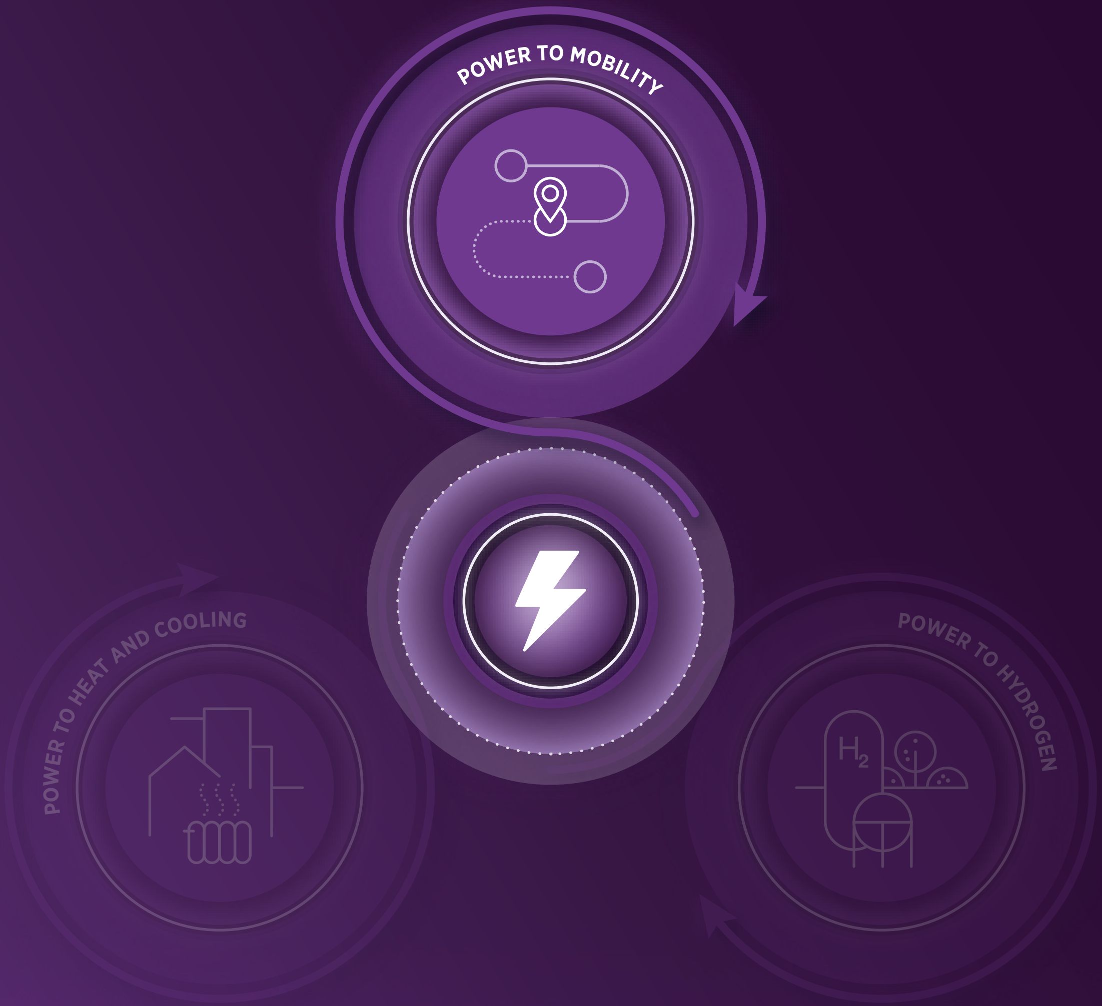
BUSINESS MODELS

- **26** Local hydrogen demand
- **27** Hydrogen trade
- **28** Hydrogen industrial hub
- **29** Revenues from flexibility provided to the power system
- **30** Sale of electrolysis by-products (oxygen and heat)

Notes: AEM = anion exchange membrane; AI = artificial intelligence; ALK = alkaline; DER = distributed energy resources; DHC = district heating and cooling; EV = electric vehicle; IoT = Internet of Things; PEM = polymer electrolyte membrane; PPA = power purchase agreement; P2P = power-to-power; SOEC= solid oxide electrolyser cell; TES = thermal energy storage; TSO = transmission system operator; VRE = variable renewable energy; V2G = vehicle to grid.

SECTION I

POWER TO MOBILITY



CHAPTER 1

ELECTRIFICATION OF MOBILITY

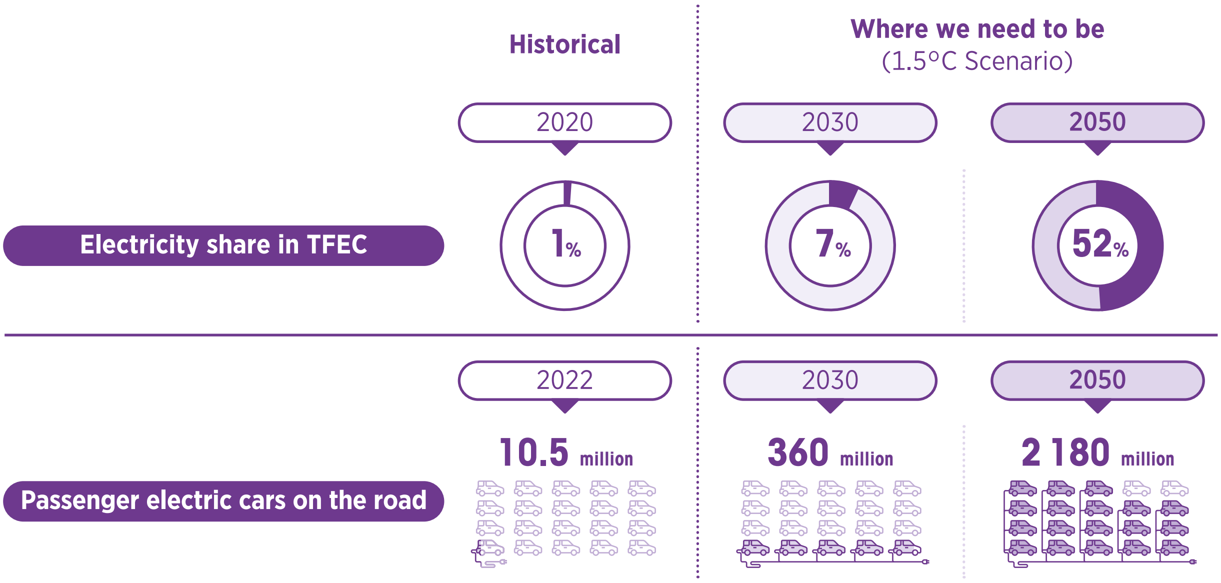
STATUS AND PACE OF PROGRESS

Adoption of new electric vehicles (EVs) is accelerating. Under IRENA's 1.5°C Scenario, the number of electric passenger cars would grow to 360 million by 2023, and 2 180 million by 2050 (IRENA, 2023). The transition is being boosted by planned bans on the sales of new fossil fuel–powered vehicles, net-zero emissions targets, climate policies and other pollution-driven regulations. At the same time, as technological progress and innovation are lowering the cost of EVs, users are realising the benefits of the technology (such as less noise pollution, a better driving experience and the convenience of charging while parked) and modifying their consumption behaviour by making more sustainable decisions.

Meanwhile, the rapid growth of EVs poses a challenge for the electricity system: Can it cope with the additional demand? IRENA estimates that electricity's share of total final energy consumption in the transport sector will grow to 7% by 2030 and to 52% by 2050 (IRENA, 2023) (Figure 1.1). As a result, the global electricity demand from all EVs is expected to reach almost 3 000 terawatt hours (TWh) by 2040 in BloombergNEF's (BNEF) Economic Transition Scenario (BloombergNEF, 2021a) and 4 500 TWh in the Net Zero Scenario, up from 106 TWh in 2021.

The BNEF scenarios show that about 35% of EV charging will be done at home in 2040. Public fast charging will make up about 24% of the total, with slow public chargers and workplace charging comprising another 7% each. Ultra-fast charging for e-buses and trucks will account for 27% of the electricity demand. All of these will require major investments in charging infrastructure; under IRENA's 1.5°C Scenario, electric charging infrastructure would require a cumulative investment of USD 9 trillion through 2050 (IRENA, 2023). BNEF estimates that, cumulatively, USD 1-1.4 trillion will have to be invested in charger hardware, installation and maintenance. Fast charging – from 50 kilowatts (kW) to 1 megawatt (MW) – for passenger and commercial vehicles, which accounted for 70% of all investments in 2022, will drop to around 60% of spending in 2040 (BloombergNEF, 2021a).

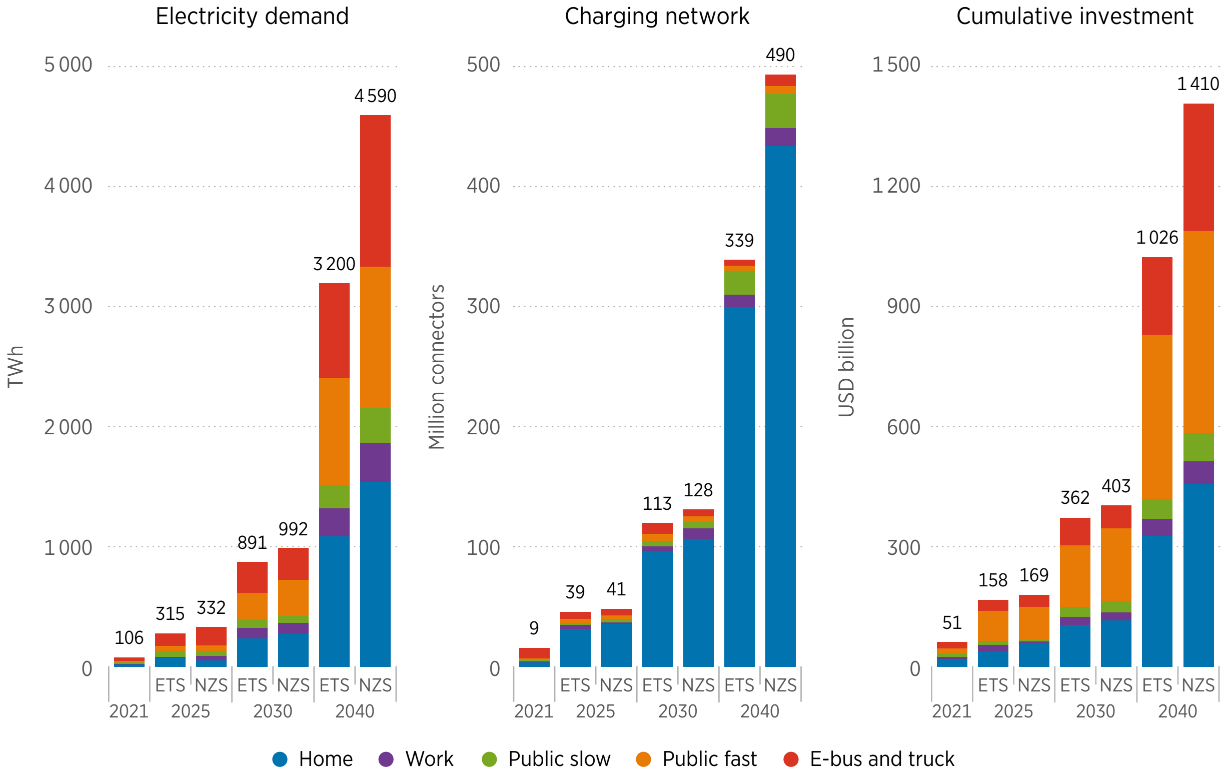
FIGURE 1.1 | **Electricity share in transport and EV stock in IRENA's 1.5°C Scenario**



Source: IRENA (2023b).
Note: TFEC = total final energy consumption.

Growth in charging infrastructure will help to accelerate EV sales by reducing drivers' range anxiety and increasing confidence in EVs (Figure 1.2).

FIGURE 1.2 | **Global EV demand for electricity, charging infrastructure and investment**



Source: (BloombergNEF, 2022).
Notes: Excludes two- and three-wheelers. Investment includes hardware, installation and maintenance costs.
ETS = Economic Transition Scenario; NZS = Net Zero Scenario.

Norway's experience with EVs points to the path ahead, although the country enjoys some attributes that are by no means universally shared (Box 1.1).

BOX 1.1 | Norway's progress in electrifying mobility

Norway has made remarkable progress in increasing its share of EVs, with the share rising to almost 86% of cars sold in 2021. By 2021, 16% of all vehicles were electric. The rapid growth has been driven by a large range of incentives, from tax breaks and exemptions to waivers on road tolls and ferry fees.

Norway is uniquely positioned to power its EVs with clean electricity. Not only is nearly 98% of the country's electricity generated from renewable sources, chiefly hydropower plants, but the total number of EVs in Norway is small compared with Chinese and US markets. If all 2.7 million cars in Norway were EVs, they would use only 5-6% of the country's annual hydropower output (Paulraj, 2019). In addition, hydropower is more flexible than variable renewables like solar and wind, reducing the challenges of charging EVs. For other countries, however, smart electrification also has an important role to play.

1.1 The importance of smart electrification for decarbonising mobility

A major challenge to widespread EV adoption is ensuring that the power grid can supply the increased demand with renewable-based electricity. Meeting this challenge requires smart electrification strategies that will increase renewable integration and reduce peak loads, thus decreasing grid congestion. Smart electrification also provides important operational benefits for power systems through flexibility and storage services. These benefits include reducing greenhouse gas emissions, peak loads and operational costs, and the curtailment of variable renewable generation. A corollary of smart electrification is smart charging to cut the need for additional generation, transmission and distribution capacity, all in the interest of minimising investment costs. In uncontrolled (or unco-ordinated) charging, EVs begin charging as soon as they are connected to a charging point. In smart charging, by contrast, intelligent algorithms optimise the charging process, considering electricity prices (or renewable generation), local congestion and battery ageing. Where electricity prices vary over time, smart charging allows EV owners to charge when prices are lower.

All these benefits increase further when EVs can supply power back to the grid (vehicle to grid [V2G]), thus reducing the need for inefficient peaking generators.

Vladimka production © Shutterstock.com

Figure 1.3 summarises the results from several studies of the impact of charging options on the power system. Box 1.2 explores these impacts in Belgium and Germany.

FIGURE 1.3 | Impact of EV smart charging on the electricity grid

Study	Scenario	Uncontrolled charging	Smart charging
IRENA, 2019	50% penetration in an isolated system with 27% solar share	↑ 9% increase in peak load 0.5% solar curtailment	↑ 5% increase in peak load (V2G) Down to 0% curtailment
RMI, 2016	23% penetration US (California, Hawaii, Minnesota, New York, Texas)	↑ 11% increase in peak load	↑ 1.3% increase in peak load (V1G)
Taljegard, 2017	100% penetration Denmark, Germany, Norway & Sweden	↑ 20% increase in peak load	↓ 7% decrease in peak load (V2G)
McKenzie, 2014	50% penetration in Island of Oahu, Hawaii, US 23% VRE share	10-23% VRE curtailment without EVs	8-13% VRE curtailment with smart charging EVs
Chen and Wu, 2018	1 MILLION EVs in Guanzhou region, China	↑ 15% increase in peak load	↓ 43-50% reduction in valley/peak difference

Source: IRENA (2019).

At the distribution grid level, smart charging can avoid overloading distribution components and assets, improve voltage quality and reduce energy losses. These benefits also make it possible to increase the use of distributed energy resources (DERs) without violating network operational constraints.

While studies of the operational value of smart charging on the distribution system are difficult to compare (Anwar *et al.*, 2022), two common findings are:

- **Smart charging can noticeably reduce peak loads and congestion in the distribution grid.** These benefits increase as more EVs are connected and are greater with bidirectional smart charging (V2G) than unidirectional smart charging (V1G).
- **Smart charging can reduce voltage drops** caused by uncontrolled EV charging, especially at high levels of EV penetration. The provision of reactive power from EVs also leads to greater improvements in distribution system voltage.

For power system operations (Anwar *et al.*, 2022), the benefits of smart charging include:

- Cost savings of USD 15-360 per EV per year.
- CO_2 emission reductions of 0.1-2.5 tonnes per EV per year.
- Peak load reductions of 0.2-3.3 kW per EV.
- Reductions in the curtailment of variable renewable energy (VRE) of 23-2 400 kWh per EV per year.

Realising these benefits will depend on the application of business models capable of extracting the maximum amount of grid flexibility from mobility.

BOX 1.2 | **Impact of smart charging in Belgium and Germany**

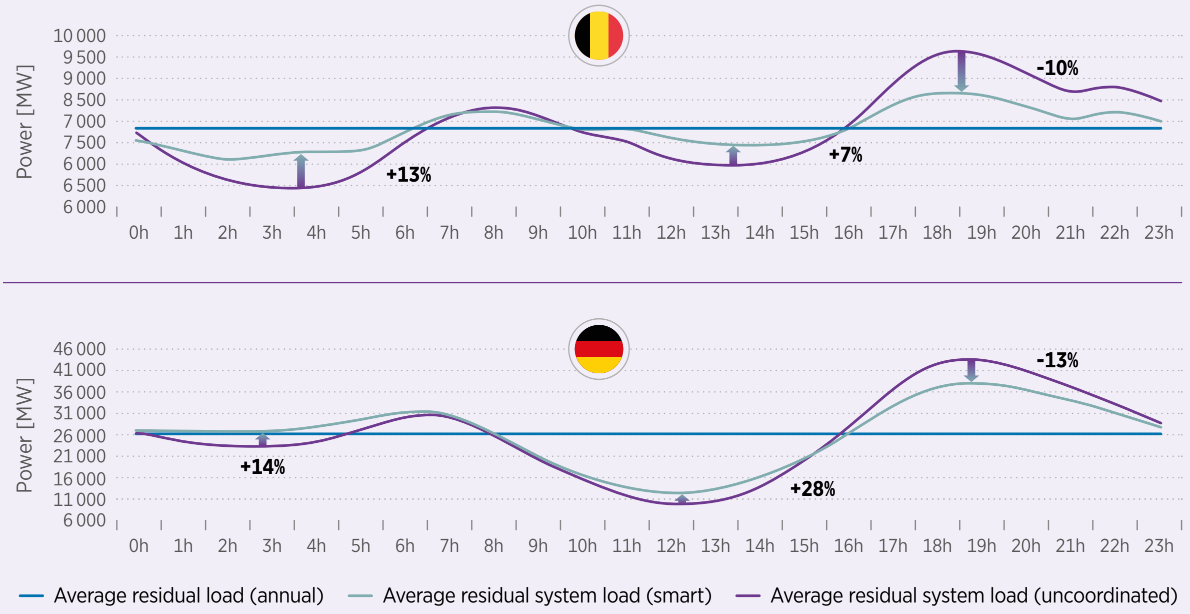
The Belgian transmission system operator Elia performed an in-depth analysis of the impact of electric passenger vehicles on the power system. The study found that smart charging – in which algorithms are used to optimise the charging process, considering electricity prices (or renewable generation), local congestion and battery ageing – increased the integration of renewables, reduced peak loads and saved drivers money.

Smart charging would enable the integration of an additional 1.4-1.7 TWh of renewable energy sources by 2030, increasing renewable generation by 30% in Belgium and 37% in Germany. That, in turn, would reduce the system load that would have to be supplied from non-renewable generation, making it easier to transition towards a fully decarbonised power system.

Smart charging can shift charging away from times of peak demand, promoting charging overnight or at times when the supply of renewable energy is high. Unmanaged charging would raise demand by 1.2 gigawatts (GW) in Belgium and 6.5 GW in Germany by 2030, whereas smart charging would reduce 2030 peak load by 13% in Germany and 10% in Belgium, as Figure 1.4 shows.

By shifting charging to times when electricity prices are lower, EV owners can lower their annual electricity costs by 15% (EUR 30-35) when electricity flows only from the grid to their cars and by 25% (EUR 50-55) when EVs also supply electricity to the grid. These savings might increase further after 2030, as rising levels of renewable energy increase the spread between high and low prices at different times of day.

FIGURE 1.4 | **Impact of EV smart charging on electricity grids in Belgium and Germany**



Source: Elia Group (2020).

1.2 Blind spots for policy makers

The main barriers to rapidly electrifying transportation are the costs of vehicles and the charging infrastructure they require. As the transition accelerates, economies of scale and continued innovation will reduce those costs, unlocking investment, boosting sales, and bringing the benefits of clean transportation to more cities and communities.

But there are other challenges as well. One is the lack of a clear business model for deploying public charging and ensuring interoperability among charging services. Others are incompatible payment systems, issues of cybersecurity and data protection, and complicated permitting procedures and regulatory measures. Bringing smart electrification to people living in multi-residential buildings can be especially difficult.

In addition, policy makers may harbour misconceptions or have blind spots that hinder the deployment of sound strategies. These are presented in brief below.

Smart charging does not necessarily mean bidirectional charging (V2G).

→ Achieving many of the benefits of smart charging – such as peak load reductions – may not require sending electricity back to the grid from vehicles. The implementation of smart charging should thus not be delayed until bidirectional capabilities are included. To accelerate that implementation, it is important to design dedicated smart energy tariffs that reward flexibility and consider EV users as reliable participants in the electricity system. However, whenever possible, barriers to bidirectional charging should be removed because of the additional benefits it can provide.

Development of charging infrastructure should not mimic the petrol filling stations nor focus only on fast charging.

→ Charging stations should be everywhere. Most charging will happen at night or at work, when vehicles are parked for a long time. Even on-the-go drivers make pauses in their journeys that can be long enough for a full charge at normal power (such as during lunch breaks or when travelling with children). Policy makers must keep in mind that the correct paradigm for EVs is to charge when parked, not to park for charging. However, fast charging stations will be needed for longer trips, when charging at lower power will take too long.

Charging infrastructure should be standardised and interoperable.

- The current rush to build charging infrastructure has led to incompatible, competing systems, creating an unfortunate barrier to EV adoption. It is crucial, therefore, to develop technologies and implement standards to ensure that vehicles, charging systems and communication networks are interoperable.

Planning for EV charging infrastructure deployment should be inclusive and reflect the local setting.

- In some countries, most drivers live in multi-dwelling units, and most companies are in multi-tenant buildings. Many do not have off-street parking. Providing convenient and affordable charging in these settings is not only necessary for a fair and just transition, it also avoids a backlash from those who might be left out of charging options. One key policy step, therefore, is “right to plug” regulation, which provides access to convenient and cheap charging.

Mobility trends need to be considered in electrification strategies.

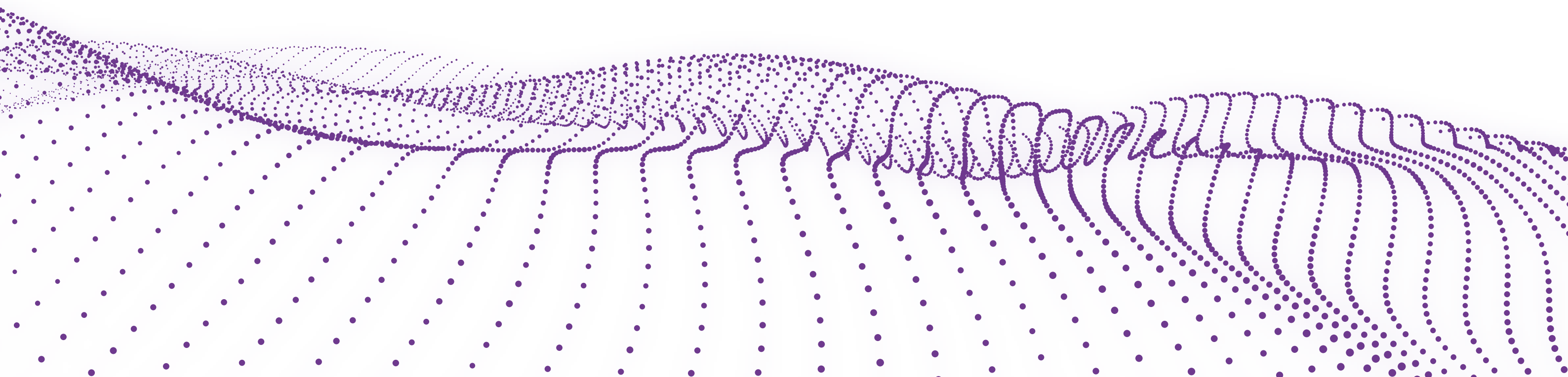
- Mobility patterns are constantly changing, such as the recent growth in remote work and the potential shift from EV ownership to “mobility as a service”. Planning strategies thus should be tailored for each specific power system and mobility behaviour trend.

Co-location of EV charging points with solar generation can minimise impact on the grid.

- Peak solar generation occurs in the middle of the day – when most passenger vehicles are parked. Workplace charging, combined with solar photovoltaic rooftop arrays and solar canopies over parking lots, should thus be encouraged. Charging directly from solar arrays also decreases the overall EV load on the grid, and off-grid solar charging systems can accelerate the switch to EVs in places with low-capacity grids, avoiding the need for grid expansion.

State agencies should co-ordinate and maintain consistency.

- Co-ordination should ensure roles are clear, regulations on vehicles and grid integration are not duplicated, and the vision for EVs is shared and consistent.



CHAPTER 2

TOOLBOX FOR SMART ELECTRIFICATION OF MOBILITY

The design of an optimal smart electrification strategy depends on many variables, such as the extent of flexibility in the power system, the capacity of the grid and mobility needs. However, a successful strategy can be developed and implemented for different contexts using 35 innovations for electrifying mobility.

These innovations cover a wide range of areas, from advances in electric vehicles (EVs), charging infrastructure and power systems to improved regulations, system planning and business models. They apply to all five transportation segments: passenger cars, two- and three-wheelers, light commercial vehicles, heavy-duty vehicles and buses. Table 2.1 lists the main differences between the segments that affect the choice of the best smart charging strategy.

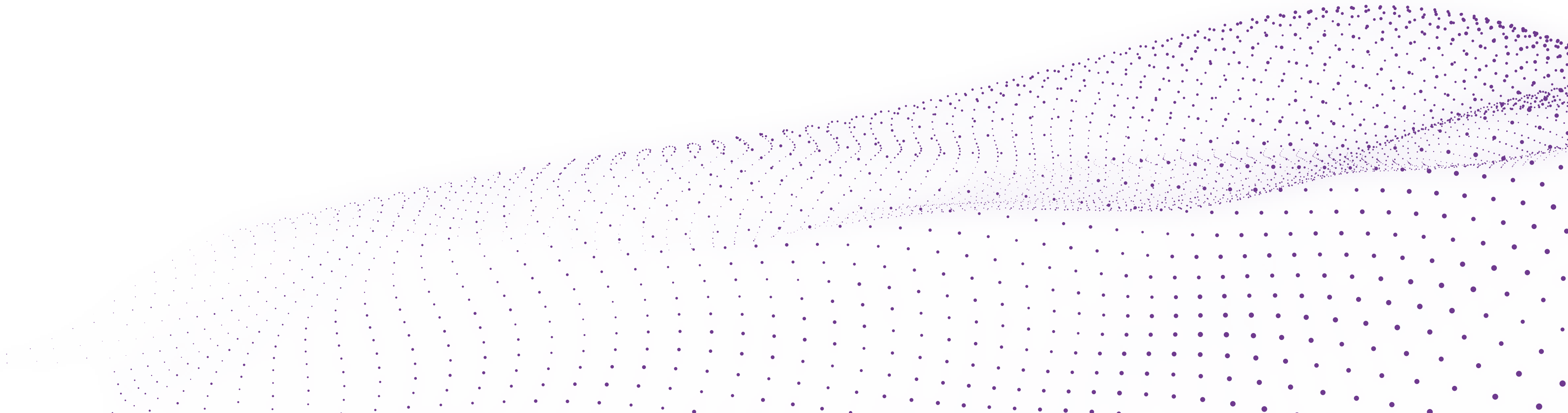


TABLE 2.1 | Main characteristics of transport segments influencing the choice of a smart electrification strategy

Segment	Use case	Charging time	Charging location	Parking times	Main characteristics affecting electrification strategy
Two- and three-wheelers	Private and commercial trips	Anytime (day, night)	Public charging, private charging	30-90% of the time	Strategy is most important in countries where this is the predominant transportation mode
Passenger cars	Private trips (including commutes to work)	Overnight, work hours, on the road	Private home charger, workplace charger, public charger	90% of the time	Strategy is informed by driving patterns and the fact that cars are parked most of the time
Light commercial vehicles	Commercial trips (*e.g.* deliveries to customers)	Mainly overnight	Private depot (fleet)	Mostly overnight	Strategy is business driven and crafted to suit the local and regional contexts
Heavy-duty vehicles	Logistics trips (*e.g,* long hub-to-hub deliveries)	Overnight and on-road (public)	Private and public depots (fleet), on the road	Strict driving schedule, parking based on drivers' official breaks	Strategy is business driven and involves infrastructure covering long distances
Buses	Fixed public route (including schedule)	Overnight and on-road (public)	Public depot (fleet), fast charging at bus stations	Short breaks during the day; parked overnight	Strategy must be suited to public service, public ownership and fixed routes inside a city

Table 2.2 lists the 35 innovations in each of the four dimensions of systemic innovation presented in the Introduction.

TABLE 2.2 | Innovation toolbox for smart electrification of the transport sector

TECHNOLOGY AND INFRASTRUCTURE

Electric vehicles

- **1** EV model evolution
- **2** EV batteries
- **3** Battery recycling technology

Charging infrastructure

- **4** Diversity and ubiquity of charging points
- **5** Wireless charging
- **6** Overhead charging
- **7** Portable charging stations
- **8** V2G systems

Digitalisation

- **9** Digitalisation for energy management and smart charging
- **10** Blockchain-enabled transactions

Power system enablers

- **11** Smart distribution transformers
- **12** Smart meters and submeters

MARKET DESIGN AND REGULATION

Electricity market design

- **13** Dynamic tariffs
- **14** Smart charging for local flexibility
- **15** Smart charging for system flexibility

Regulation for charging infrastructure

- **16** “Right to plug” regulation
- **17** Streamlining permitting procedures for charging infrastructure
- **18** Standardisation and interoperability
- **19** V2G grid connection code

SYSTEM PLANNING AND OPERATION

Strategic planning

- **20** Cross-sectoral co-operation and integrated planning
- **21** Including EV load in power system planning
- **22** Grid data transparency
- **23** Clean highway corridors

Smart operation

- **24** Operational flexibility in power systems to integrate EVs
- **25** Management of flexible EV load to integrate VRE
- **26** Management of flexible EV load to defer grid upgrades
- **27** EV as a resilience solution

BUSINESS MODELS

Services for the power system

- **28** EV aggregators
- **29** Shaving of EV peak loads using DERs
- **30** Battery second life and end-of-life reuse

Models to enable EV deployment

- **31** EV charging as a service
- **32** Electric mobility as a service
- **33** Ownership and operation of publicly available charging stations
- **34** A single bill for EV charging at home and on the go
- **35** Battery swapping

Notes: DERs = distributed energy resources; EV = electric vehicle; V2G = vehicle to grid; VRE = variable renewable energy.

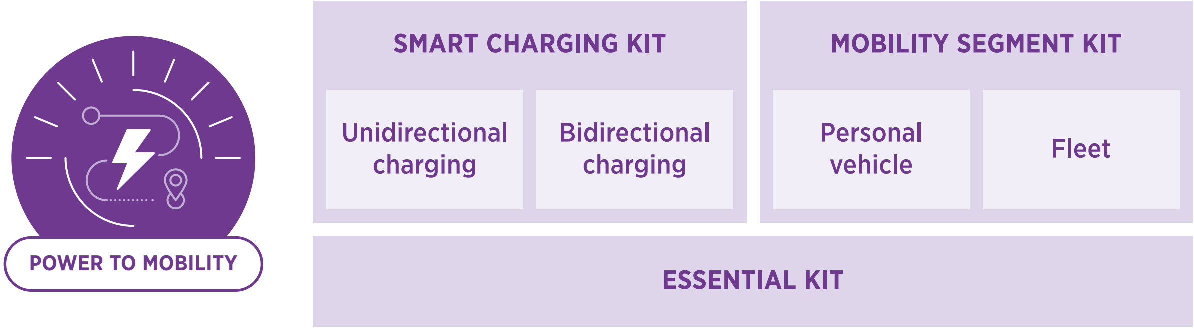
2.1 The Toolbox

Innovations are not implemented in isolation. Innovative smart electrification strategies build on synergies among different innovations across the four dimensions of technology, markets and regulation, system planning and operation, and business models.

For example, smart electrification strategies harness synergies between renewable electricity in the power system and the batteries of grid-connected EVs. However, no one-size-fits-all solution exists. Optimal smart electrification strategies depend both on the country context and on system-specific variables. They also must take social and cultural aspects into account.

To guide policy makers in formulating smart electrification strategies in their own contexts, we propose a toolBox with three main toolkits: the essential kit, the smart charging kit and the mobility segment kit (Figure 2.1).

FIGURE 2.1 | Implementation guidelines for smart electrification strategies for e-mobility



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Essential kit

The essential kit for smart electrification for e-mobility includes innovations that cut across the four dimensions, focusing on the necessary infrastructure for the deployment of EVs and the digital infrastructure that enables data exchange between the assets connected to the grid (Table 2.3).

The essential kit also includes key regulations to ensure the accessibility, interoperability and deployment of the charging infrastructure. These regulations ensure that the deployment of new infrastructure is fully co-ordinated between the power and transport sectors, and that suitable ownership and operation models exist for publicly available charging stations.

TABLE 2.3 | The essential kit for power to mobility

ESSENTIAL KIT

TECHNOLOGY AND INFRASTRUCTURE

- **1** EV model evolution
- **2** EV batteries
- **4** Diversity and ubiquity of charging points
- **11** Smart distribution transformers
- **12** Smart meters and submeters

MARKET DESIGN AND REGULATION

- **16** “Right to plug” regulation
- **17** Streamlining permitting procedures for charging infrastructure
- **18** Standardisation and interoperability

SYSTEM PLANNING AND OPERATION

- **20** Cross-sectoral co-operation and integrated planning
- **21** Including EV load in power system planning
- **22** Grid data transparency
- **24** Operational flexibility in power systems to integrate EVs

BUSINESS MODELS

- **33** Ownership and operation of publicly available charging stations
- **34** A single bill for EV charging at home and on the go
- **35** Battery swapping

Note: EV = electric vehicle.

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Smart charging kit

The smart charging kit adds onto the essential kit to ensure that the electrification strategy is executed in a smart way, minimising the impact of uncontrolled charging on the power system. It is a mandatory step because it identifies the most suitable strategy based on the specific power system and the country context and includes innovations in market design and regulation to ensure adequate remuneration for the services provided to the power system.

Smart charging can be unidirectional (V1G) or bidirectional (V2G) (Table 2.4). While both require advanced digital infrastructure for energy management and information collection, bidirectional charging also requires V2G technology, which can be costly and difficult to add to a V1G charging infrastructure once the latter is deployed. Whether or not to include V2G charging, therefore, should be decided at the early stages of planning for a given location or project.

For V2G, one key innovation is a V2G grid connection code to boost deployment and allow EVs to smartly exchange energy with the grid. All the other innovations in this kit are important for both unidirectional and bidirectional charging. Bidirectional charging allows more service options but also increases complexity (Box 2.1).

TABLE 2.4 | The smart charging kit for power to mobility

		SMART CHARGING KIT			
		TECHNOLOGY AND INFRASTRUCTURE	**MARKET DESIGN AND REGULATION**	**SYSTEM PLANNING AND OPERATION**	**BUSINESS MODELS**
BIDIRECTIONAL CHARGING	**UNIDIRECTIONAL CHARGING**	• **9** Digitalisation for energy management and smart charging	• **13** Dynamic tariffs • **14** Smart charging for local flexibility • **15** Smart charging for system flexibility	• **25** Management of flexible EV load to integrate VRE • **26** Management of flexible EV load to defer grid upgrades	• **28** EV aggregators • **29** Shaving of EV peak loads using DERs
		• **8** V2G systems • **10** Blockchain-enabled transactions	• **19** V2G grid connection code		

Notes: DERs = distributed energy resources; EV = electric vehicle; V2G = vehicle to grid; VRE = variable renewable energy.

BOX 2.1 | Bidirectional charging: When does it make sense?

By allowing plugged-in EVs to feed energy to the grid (V2G) or to homes (V2H) or other buildings (V2B), bidirectional charging systems turn EVs into an energy storage asset. When plugged in, electric cars can power homes, balance grid loads, provide frequency control and power support, and replace traditional spinning reserves. Personal EVs are parked more than 80% of the time; so they have the potential to be a major source of stored electricity.

However, implementing V2G charging systems presents challenges. One is the need for more complex and costly bidirectional chargers, communication systems and payment methods so that EV owners can be paid for the energy they provide. Another is valuing the services and flexibility that EVs provide to the grid.

The additional charging and discharging of EV batteries in V2G systems also can cause faster battery degradation and shorter battery lifetimes, creating an unwanted expense for EV owners. However, degradation can be minimised with improved battery control systems.

In any specific deployment, the benefits of V2G need to be carefully assessed against the costs. If a system already has a flexible generation fleet or good interconnections with neighbouring systems, for example, the added costs of implementing a V2G system may not be worthwhile, since other flexibility sources are available at lower costs. The deployment should also consider whether V2G could cause problems if too many EV owners respond to high electricity prices by discharging their batteries, which could cause voltage problems on the grid.

But even if V2G does not make economic sense for system operators, a business case might still exist for bidirectional charging in V2H and V2B settings by allowing consumers to manage their demand and decrease their electricity bills, and by providing back-up power during power outages (Table 2.5).

TABLE 2.5 | Advantages and disadvantages of V2G

ADVANTAGES	DISADVANTAGES
V2G is an additional source of flexibility to the system. An EV fleet would provide limited energy storage but substantial capacity addition.	V2G increases complexity and has higher implementation costs than V1G (more advanced digital technologies for bidirectional communication, bidirectional payment system, aggregators).
V2G can provide services to TSOs (load balancing, frequency control).	V2G has higher data protection risks and requires increased cybersecurity.
V2G can provide services to DSOs (congestion management, voltage control).	V2G requires a market or regulations that set an appropriate value on flexibility services.
V2G can provide an additional source of revenue to car owners.	V2G can accelerate battery degradation.
V2H/V2B can help with demand-side management, contributing to savings on electricity bills.	V2G chargers are more expensive than V1G chargers.
V2H/V2B and even V2G can be used as a resilience solution in case of system blackouts.	Too many EVs discharging at the same time can cause problems in the grid (overvoltage).

Notes: DSO = distribution system operator; EV = electric vehicle; TSO = transmission system operator; V1G = unidirectional smart charging; V2B = vehicle to building; V2G = vehicle to the grid; V2H = vehicle to home.

Mobility segment kit

The mobility segment kit covers both personal vehicles and fleets. Personal vehicles are parked most of the time. Fleets are usually parked much less than personal vehicles (Table 2.6), but when an entire fleet is parked and plugged in, the battery capacity available to the power grid is much higher.

TABLE 2.6 | The mobility segment kit for power to mobility

		MOBILITY SEGMENT KIT		
		TECHNOLOGY AND INFRASTRUCTURE	**SYSTEM PLANNING AND OPERATION**	**BUSINESS MODELS**
	PERSONAL VEHICLES	- **7** Portable charging stations		- **34** A single bill for EV charging at home and on the go
FLEET		- **3** Battery recycling technology		- **30** Battery second life and end-of-life reuse - **31** EV charging as a service - **35** Battery swapping
		- **5** Wireless charging - **6** Overhead charging	- **23** Clean highway corridors	- **32** Electric mobility as a service

Note: EV = electric vehicle.

For drivers of personal vehicles, key strategies include innovations that make the payment process easy (such as a single bill for EV charging), avoid the upfront costs of EV chargers (such as EV charging as a service), or enable drivers to charge their cars in any suitable outlet, thus reducing range anxiety (such as portable charging stations).

For fleets, such as buses or delivery trucks, key innovations include wireless charging or overhead charging as alternatives to charging points. For long-distance vehicles, it will be critical to create clean energy corridors with charging infrastructure and renewable electricity.

New business models may emerge for all types of vehicles. For two- and three-wheelers, battery swapping is an interesting business model, since the batteries are relatively light and easy to handle. Battery swapping could also be automated for larger vehicles, making it possible for fleet managers to transition to e-mobility without changing the way they operate their fleets to accommodate long charging times.

2.2 Case study: California

In California, the innovations shown in Table 2.7 have already been implemented to support the smart integration of EVs into the power system. Together with Norway, California is one of the leading regions worldwide in the transition to EVs and zero-emission vehicles. California's goal is 5 million zero-emission vehicles by 2030 and 250 000 charging stations by 2025.

TABLE 2.7 | Smart electrification strategy in California

TECHNOLOGY AND INFRASTRUCTURE	MARKET DESIGN AND REGULATION	SYSTEM PLANNING AND OPERATION	BUSINESS MODELS
ESSENTIAL KIT			
1 EV model evolution **2** EV batteries **4** Diversity and ubiquity of charging points **12** Smart meters and submeters	**17** Streamlining permitting procedures for charging infrastructure **18** Standardisation and interoperability	**20** Cross-sectoral co-operation and integrated planning **21** Power system planning for EV load **22** Grid data transparency	**33** Ownership and operation of public charging stations
SMART CHARGING KIT			
8 V2G systems **9** Digitalisation for energy management and smart charging	**13** Dynamic tariffs **15** Smart charging for system flexibility **19** V2G grid connection code	**25** Management of flexible EV load to integrate VRE **26** Management of flexible EV load to defer grid upgrades **27** EV as a resilience solution	**28** EV aggregators **29** Shaving of EV peak loads using DERs
MOBILITY SEGMENT KIT			
3 Battery recycling technology **5** Wireless charging		**23** Clean highway corridor	**30** Battery second life and end-of-life reuse **31** EV charging as a service **32** Electric mobility as a service **35** Battery swapping

Notes: DERs = distributed energy resources; EV = electric vehicle; V2G = vehicle to grid; VRE = variable renewable energy.

From the essential kit, California is already making considerable investments in EV infrastructure, adding thousands of charging systems. The state also has a Vehicle Grid Integration Working Group, which brings together all relevant state entities to address challenges and questions and ensure interoperability.

California is implementing both unidirectional and bidirectional charging. Several projects and pilots are testing vehicle–grid integration, such as the Grid Communication Interface for Smart Electric Vehicle Services Research and Development project (InCISIVE) and the BMW ChargeForward pilot. The state's independent system operator (CAISO) is enabling EVs to participate as a demand-response resource in the California wholesale power market. The California Public Utilities Commission designed new rules that allow faster deployment of distributed energy resources (DERs), including solar and behind-the-meter batteries, and bidirectional V2G charging with a V2G grid code. Also, a utility in California offers time-of-use tariffs for residential EV owners, and the utility (PG&E) is using DERs, including EVs, to avoid or defer utility distribution investments. In addition, Nuvve Corporation is planning to use V2G electric school buses to increase grid resilience.

Results from the BMW ChargeForward pilot show that smart charging of 2 million EVs by 2030 could help integrate 2 400 GWh of renewable energy sources, equal to 13% of California's 2018 utility-scale solar systems (BMW, 2020).

California also has adopted several innovations in the mobility kit segment. The state plans to build a clean highway corridor, called The West Coast Clean Transit Corridor, with charging facilities from San Diego to British Columbia for heavy- and medium-duty trucks. Momentum Dynamics and Solano Transportation Authority (STA) plan to deploy a 300-kW automatic wireless fast-charging network along a bus transit corridor. Different business models are emerging in California; for example, SemaConnect is providing EV charging as a service, and Ample is providing modular battery swapping for fleets.

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CHAPTER 3

INNOVATION LANDSCAPE FOR SMART ELECTRIFICATION OF MOBILITY

For each of the 35 innovations introduced in Chapter 2, this chapter answers two main questions:

WHAT What is the innovation

WHY Why is it important for smart electrification?

The chapter uses the following icons (Table 3.1) to describe each innovation's readiness, its impact on electrifying the transport sector uptake of EVs and its impact on smart electrification (how much it contributes to the demand response and increased flexibility in the power system). Table 3.2 then provides an overview of innovations.

FIGURE 3.1 | Indicators of the impact of innovations on the electrification of end uses

●○○○ → The innovation is in an early stage, with few demonstration projects.

●●○○ → The innovation is in the early commercialisation stage, with few pilot projects.

●●●○ → The innovation has been implemented in a few countries.

●●●● → The innovation is mature and widely deployed in some regions.

TABLE 3.2 | Overview of the status and impact of innovations for smart electrification of the mobility sector

Dimension	Category	Innovation	Innovation readiness level	Impact on electrification of end uses	Smart electrification
TECHNOLOGY AND INFRASTRUCTURE	ELECTRIC VEHICLE	1 EV model evolution	●●●○	●●●●	●●○○
		2 EV batteries	●●●○	●●●●	●●●○
		3 Battery recycling technology	●●○○	●○○○	●○○○
	CHARGING INFRASTRUCTURE	4 Diversity and ubiquity of charging points	●●●○	●●●●	●●○○
		5 Wireless charging	●○○○	●●●○	●●○○
		6 Overhead charging	●●●●	●●●○	●●○○
		7 Portable charging stations	●●○○	●●●○	●●○○
		8 V2G systems	●●○○	●●○○	●●●●
	DIGITALISATION	9 Digitalisation for energy management and smart charging	●●○○	●●○○	●●○○
		10 Blockchain-enabled transactions	●●○○	●○○○	●○○○
	POWER SYSTEM ENABLERS	11 Smart distribution transformers	●●●○	●●○○	●●●●
		12 Smart meters and submeters	●●●●	●○○○	●●●○
MARKET DESIGN AND REGULATION	ELECTRICITY MARKET DESIGN	13 Dynamic tariffs	●●○○	●●○○	●●●●
		14 Smart charging for local flexibility	●○○○	●○○○	●●●●
		15 Smart charging for system flexibility	●●○○	●○○○	●●●●
	REGULATION FOR CHARGING INFRASTRUCTURE	16 "Right to plug" regulation	●●○○	●●●●	●○○○
		17 Streamlining permitting procedures for charging infrastructure	●●○○	●●●●	●○○○
		18. Standardisation and interoperability	●●●○	●●●●	●●●●
		19 V2G grid connection code	●●○○	●○○○	●●●●

●●●● Very high ●●●○ High ●●○○ Medium ●○○○ Low

Dimension	Category	Innovation	Innovation readiness level	Impact on electrification of end uses	Smart electrification
SYSTEM PLANNING AND OPERATION	**STRATEGIC PLANNING**	• **20** Cross-sectoral co-operation and integrated planning	●●○○	●●○○	●●●●
		• **21** Including EV load in power system planning	●●○○	●●●○	●●●●
		• **22** Grid data transparency	●●○○	●○○○	●●●●
		• **23** Clean highway corridors	●○○○	●●●●	●●○○
	SMART OPERATION	• **24** Operational flexibility in power systems to integrate EVs	●●○○	●●●○	●○○○
		• **25** Management of flexible EV load to integrate variable renewable energy	●●○○	●●●●	●●●●
		• **26** Management of flexible EV load to defer grid upgrades	●●○○	●●○○	●●●●
		• **27** EV as a resilience solution	●●○○	●○○○	●●●○
BUSINESS MODELS	**SERVICES FOR THE POWER SYSTEM**	• **28** EV aggregators	●●●○	●○○○	●●●●
		• **29** Shaving of EV peak loads using DERs	●●●○	●○○○	●●●●
		• **30** Battery second life	●●○○	●●○○	●○○○
	SERVICES FOR THE TRANSPORT SECTOR	• **31** EV charging as a service	●●●○	●●●○	
		• **32** E-mobility as a service	●●●●	●●●○	●○○○
	MODELS TO ENABLE DEPLOYMENT	• **33** Ownership and operation of public charging stations	●●●○	●●●●	●○○○
		• **34** A single bill for EV charging at home and on the go	●●○○	●●●○	●●○○
		• **35** Battery swapping	●●○○	●●●○	●●●○

●●●● Very high ●●●○ High ●●○○ Medium ●○○○ Low

Notes: DERs = distributed energy resources; EV = electric vehicle; V2G = vehicle to grid.

3.1 Technology and infrastructure

Innovations in technology and infrastructure are fundamental for the decarbonisation of mobility. They are split here into four main categories: electric vehicles, charging infrastructure, digitalisation and power system enablers (Figure 3.1). Each innovation is discussed in detail, starting with electric vehicles.

FIGURE 3.2 | Innovations in technology and infrastructure for power to mobility

TECHNOLOGY AND INFRASTRUCTURE	**ELECTRIC VEHICLE**	**1** EV model evolution
		2 EV batteries
		3 Battery recycling technology
	CHARGING INFRASTRUCTURE	**4** Diversity and ubiquity of charging points
		5 Wireless charging
		6 Overhead charging
		7 Portable charging stations
		8 V2G systems
	DIGITALISATION	**9** Digitalisation for energy management and smart charging
		10 Blockchain-enabled transactions
	POWER SYSTEM ENABLERS	**11** Smart distribution transformers
		12 Smart meters and submeters

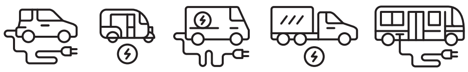
Notes: EV = electric vehicle; V2G = vehicle to grid.

Jeerasak banditram © Shutterstock.com

Electric vehicles

ELECTRIC VEHICLES

1 EV model evolution

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●●●	●●○○	

WHAT Technological innovation in all types of EVs (two- and three-wheelers, passenger cars, light passenger vehicles, commercial vehicles, heavy-duty vehicles and electric buses) is key for accelerating the electrification of the transport sector (Box 3.1). Manufacturers need to continue diversifying models to satisfy the wider consumer demand, and improvements need to be made in engine efficiency, range, charging times, battery management systems, durability, ride comfort, cost and connectivity.

WHY EV model evolution will make EVs more attractive and more cost-effective for owners and fleet operators, helping to accelerate their adoption.

BOX 3.1 | Innovation areas in EV model evolution

The market for **electric two- and three-wheelers** has grown significantly with the launch of many models of e-scooters, e-bikes, three-wheel cargo bikes, e-motorcycles and auto rickshaws (tuk-tuks). Particular focus has been placed on improving mileage, charging time, battery management systems and connectivity, and increasing durability and ride comfort.

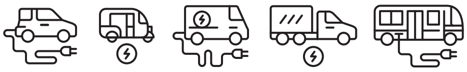
For **light EVs**, technology advancements in motors, inverters, aerodynamics, heating and battery packs are leading to greater efficiencies every year, reducing the battery size needed to cover a given range. On average, efficiencies have already improved to 150-170 Wh/km, while some vehicles are down to 147-150 Wh/km (Electric Vehicle Database, 2022).

In **heavy-duty EVs,** BYD, Daimler, Ford, Tesla and Volvo are already selling all-electric trucks, but increases in range are needed for long-distance use. In addition, high-powered fast charging is needed to avoid delays in operations and services. Manufacturers must consult closely with potential users especially for logistical vehicles such as delivery vans. An example is Tata Ace EV, the electric version of India's most successful commercial vehicle, which was co-developed with users, including Amazon, BigBasket and Flipkart.

Electric buses are in use in many cities, offering one of the most successful examples of electrification in high-use vehicles. The world's first and largest fully electric bus fleet is in Shenzhen, China. Technology advancements focus chiefly on battery range and efficiency to reduce operational costs and on digitalisation for optimal operation.

ELECTRIC VEHICLES

2 EV batteries

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●●●	●●●○	

WHAT Batteries for new EVs already provide good ranges, with the best-performing models offering 800 kilometres (km), and some batteries can be charged in an hour. At the same time, prices have dropped dramatically, from USD 1 200/kWh in 2010 for Li-ion batteries to USD 132/kWh in 2021 (BloombergNEF, 2021b). Battery improvements are a complex undertaking involving several trade-offs (Box 3.2), but the top priority is to continue cutting cost, increasing range and shortening charging cycles. That said, range becomes less important if batteries can be correctly sized for the intended uses and charging is readily available. Automakers should consider warrantying the number of cycles, not just the kilometres covered, so that the batteries of passenger and fleet vehicles can more readily be used in vehicle to grid (V2G). Proper accounting of battery health and cycles will also facilitate second uses for batteries after the original vehicles are no longer on the road.

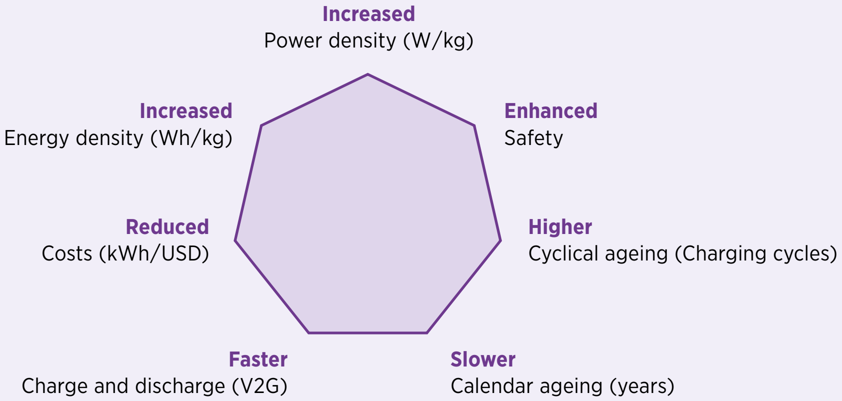
An emerging technology concern for EV batteries is the availability of critical materials used to make the batteries, such as cobalt. Viable cobalt-free battery technologies exist – one is lithium iron phosphate – but their energy density needs to be improved.

WHY Innovation in battery technology will improve performance, increase range and battery lifetimes, and stimulate further adoption of EVs.

BOX 3.2 | Innovation areas in EV battery technology

Research efforts are aimed at improving at least seven battery performance metrics (Figure 3.2), but there are complex trade-offs among those properties, and improving one criterion typically results in the deterioration of at least one other.

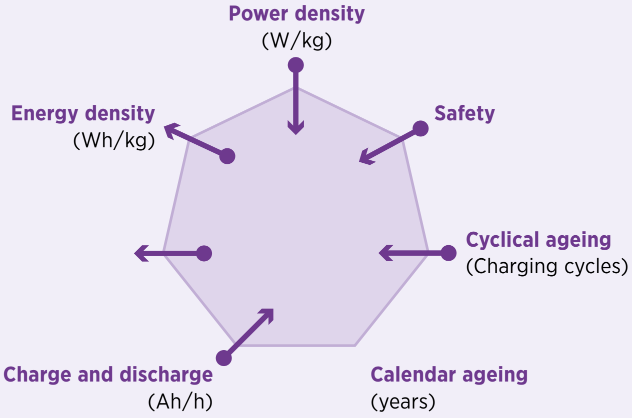
FIGURE 3.3 | The battery performance dilemma



Adapted from: (Sauer, 2018).

In general, the focus has mostly been on improving energy density and safety while reducing costs, and to a lesser extent on increasing charging cycles. But further improvements are necessary in cyclical ageing, power density and fast-charging capability as well. These depend highly on the battery cell type, how the cells are packed together and how charging is managed. Figure 3.3 shows how an innovation that improves energy density and cost comes at the expense of power density, security and cyclical ageing.

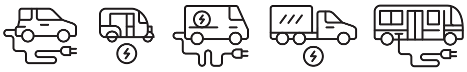
FIGURE 3.4 | Example of battery innovation



The CTC (cell to chassis) grouping technology developed by CATL improves the volume utilisation of battery packs through highly integrated structural design. In terms of material innovation, CATL released the first generation of sodium-ion batteries, with energy density of up to 160 Wh/kilogramme (kg) of a single cell, which can be applied to various transportation electrification scenarios, especially in cold regions, and can flexibly adapt to all scenarios in the field of energy storage. Industrial application of sodium-ion batteries is expected to be demonstrated in 2023, which can reduce the demand for lithium resources.

ELECTRIC VEHICLES

3 Battery recycling technology

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●○○○	●○○○	

WHAT Batteries contain materials such as lithium, nickel, cobalt, manganese, graphite, copper and lead, the extraction and improper disposal of which carry significant environmental and health dangers (Jacoby, 2019). Currently, not all minerals are recycled due to technology pathways and economic incentives. That is why efforts are underway to address various challenges, including logistical, technical, economic and regulatory challenges, and design batteries for recycling, with a goal of achieving flexibility, scalability and efficiency in recycling. Compared with lead batteries, the complexity of lithium-ion batteries and their various chemistries makes it difficult to establish one robust recycling process for all types and make a business case for recycling. Currently used recycling methods and their combination include using high temperature or aqueous solutions to extract metals, cathode components and other materials for reuse in new batteries or other industries. Innovation is critical here since these methods will need to be flexible and adaptable to future battery chemistries.

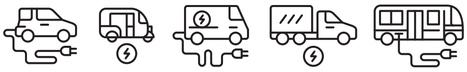
WHY The increasing number of EVs could well aggravate environmental damage from mining and battery waste unless recycling programmes are expanded, and various challenges are quickly and properly addressed. Governments are increasingly mandating recycling, such as the Battery Regulation in the EU, and providing government funding to innovate and scale up recycling, including lowering recycling costs, increasing recovery rates, and improving the carbon and energy footprint. Sourcing of materials through recycling is, however, not expected until mid-to-late 2030s, and by 2030, a primary recycling source will be processed scrap, recalls and discarded products (IRENA, forthcoming).

BOX 3.3 | Innovation areas in battery recycling technology

The recycling of battery materials has attracted attention worldwide. Recovery rates of nickel and cobalt are about 95% in recycling plants, while that of lithium, manganese and graphite (with impurities) has reached around 95%, and the recovery rate is up to 99% in laboratory testing. Improving and scaling up the recycling of all materials will not only help to avoid the adverse environmental, health and social impacts associated with mining and processing, but will also minimise dependency on material imports, unlock new domestic value streams and job opportunities, and may reduce the costs of batteries (IRENA, forthcoming).

Charging infrastructure

CHARGING INFRASTRUCTURE | **④ Diversity and ubiquity of charging points**

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●●●	●●○○	

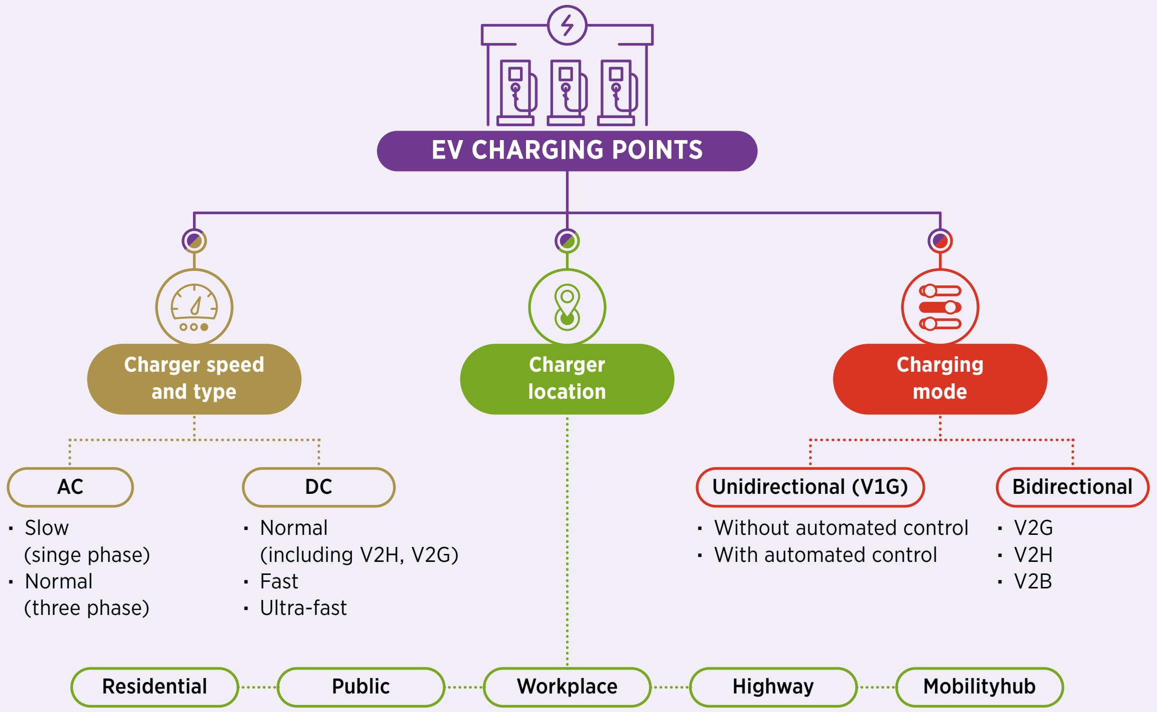
WHAT The development of charging infrastructure must consider location, charging types, charging modes and other capabilities, with a goal of providing universal access. In cities, any shared parking space could become a charging point with an electricity connection, creating opportunities to charge at workplaces, commercial establishments and public spaces. Residential charging on private driveways is inexpensive and largely free of barriers, but innovative shared charging solutions are needed for communities and apartments with limited parking spaces. Where vehicles are parked for longer periods, as at homes and workplaces, V2G capabilities would provide important flexibility and other services to the grid (Box 3.4).

WHY To achieve the goal of universal access to charging, any parking spot must be considered a potential charging point. The key aim should be switching from the idea of EVs "parking to charge" to EVs "charging while parked". Shared charging infrastructure available to multiple parking slots is better than single parking slots equipped for EV charging.

BOX 3.4 | Key aspects for developing charging infrastructure

Development needs to be diverse in terms of charger location, speed, type and mode, as shown in Figure 3.4.

FIGURE 3.5 | The necessary diversity of charging infrastructure



The following factors must also be considered:

- **Safety and comfort:** It should be easy for customers to charge their EVs.
- **Scalability:** The number of public charging stations should keep up with growing demand.
- **Visibility:** Charging stations should be visible to drivers, although municipal aesthetics laws may oblige charging stations to blend in with the architecture of the city.
- **Sustainable:** Stations should draw on renewable electricity.
- **Good customer service and maintenance:** Possibilities include multiple languages and remote maintenance.
- **Universality and interoperability:** All users should be able to charge all their vehicles. There are four standards now for DC fast charging (in addition to Tesla's proprietary one); hence, multi-standard charging stations should be encouraged or should be required.

CHARGING INFRASTRUCTURE

5 Wireless charging

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●○○○	●●●○	●●○○	🚗 🚐 🚛 🚌

WHAT Wireless charging – now used for cell phones, watches and other small devices – is increasingly used for EVs, with efficiencies improving over time. EVs can be charged wirelessly via power transmitters in the ground when parked (static charging) or moving (dynamic charging).

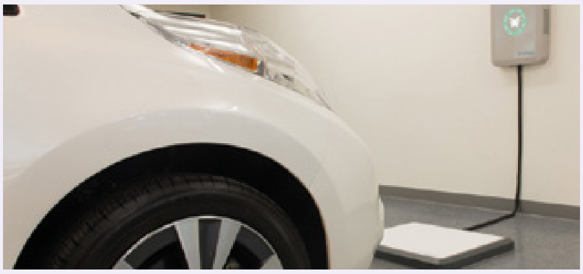
WHY Wireless charging eliminates the need for the bulky cables and connectors at charging stations. It is equally suitable for large trucks that must travel long distances and for vehicles moving along busy roads in cities. It is also effective for fleets of buses or delivery vehicles (Box 3.5). However, wireless EV charging is capital intensive and requires more research and development.

BOX 3.5 | Wireless charging solutions

The IPT-PRIMOVE system uses energy induction to charge light or heavy-duty vehicles, allowing them to charge automatically at pickup or waiting points. For example, IPT wireless charging infrastructure at one or both ends of a route allows buses to charge for 5-10 minutes while waiting, and it is being tested in London, Bristol, Madrid, Aachen and other cities (IPT Technology, 2021).

Source: (Green Car Congress, 2020).

In China, Hongqi E-HS9, a Chinese car marque, is equipped with an 11-kW wireless charging system, which works together with an auto parking assist function to enable automatic parking and charging of the vehicles. Similarly, IM Motors' L7 provides a mass production solution of an 11-kW wireless charging system. The IM L7 can park automatically and start wireless charging.



Source: (IPT Technology, 2021).

CHARGING INFRASTRUCTURE

6 Overhead charging

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
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WHAT Overhead charging (also known as a pantograph) is already widely used for trams and trains. It reduces the need to plug in and unplug and can safely provide AC or faster DC power.

Overhead charging has the advantage of being able to supply power to multiple vehicles, of being easily scalable and of not requiring vehicles to stop for charging. Vehicles may also be equipped with batteries or ultra-capacitors, which allow them to travel outside the overhead charging network (Siemens, 2021). However, it requires high investments and is less flexible than other methods.

WHY Overhead charging enables dynamic charging, which helps reduce peak loads on the grid. *En route* charging also enables vehicles to have smaller batteries, leading to higher overall energy efficiencies, lighter vehicles and lower vehicle costs.

CHARGING INFRASTRUCTURE

7 Portable charging stations

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
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WHAT While most EVs have on-board chargers, portable charging stations can be used instead, particularly for two- and three-wheelers and light vehicles or as emergency roadside assistance. These chargers can be programmable, with advanced charging control and protection functions, or non-programmable, which is cheaper and simpler.

WHY This solution can reduce range anxiety for drivers of two- and three-wheelers and light vehicles. It also allows automakers to remove on-board chargers, reducing weight, cost and complexity.

BOX 3.6 | Portable charging for a fleet of three-wheelers in India

eFleet Logix, a fleet operator of electric three-wheelers in India, charges its fleet twice a day at a centralised charging facility. The charging time is between two and four hours.

eFleet Logix learned that the simple portable charger technology typically used for lead acid batteries can damage lithium-based batteries through overcharging. Now it either charges batteries at a low rate (0.20-0.25 C-rate, meaning a five-hour charging time) with non-programmable chargers or uses programmable chargers with advanced control and protection functionalities to charge at a 0.5 C-rate, meaning a two-hour charging time.

Source: (Das *et al.*, 2020).

CHARGING INFRASTRUCTURE

8 V2G systems

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
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WHAT V2G capability makes it possible for electricity to flow from the grid to a vehicle and from the vehicle to the grid. Since the output of an EV battery is DC, an inverter is needed to transform the current to AC, which is used on the grid. The inverter can be built into the EV (V2G-AC) or the charging station (V2G-DC). V2G-DC has already been successfully commercialised in the United Kingdom, Denmark and Japan using the CHAdeMO standard (IEC 61851-23, -24). Some V2G-AC examples also exist, such as school bus projects in the United States and Europe (*e.g.* the WeDriveSolar project in Utrecht). V2G systems are already technically viable, but regulatory, business and operational challenges remain.

Both V2G-AC and V2G-DC technologies are needed, but they have different uses – for example, DC for behind-the-meter optimisation and AC for public chargers. DC is the more straightforward option today because there already is a valid ISO standard that ensures home safety.

WHY V2G charging offers major benefits beyond just mobility; for example, it is a way to dampen variations in loads and generation on the grid, it provides flexibility and balancing services, and it gives EV owners a potential source of revenue that reduces their ownership costs.

BOX 3.7 | V2G Demonstration Station in China

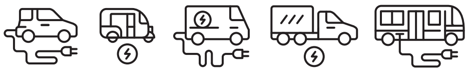
Beijing Zhongzai V2G Demonstration Station is the first commercially operated V2G station in China. The charging station allows official and private cars to discharge to supply the building loads during peak hours. The discharge revenue is RMB 0.7/kWh, and the station has a peak–valley charging price difference of about RMB 0.4/kWh. In the second half of 2020, the Zhongzai V2G station had a total of 1 228 intelligent charging and discharging orders, and the accumulated discharge income of all owners was about USD 2 180. By the beginning of 2021, the State Grid Electric Vehicle Company had built 42 V2G projects and 609 V2G interactive terminals in 15 provinces and cities in China, including Beijing, Tianjin and Shanghai.

Source: (Zinc Finance, 2021).

Digitalisation

DIGITALISATION

9 Digitalisation for energy management and smart charging

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●●○○	●●○○	

WHAT An important example of the use of digital technologies to manage energy is management systems for distributed energy resources (DERs) such as rooftop solar photovoltaic (PV), battery storage or EVs. DERs make it more challenging for grid operators to maintain power stability and reliability, but they also offer major opportunities for a more efficient and robust power system. For example, plugged-in EVs can help prevent expensive load peaks, reduce the need to expand the grid and make it easier to incorporate variable generation of renewable energy. However, more innovation is needed to develop energy management platforms and address issues of cybersecurity and data protection.

WHY Management systems for DERs can provide significant value to utilities and grid operators, while also lowering costs for EV owners. These benefits will help accelerate the adoption of EVs.

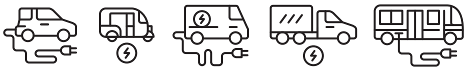
BOX 3.8 | BMW ChargeForward in California

On BMW's ChargeForward smart charging platform, plugged-in vehicles send information about their state of charge to BMW. The system combines this information with data about the grid, the cost of charging and drivers' preferences to calculate the optimal time to charge and control the charging time and rate. Owners can change their preferences using smartphones, for example, charging when costs are lowest or when renewable energy generation is highest. The longer a vehicle is plugged in, the more scope there is for adjusting or shifting the charge; this in turn increases the benefits to both the grid and customers.

Source: (BMW, 2020).

DIGITALISATION

10 Blockchain-enabled transactions

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●○○○	●○○○	

WHAT Blockchain technology is a distributed, digital ledger for verifying transactions. It can help manage automated EV charges using renewable energy, allow EV owners to seamlessly charge at any charging station (called eRoaming) and provide better access to data. It can also enable payment with offline digital “coins” in locations where neither the EV nor its owner’s phone has an internet connection.

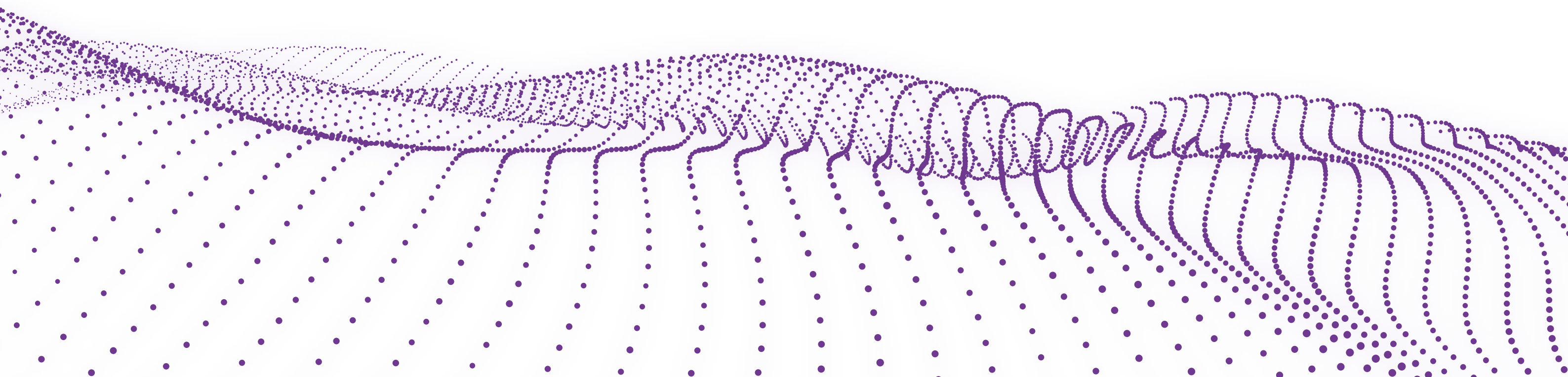
WHY Blockchain can offer multiple advantages: it can automatically match the charging process with renewable energy purchases, and allow additional value streams, such as tracking, reporting and proof of renewable energy use. It also allows cost-efficient EV charge payments through digital identifiers or mobile wallets.

BOX 3.9 | E-mobility blockchain applications

In 2018, TenneT launched two pilots with blockchain technology developed by IBM and administered by Vandebron to use electric cars and household batteries to help balance the grid. The technology has been scaled up and used to develop a platform called the Crowd Balancing Platform – Equigy. In the Netherlands, Equigy is being used in the automatic Frequency Restoration Reserve project. In Germany, TenneT is investigating the use of Equigy to adjust the operating schedules of power plants (TenneT, 2019).

Meanwhile, the Oslo2Rome initiative is using blockchain technology to create an “e-mobility wallet”. Oslo2Rome has proven that the technology can solve roaming problems for EV charging transactions across different countries in Europe. Its benefits include real-time transactions without middlemen, access and payment without contracts, and easy, cost-efficient asset integration and operation (Share&Charge, 2020).

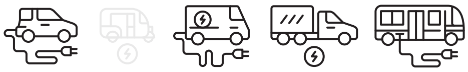
Another project is the BANULA initiative supported by a consortium of 10 partners, including TransnetBW TSO, BBH, Badenova, Fraunhofer IAO, OLI Systems, Schwarz Gruppe, Smartlab and the University of Stuttgart. Its blockchain technology enables secure data exchange among all participants in charging networks, bringing significant improvements in energy management processes (Fraunhofer IAO, 2021).



Power system enablers

POWER SYSTEM ENABLERS

11 Smart distribution transformers

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●○○	●●●●	

WHAT Smart distribution transformers are equipped with remote monitoring, access and control capabilities, which allows them to better control electricity use and direction.

WHY These advanced features improve grid security and power services and increase reliability by constantly adjusting the voltage on feeders to grid substations; this enables the grid to adapt to the changing charging loads of vehicles connected to the same feeder, thereby making it possible to increase the EV charging capacity.

BOX 3.10 | Smart transformer terminals facilitate EV charging in China

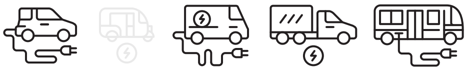
In 2021, China started to pilot the application of the smart power distribution transformer terminal to support optimal EV charging. The terminal creatively uses architecture comprising a common hardware platform, an edge operating system and app-based service applications and has the functions of data collection, storage, computation and secure encryption communication to support secure, efficient and effective interoperation between power distribution networks and customers. The terminal supports area load monitoring, equipment health status analysis, charging load control and other services.

The terminal is installed on the low-voltage side of the transformer; communicates with the charging piles in the transformer service area; and enables operation monitoring for the charging piles, charge state uploading, the regulation of charging/discharging power and the control of charging/discharging, among other functions. Supported by these functions, the terminal enables a comprehensive data analysis of the local load condition, user behaviour and charging facility operation and provides optimised charging schemes to realise orderly charging. The terminal has been deployed in pilot projects in more than 10 provinces of China and received positive social and economic benefits.

Source: CEPRI, personal communication, 2022.

POWER SYSTEM ENABLERS

12 Smart meters and submeters

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●●	●○○○	●●●○	

WHAT Smart meters measure and record electricity usage (typically in real time), communicate the information to consumers and grid operators, and report back to electricity suppliers for monitoring and billing. By supporting two-way communication and bidirectional flows of information, smart meters have become a significant component of today's power networks and utilities. In addition, "submeters" have emerged to monitor the energy demand of particular appliances. They make it possible to bill EV load on a different rate schedule than that of the rest of the household load.

WHY Smart meters are essential for allowing EV charging at the best times for both the power system and drivers, bringing more value to both. Meanwhile, smart submeters for EV chargers remove a barrier to V2X adoption (Box 3.11).

BOX 3.11 | Avoiding the need for new EV submeters in California

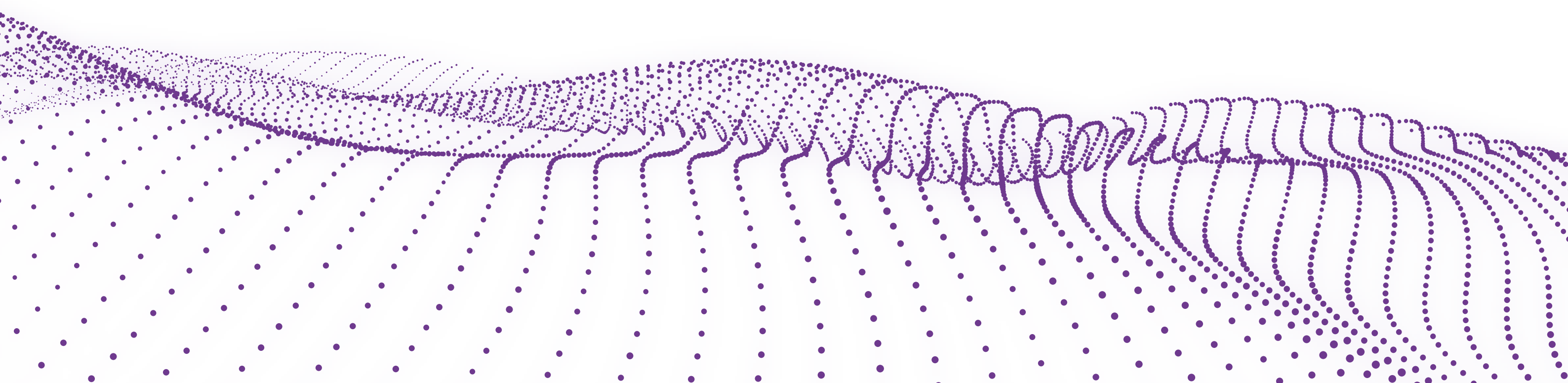
Utilities in California have for some time offered special electricity prices for EV charging, but few customers were taking advantage of these prices because of a requirement that they install a separate submeter to measure EV charging. In 2022, regulators in California approved a protocol that enables installed smart meters to measure and bill EV charging separate from other electricity uses, thus accelerating vehicle-grid integration.

Source: (State of California, 2022).

BOX 3.12 | Submeters for the EV charging platform of State Grid, the electric utility in China

On State Grid's orderly charging platform for EVs, submeters are integrated into the charging pile as core control units; the charging pile receives the orderly charge and discharge instructions from the energy controllers upstream and connects the orderly charging piles downlink to control the charging of electric vehicles. In addition, submeters also support information exchange with users' mobile phones. The main idea is to implement dynamic tariffs, which offer different prices for electricity at different times of the day and enable electricity users to choose power consumption periods and preferred charging modes. This strategy can effectively improve users' charging service experience, including enjoying more favourable charging prices, higher charging efficiency and many other benefits.

Source: (Ting *et al.*, 2021).



3.2 Market design and regulation

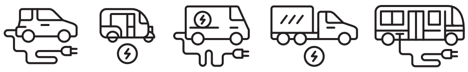
In addition to the new technologies described, innovations in market design and regulation are needed to raise incentives for smart charging and enable the rapid deployment of charging infrastructure. Figure 3.5 illustrates key market designs and regulations, which are then discussed in detail.

FIGURE 3.6 | Innovations in market design and regulation for power to mobility

MARKET DESIGN AND REGULATION	**ELECTRICITY MARKET DESIGN**	**13** Dynamic tariffs **14** Smart charging for local flexibility **15** Smart charging for system flexibility
	REGULATION FOR CHARGING INFRASTRUCTURE	**16** "Right to plug" regulation **17** Streamline permitting procedures for charging infrastructure **18** Standardisation and interoperability **19** V2G grid connection code

Electricity market design

ELECTRICITY MARKET DESIGN | **13 Dynamic tariffs**

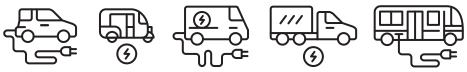
Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●●○○	●●●●	

WHAT Dynamic tariffs are prices that vary over time, allowing consumers to reduce their energy expenses, while also bringing important benefits to the power system.

WHY Dynamic tariffs provide incentives for consumers to delay charging until electricity is less expensive. They are needed to reduce coincident loads and network congestion (which would occur, for example, if all EV drivers plugged in after arriving at home in the evening) and lower the costs of charging EVs. Other benefits include reduced peak loads and easier integration of variable renewable generation. Dynamic tariffs can be designed in a way that is easy to understand and adopt (using EV aggregators and apps), and could provide considerable savings to an average EV user.

ELECTRICITY MARKET DESIGN

⑭ Smart charging for local flexibility

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●○○○	●○○○	●●●●	

WHAT Smart charging allows distribution system operators (DSOs) to use the flexibility enabled by smart charging to reduce the need to reinforce their distribution infrastructure (smartEN, 2022). Regulations can encourage this use of flexibility by enabling DSOs to take direct control of the EV load and manage vehicles' charging capacities and charging speeds as agreed by customers. Load can be controlled directly by DSOs or via aggregators, which have more complete information on EV loads.

Controlling EV charging as a demand-response tool can also provide the control services needed to cope with voltage changes caused by sudden changes in demand. Charging can be controlled using information communicated from vehicles or chargers, or directly via chargers (California Public Utilities Commission, 2020; ENTSO-E, 2022a; EERE, 2011).

Another way of providing local flexibility is via designated marketplaces. Local markets for trading electricity flexibility can be created for neighbourhoods, communities or small cities. These markets then provide revenues to market operators and participants, while also improving the operation of the distribution grid.

WHY Smart charging of EVs can be an important local flexibility source, helping DSOs manage grid congestion and control voltage. It is important to design supportive regulatory frameworks and set an appropriate value for these services.

BOX 3.13 | Regulatory framework for the distribution system operator in Great Britain

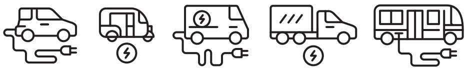
The British regulator Ofgem created a new price control framework for DSOs in 2019, providing an incentive for the creation of local flexibility markets and the use of flexibility services as an alternative to adding generation or distribution infrastructure. The framework requires DSOs to submit a business plan for using flexibility to maximise the use of existing network capacity. The plan must be fair, simple and transparent.

The new regulations have prompted six DSOs in Great Britain to use flexibility markets. The framework has also attracted new players like EPEX SPOT, which has launched new flexibility platforms: the NODES marketplace and Piclo Flex. Ofgem estimates savings of up to GBP 4.5 billion per year for customers by reducing the need for new generation capacity and grid expansion.

Source: (smartEN. 2022).

ELECTRICITY MARKET DESIGN

15 Smart charging for system flexibility

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●○○○	●●●●	

WHAT The flexibility from smart charging not only benefits local distribution systems, it can also benefit the entire system through interoperability among local flexibility markets. The principle is simple: non-activated bids in local flexibility markets are forwarded to transmission system operator (TSO) markets with similar requirements (*e.g.* manual frequency restoration reserve) as long as they do not create additional congestion in the local grid (smartEN, 2022). Using this approach for frequency regulation is already technically feasible and economically profitable, as shown in the Nordic grid, Great Britain, France and Germany, among others.

New rules and regulations that can support this innovation include increasing the time granularity in electricity markets, defining new ancillary services, allowing DERs' participation in wholesale and ancillary service markets, and increasing co-operation between TSOs and DSOs.

WHY System flexibility provisions will help place a monetary value on flexibility and increase the ability to control demand, enabling both TSOs and DSOs to better integrate EVs into the grid and realise the many benefits of that integration. That, in turn, will encourage faster adoption of EVs.

BOX 3.14 | Examples of smart charging providing system flexibility

Norway's NorFlex project was able to supply 3 MW of flexibility from the local flexibility platform to the transmission system operator's (TSO) manual frequency restoration reserve (mFRR) market in January 2022; this was made possible by the lowering of the minimum bid for the procurement of mFRR. This example shows how regulatory changes can speed up innovation. However, a full regulatory framework is needed to guarantee interoperability across markets by allowing distribution system operators to participate in different markets.

Frequency regulation from fleets of electric vehicles in France: RTE, France's TSO, has certified the use of EV batteries from company fleets for V2G smart charging. The practice allows real-time balancing of supply and demand to provide frequency control services, helping to ensure smooth operation of the French (and European) electricity system.

Frequency regulation from fleets of electric vehicles in Denmark: The V2G technology company Nuvve aggregates multiple EV batteries to provide a primary frequency-controlled reserve service (FCR-N) to Energinet, the TSO in Denmark. Vehicles are connected to 10 kW bidirectional DC chargers controlled by Nuvve's V2G GIVe platform. Nuvve's software bids the available capacity in the batteries for use in the frequency-controlled reserve market, while also ensuring that the vehicles retain sufficient energy to operate when needed. Fleet owners can use Nuvve's management app to set the driving needs for any given day.

Nuvve has used the system to manage the EV fleet at Frederiksberg Forsyning, a water and gas utility. The vehicles are parked at night and on weekends, allowing each to provide about 17 hours of market participation per day. Results show that each vehicle contributed about USD 2 000 in market revenue in 2017 and 2018. The revenue allows Nuvve to lower the total cost of EV ownership for its customers.

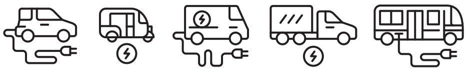
The Parker project in Denmark is using a commercial V2G hub and EVs to provide frequency regulation services. The project showed that individual cars can each supply thousands of hours of frequency services, generating annual revenue of EUR 1 860 per car.

Frequency regulation from fleets of electric vehicles in Zhejiang, China: In September 2021, State Grid aggregated multi-type adjustable load resources to provide a regional frequency modulation response test for the first time. As an important adjustable load resource, EV fleets participated in the regional frequency regulation response test with a cumulative response power of 1 452 kW. The test results show that 2 minutes after receiving the instruction, the charging power of the adjustable EV fleets in Anhui province was reduced by 452 kW. Eight minutes later, the charging power of the adjustable EV fleets in Zhejiang province was reduced by 1 000 kW. During the test, the frequency was reduced to 49.897 Hz at the lowest level. The load-side resources have response time ranging from seconds to minutes.

Source: (smartEN, 2022; CHAdeMO, 2022a; Nuvve, 2020; SGCC, 2021).

Regulation for charging infrastructure

REGULATION FOR CHARGING INFRASTRUCTURE | **16 “Right to plug” regulation**

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●●●●	●○○○	

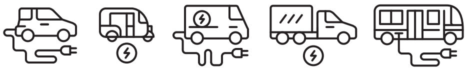
WHAT “Right to plug” regulations give all EV drivers the legal right to install or have access to a charger. This is crucial for providing access to charging for people who live in multi-dwelling units, work in multi-tenant buildings or lack convenient off-street parking.

The regulation could require pre-cabling of parking spaces for new and existing residential buildings, for example, or specify a minimum number of chargers for buildings, especially new ones. One possible innovation is wiring lamp posts for kerbside charging.

WHY Providing universal access to charging is vital for widespread EV adoption and for a just and fair transition.

REGULATION FOR CHARGING INFRASTRUCTURE

17 Streamlining permitting procedures for charging infrastructure

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●●●●	●○○○	

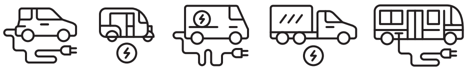
WHAT A streamlined permitting process makes it easy to obtain permits, for example, from a "one-stop shop". Close co-ordination among different decision makers is needed to make permitting requirements easily accessible, clear and streamlined. To avoid unnecessary burdens, permits can be tailored to different categories and types of chargers; they should be accompanied by installation guidelines with key steps, requirements and cost calculations. Permitting procedures can be more effective if targeted at specific audiences, such as homeowners, renters or commercial installers. Furthermore, the process should include inspections of locations and configurations for EV charging infrastructure to ensure the safety of those systems. Recommendations for streamlining permitting procedures include the ones given below.

MAKING INFORMATION EASILY AVAILABLE	MAKING THE APPLICATION PROCESS EASY
Installation guidelines	Enable online application
Requirements checklist	Classify some infrastructure installations as minor work
Outreach and education programmes	Create flexible inspection requirements

WHY Streamlining permitting procedures would help accelerate the deployment of charging infrastructure. It would also create a level playing field with incumbents, especially along highways where gas stations are already present, and may motivate new consumers to purchase EVs, since charging points would be easier to install or access.

REGULATION FOR CHARGING INFRASTRUCTURE

18 Standardisation and interoperability

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●●●	●●●●	

WHAT Standards and protocols are needed across the entire EV value chain to support two-way communication and interoperability at multiple levels: grid to charger, charger to vehicle, charging point operator to charger, among charging point operators, aggregator to grid, charging point operator to aggregator and aggregator to charger. Interoperability is especially important for commercial fleets. Software platforms for EV fleet charging must be compliant with the latest standards to support communication and meet business needs regardless of location or hardware. SAE International and the International Electrotechnical Commission have already developed some standards supporting multiple communication protocols between vehicles and charging stations. Those standards are advancing to accommodate new features and needs, for example, for medium- and heavy-duty vehicles, smart charging and grid services. One challenge is the proprietary nature of some automakers' telematics protocols for communicating information between vehicles and aggregators.

WHY Standardisation and interoperability are crucial to ensure compatibility and communication flow among all types of charging stations, charging applications and hardware devices that EVs introduce into the system.

BOX 3.15 | Smart charging standards

Important V1G/V2G smart charging standards include:

- IEC 61851-24: Digital communication between a DC EV charging station and an EV
- IEC 62909s: Grid-connected bidirectional converter
- IEC 61850: Communication systems for distributed energy resources

In addition, ISO 15118-20 (V2G interface) is an international standard for EV-to-charger communication that is now under development by the International Electrotechnical Commission and the International Organization for Standardization. It would allow such innovative techniques as plug-and-charge, where charging and payment begin immediately when an EV is plugged into a charger, and smart bidirectional charge management, which can provide tremendous benefits for grid resilience and load management. Standard-compliant products are expected to become widely available in four to five years.

In 2022, the US government proposed to adopt ISO 15118 (Department of Transportation, 2021). Also in 2022, the CHAdeMO Association released a protocol for motorcycles and small vehicles (CHAdeMO, 2022b). A DC fast charging standard for e-bikes is also in development.

REGULATION FOR CHARGING INFRASTRUCTURE

19 V2G grid connection code

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
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WHAT Since EVs can require charging power higher than that offered by normal household connections, grid codes will have to weigh requirements for EV charging. For example, EV charging facilities typically must meet the requirements applicable to generators exporting active power to the grid (IRENA, 2022b) In Europe, ENTSO-E concluded that the connection network codes covering EVs (V1Gs and V2Gs) fall within the scope of connection network codes and do not require special treatment. A V1G connection would fall under the demand connection code and a V2G would fall under the requirements for generators.

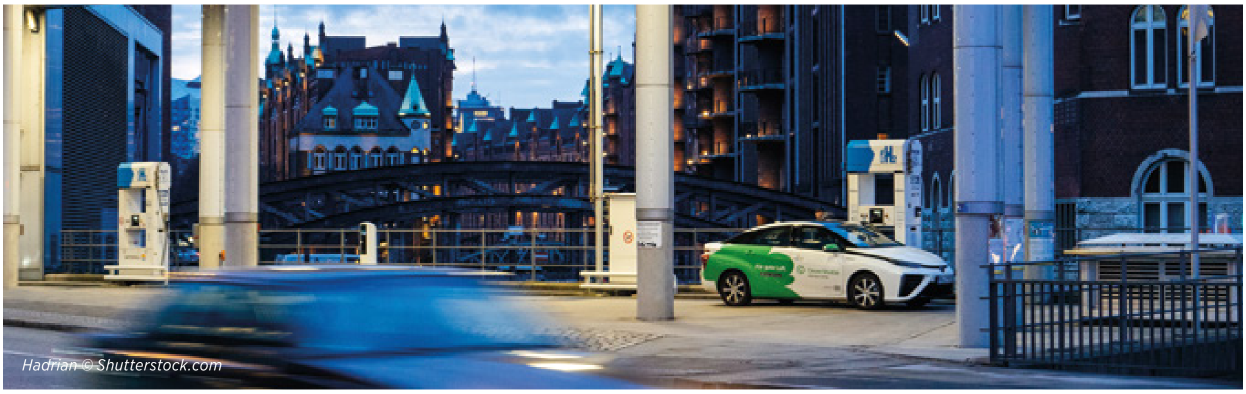
WHY Defining V2G grid codes is important to allow EVs to connect easily to, and smartly exchange energy with, the grid. The codes allow smart and bidirectional charging, which helps control peak loads and provides many other grid benefits. Those benefits can reduce investments in the grid and in distribution transformers and cables by approximately 50% (ElaadNL-CHAdeMO, 2022c).

BOX 3.16 | V2G grid connection codes in Germany, Australia and the United States

German rules specify that EV charging facilities must be able to ride through the same type of voltage dips as generators while in discharging (exporting) mode without disconnecting from the system (VDE FNN, 2019). Charging facilities with higher active power ratings (above 100 kW, like storage) must be equipped with bidirectional communication to enable remote control and monitoring.

Australia is revising its national standard, AS4777.2. The revised standard will require EV charging stations to meet the requirements for inverters, which include electrical safety, power quality, voltage support, demand-response modes, anti-islanding requirements and “fault ride-through” capabilities. An ongoing pilot project, called the REVs project, will validate a vehicle-to-grid charger against the AS4777 standard (Jones *et al.*, 2021).

Similarly, the United States is working on regulations to support V2G and define the roles of EV batteries in the grid (such as storage or small generators). In California, revisions of Rule 21 cover flexible solar storage and V2G (California Public Utilities Commission, 2018).



Hadrian © Shutterstock.com

3.3 System planning and operation

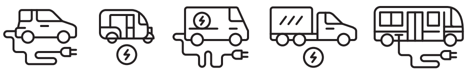
Electrification of the mobility sector requires unprecedented coupling and co-ordination between the power and mobility sectors to fully harness the synergies between EVs and renewable electricity. Figure 3.6 shows the innovations in system planning needed to prepare power systems for the extra load and to harness EVs' ability to significantly increase the resilience of power systems worldwide, which are already experiencing more frequent blackouts due to extreme weather and natural disasters. The next section discusses these innovations in detail.

FIGURE 3.7 | Innovations in system planning and operation for power to mobility

SYSTEM PLANNING AND OPERATION	**STRATEGIC PLANNING**	• **20** Cross-sectoral co-operation and integrated planning
		• **21** Including EV load in power system planning
		• **22** Grid data transparency
		• **23** Clean highway corridors
	SMART OPERATION	• **24** Operational flexibility in power systems to integrate EVs
		• **25** Management of flexible EV load to integrate VRE
		• **26** Management of flexible EV load to defer grid upgrades
		• **27** EV as a resilience solution

Strategic planning

STRATEGIC PLANNING | **20 Cross-sectoral co-operation and integrated planning**

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●●○○	●●●●	

WHAT To achieve a zero-emission transport sector and a carbon-free electricity grid, all stakeholders in the EV ecosystem will need to co-operate and align their policy agendas and incentives to support integration with the grid. These stakeholders include regulatory agencies, grid operators, energy retailers, charging point operators, mobility service providers and, on the demand side, consumers.

WHY Co-operation and policy harmonisation will reduce regulatory barriers to EV adoption and lower costs for businesses, citizens and governments. If assiduously pursued, they will ensure that all stakeholders (and their expertise and experiences) are considered in the policy making process and best practices inform the design and updating of policies affecting the EV ecosystem.

3
20 21

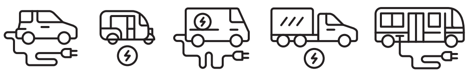
BOX 3.17 | Stakeholder co-operation for e-mobility in the United States and Germany

California's Vehicle Grid Integration Working Group, which was established in 2019 to address challenges and questions on vehicle–grid integration, has brought together more than 80 stakeholders, including the California Air Resources Board, the California Transmission System Operator, the California Energy Commission and the California Public Utilities Commission. It has developed 92 recommendations for policy actions to advance vehicle–grid integration (Gridworks, 2019).

The "Electrify Buildings for EVs" project in Hamburg, Germany, aims to install 7 400 private charging points. The project requires co-ordination among Hamburg's Departmental Authority for Economic Affairs, Transport and Innovation (project co-ordination); hySOLUTIONS GmbH (project management); IFB Hamburg (investment and development bank); Stromnetz Hamburg (network operator); Helmut Schmidt University (scientific support); and local grid operators and investors (Electrive, 2019).

STRATEGIC PLANNING

21 Including EV load in power system planning

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●●●○	●●●●	

WHAT Planning for the grid and forecasting future demand as EV adoption accelerates must consider the extra load from EVs in both the short and long terms. The extra load from EVs would be calculated based on the number of EVs on the road as well as the potential for smart charging and V2G functionality to make the grid more flexible. The additional EV load will create two main challenges, grid congestion and component overloading, while the main opportunity is EVs' ability to absorb power fluctuations and provide grid resiliency. The fact that EVs will be connected at many different charging locations on the grid adds extra complexity to planning efforts. Different scenarios of EV penetration and grid impacts can help plan future needs for generation capacity, transmission and distribution.

WHY Planning and monitoring for flexible loads within power and charging systems will help mitigate congestion and defer grid upgrades, while identifying grid extension needs. Power system planning for flexible loads will also reduce the impacts of electric trucks and the large-scale charging hubs for long-distance travel in or around large urban centres.

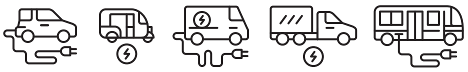
BOX 3.18 | Smart planning for EV charging in Hamburg, Germany

The peak load in the distribution network in Hamburg is expected to increase 40% from the current 1.8 GW over the next 20 years, mainly due to increases in EVs, heat pumps and public transport electrification. Charging the 100 000 EVs expected to be on the road by 2030 (out of 700 000 total vehicles) could critically overload transformers. But Hamburg intends to reduce the need for new investments in lines, cables and transformers through a combination of digital technologies, new business models and market regulation to allow smart charging. The proposed solution (estimated to cost EUR 2 million) would avoid a EUR 20 million network upgrade.

Source: (IRENA, 2019).

STRATEGIC PLANNING

22 Grid data transparency

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●○○○	●●●●	

WHAT Rapid digital transformation over the past decade has led the grid to become highly interconnected and automated. It generates vast amounts of data from customers' meters, from measurements on the grid, from other grid assets and from markets of immense value to multiple stakeholders. These data should be made as transparent as possible, using communication frameworks and data management infrastructure to support the collection, exchange, use and security of the information.

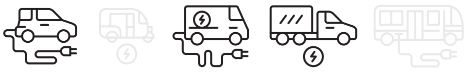
WHY Transparency of data and digital communication is essential to the power system planning needed for large-scale EV adoption. Data are vital for making optimal decisions on charging infrastructure locations, charging times and duration, grid services and participation in local flexibility markets, among other matters.

BOX 3.19 | Grid transparency efforts by ELIA, Belgium's transmission system operator

The ELIA platform shares data on the status of the grid as well as qualitative data, including issues and reports. Users can download data to improve operations. For example, data on grid imbalances enable entities active in the system to co-operate to avoid grid problems. ELIA is also creating an advanced platform that includes historical load data on EVs and wind power, which will also help solve grid-related problems (Elia Group, 2022). Similar platforms are also being developed by Energienet in Denmark and TenneT in the Netherlands.

STRATEGIC PLANNING

23 Clean highway corridors

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●○○○	●●●●	●●○○	

WHAT Clean highway corridors are routes that provide charging to electric trucks and passenger cars for long-distance travel. Creating such corridors will require partnerships among utilities, vehicle manufacturers, charging equipment providers and states to assure interoperability and address grid impact challenges.

WHY Clean highway corridors can address one of the biggest challenges to widespread EV adoption – the ability to travel long distances without lengthy waits for charging. Corridors could use charging points or overhead charging; their implementation will have to consider traffic flows, power grid strength and the availability of locally produced renewable electricity.

BOX 3.20 | Clean transportation corridors in the United States and Uruguay

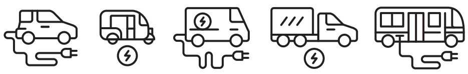
The West Coast Clean Transit Corridor Initiative in the United States includes nine energy retailers and two agencies representing more than 24 municipal electric utilities. The goal is to have 27 charging locations with at least 3.5 MW charging capacity situated about 50 miles apart along interstate freeway I-5 from the Mexican border to the Canadian border (Griffo, 2022).

Uruguay has installed charging stations along its entire coast and at several points in the interior, creating the region's first electric vehicle corridor. The goal is to install charging stations no more than 60 km apart throughout the country (UNEP, 2020).

Smart operation

SMART OPERATION

㉔ Operational flexibility in power systems to integrate EVs

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●●●○	●○○○	

WHAT Even though EV smart charging can add valuable flexibility to the power system, many EVs may still charge quickly and uncontrollably, causing voltage instability, congestion at transformers or on lines, or other issues.

However, system operators can use already installed assets of their own to provide flexibility and resolve such issues. Such assets include tap-changer transformers (which can change voltage), capacitors and similar devices providing reactive control, and inverter-based generators.

System operators can also ask for contributions from other flexibility service providers, such as generators or aggregated demand-response providers. Using market-based mechanisms would help ensure the fair and competitive provision of flexibility services.

WHY Using power systems' flexibility resources and encouraging assets to participate in flexibility markets or demand-response programmes will enable system operators to prevent unco-ordinated integration of EVs or uncontrolled charging from causing problems on the grid. Doing so will avoid technical and financial losses and allow power systems to operate optimally. It will also be important to co-ordinate EV charging with the use of system flexibility resources to maximise system-level flexibility.

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25

SMART OPERATION

25 Management of flexible EV load to integrate variable renewable energy

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●●●●	●●●●	

WHAT Decarbonising the transport sector requires transitioning to EVs and charging those EVs with electricity generated from renewable sources. And here lies an important synergy: increasing the use of EVs makes it easier to integrate more renewables into the electricity grid. In the short term, EVs can absorb excess renewable power and avoid curtailment during hours of high generation; later, they can feed back renewable energy into homes or the grid with bidirectional charging. In the long run, increases in EVs will add flexibility, which will make it possible to integrate more renewables into the power system.

WHY Harnessing the synergies between EVs and renewable energy will allow system operators to smoothly integrate both the growing numbers of EVs on the grid and the necessary increases in renewable generation share in the energy mix, significantly reducing the use of fossil fuel–fired peaking power plants and accelerating the energy transition.

BOX 3.21 | Nova Scotia Power's smart charging pilot increases the use of renewable electricity

In 2020, the Canadian utility Nova Scotia Power began a pilot project combining renewable energy generation, EV charging and integrated monitoring. Household customers pay CAD 350 for a ChargePoint Home Flex EV smart charging system and receive a CAD 500 incentive if they allow Nova Power to control when the EVs are charged over a two-year period. The utility then adjusts charging time to manage the EV load and better synchronise it with solar and wind generation profiles, while guaranteeing that the vehicles will always be fully powered each morning (Jarratt, 2020).

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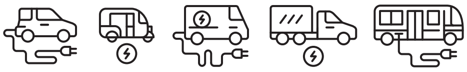
26

SMART OPERATION

26 Management of flexible EV load to defer grid upgrades

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●●○○	●●●●	

WHAT To prevent grid components from being overloaded by EV charging, especially when vehicles charge at peak times, system operators can carefully plan, monitor and control the load capacities from EVs in different locations. They can then shift charging from peak hours to off-peak hours, among other actions. This innovation applies to light-, medium- and heavy-duty vehicles, but the specific strategy may differ for different vehicle types due to different charging profiles and battery sizes.

WHY The flexible management of EV loads is important for integrating higher shares of variable renewables, minimising peak loads, avoiding grid congestion, and deferring costly grid investments and upgrades.

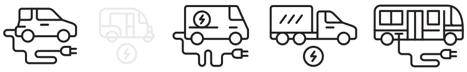
BOX 3.22 | The Netherlands reduces EV peak load by controlling charging, while Germany tests demand-side redispatch with EV charging

In a pilot project developed by Enexis Netbeheer (a grid operator in the Netherlands) involving 138 households, smart charging controlled by the DSO decreased the peak load by 40% – without drivers noticing slower charging. Data about the available grid capacity were used to manage charging (Elaadnl, 2020).

Germany's TransnetBW and Tesla have launched a project called PV shift, which controls homes with Tesla solar power systems and EVs. The project shifts home-generated solar power from EV charging to grid feed during periods of high grid load (TRANSNET BW, 2022). The project is gathering practical experience on flexibility potentials and on processes involving grid operators, equipment manufacturers and consumers. It is helping to test standardised mechanisms for demand-side redispatch that can help to stabilise the power grid in a cost-efficient way.

SMART OPERATION

27 EV as a resilience solution

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●○○○	●●●○	

WHAT The flexibility that large numbers of EVs can provide offers grid-resilience strategies that may reduce the duration and severity of shortages or blackouts. EV batteries can also become an important backup power option, especially in Europe, where gas peakers are no longer considered reliable flexibility sources owing to supply constraints. EV batteries can store and feed energy to the grid or to homes and other buildings. With a millisecond reaction time, EV batteries are the quickest flexibility option. They are also the cheapest, since their capital costs have already been paid by vehicle owners, and their marginal cost is minimal compared with other flexibility sources, including new stationary storage, pump storage and gas peakers.

WHY Resilience strategies using EVs can support the grid in cases of brownouts (whether ordered or stemming from a sudden drop in voltage), unintentional blackouts (total loss of power to an area), scheduled blackouts or public safety power shutoffs (*e.g.* during severe weather). These strategies are made possible by the availability of V2G cars and chargers.

BOX 3.23 | Example of initiatives using EVs as resilience solutions

V2G-capable electric school buses deployed by Nuvve Corporation have large batteries and are parked and idle most of the day. Nuvve is testing their ability to provide emergency backup power and increase grid resilience (Nuvve, 2020).

Similarly, the fully electric 2022 Ford Lightning can power an average home for about three days through its charging cord. Such vehicles could have made a real difference during the February 2021 Texas blackout, when winter storms left millions of people without power (Busby *et al.*, 2021; MotorTrend, 2021). Similarly, the fully electric 2022 Ford Lightning can power an average home for about three days through its charging cord. Such vehicles could have made a real difference during the February 2021 Texas blackout, when winter storms left millions of people without power (Busby *et al.*, 2021; MotorTrend, 2021).

Under Nissan's Blue Switch initiative (2018 to present), EVs are driven to disaster-affected areas and used for emergency backup power. During the critical first hours and days, they can deliver power where it is needed the most. The initiative is an interesting model of co-operation between local authorities and industry stakeholders (Nissan Motor Corporation, 2020).

3.4 Business models

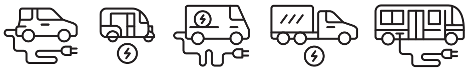
Emerging business models aim to monetise the value added by smart charging and to support the further deployment of smart electrification. As Figure 3.7 shows, innovative business models include new services for the power system and models to enable EV deployment.

FIGURE 3.8 | Innovations in business models for power to mobility

BUSINESS MODELS	SERVICES FOR THE POWER SYSTEM	**28** EV aggregators
		29 Shaving EV load peaks using DERs
		30 Battery second life
	MODELS TO ENABLE EV DEPLOYMENT	**31** EV charging as a service
		32 E-mobility as a service
		33 Publicly available charging station ownership and operation
		34 A single bill for EV charging at home and on the go
		35 Battery swapping

Services for the power system

SERVICES FOR THE POWER SYSTEM | 28 **EV aggregators**

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●○○○	●●●●	

WHAT Aggregators combine different DERs and operate them as a single entity, such as a virtual power plant. They can add multiple benefits to the grid through services such as load shifting, balancing for TSOs and local flexibility for DSOs. As digital intermediaries between a pool of EVs and the power system operator or electricity market, aggregators are fundamental for enabling EV participation in electricity and ancillary service markets. They may be owned by an independent company or an energy retailer.

WHY A single EV cannot meaningfully participate in markets or provide grid services. But a pool of EVs can offer major benefits, while also enabling new business models. Aggregators can stack different services from EVs to extract more value from several possible revenue streams, or aggregate pools of EVs with other assets such as stationary batteries or controllable loads to yield even more value.

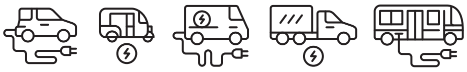
BOX 3.24 | An EV aggregator for a V2G trial in the United Kingdom

In the world's largest residential V2G trial, Project Sciurus is aggregating 320 V2G charge points in the UK to support the grid and generate revenues. The V2G units are aggregated, optimised and scheduled via the Kaluza Intelligent Energy platform; they participate in the UK's Piclo demand-response market. EV owners are paid for every kilowatt hour that is exported (UK Power Networks).

Source: (Cenex, 2022).

SERVICES FOR THE POWER SYSTEM

29 Shaving of EV peak loads using DERs

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●○○○	●●●●	

WHAT EV charging infrastructure can be combined with solar energy systems, energy storage or other on-site DERs. Such combinations are particularly viable for highway charging stations, public charging stations in cities, bus charging stations and electric truck depots. They also allow charging in off-grid areas or areas with weak grid connections. The most common type of installation pairs EV chargers with solar PV, usually in the form of solar rooftops or canopies.

WHY Charging EVs with DERs reduces peak loads and congestion on the grid. In so doing, it makes maximum use of the generated distributed energy, since plugged-in EVs will absorb electricity that could otherwise be wasted for lack of demand. It also avoids the distribution investments and grid capacity expansions that would be needed to supply large amounts of power to grid-connected charging stations. Off-grid solar charging systems will accelerate the swich to electric mobility in places with weak grids, avoiding the need for network extensions.

SERVICES FOR THE POWER SYSTEM

30 Battery second life

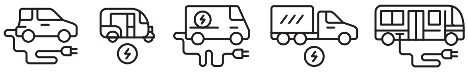
Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●●○○	●○○○	

WHAT While EV batteries have been shown to last for hundreds of thousands of kilometres, they will eventually fail to provide enough power and range to be useful for mobility. Yet they may still have up to 80% of their original capacity, allowing them to have a second life as stationary batteries powering applications that are less demanding than EVs. Second-life batteries are significantly cheaper than new batteries, thus making stationary storage less expensive.

WHY Second-life applications can extract significant amounts of value from used EV battery packs before they need to be recycled; this in turn will lower the overall costs of operating a renewables-based power system.

Models to enable EV deployment

MODELS TO ENABLE EV DEPLOYMENT | **31 EV charging as a service**

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●●○	●●●○	

WHAT In the charging-as-a-service (CaaS) business model, EV owners pay for charging their cars without actually owning or managing a charging point. Instead, a third party owns the charging stations and sells charging services. CaaS companies typically provide both the charging station hardware and back-office services, such as billing and maintenance, as a turnkey solution for customers who want to have charging stations installed. Payments can be made through contracts or pay-as-you-go arrangements for electricity used at fixed or variable rates. CaaS companies can include retailers, municipalities and businesses with parking slots for guests and employees.

WHY The CaaS business model lowers the upfront ownership costs of chargers and software for consumers, eliminating a potential barrier to greater EV adoption. It also allows service companies to contribute to a wider and more rapid uptake of EVs, which will quicken the electrification of the energy infrastructure.

BOX 3.25 | EV charging as a service in California

Most people rent or live in multi-unit dwellings, and most of these buildings were designed (and built) long before EVs. As a result, they lack charging infrastructure, and most retrofitting options are too expensive for owners to afford.

California-based EVmatch is trying to solve this problem by installing affordable smart charging stations that EV drivers can share. Customers can reserve a charger for specific time periods, which ensures that the chargers are in use most of the time. Customers can earn extra money by renting out the stations to the general public (EVmatch, 2022).

MODELS TO ENABLE EV DEPLOYMENT

32 E-mobility as a service

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●●	●●●○	●○○○	

WHAT In the mobility-as-a-service (MaaS) model, people buy transportation services instead of purchasing and owning private vehicles. MaaS bundles several transport modes, allowing travellers to organise their travels based on their own preferences, pricing and available transport modes. In the case of electric mobility as a service (E-MaaS), all the transportation modes are different types of electric vehicles, including e-scooters and e-bikes. Both the vehicles and the associated charging and energy infrastructure for E-MaaS are aggregated and owned by a third party and then used by customers, who pay for using the vehicles. E-MaaS models can be used to market the use of electric commercial fleets.

WHY E-MaaS allows people and businesses to pay only for the transportation services they use rather than having to buy and maintain a vehicle. This reduces or removes the upfront costs of switching to electric mobility and allows people and businesses to choose the cheapest, most convenient, greenest or fastest option to meet their needs. Shared vehicles in the E-MaaS model typically have higher utilisation rates than privately owned vehicles, thereby lowering the overall costs of the EVs (with their high capital cost but low operating cost) and accelerating the energy transition. Moreover, with V2G, E-MaaS operators can realise extra revenues by providing services to the grid.

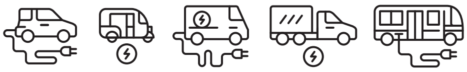
BOX 3.26 | Micro mobility platforms, an E-MaaS model

With digitalisation and new integrated software, E-MaaS businesses can optimise planning and operation, including vehicle trip scheduling (taking traffic into account), scheduling of charging, depot management, and routine service and maintenance.

One of the first E-MaaS models to emerge has been electric two-wheel scooters that are accessed through a mobile application and are readily available on street corners. E-scooters can help riders avoid traffic jams; by replacing taxi rides or ride-shares, they can reduce vehicle traffic and the associated environmental impacts.

MODELS TO ENABLE EV DEPLOYMENT

33 Ownership and operation of public charging stations

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●●●	●○○○	

WHAT Public charging infrastructure is crucial for increasing the use of EVs. The main barrier is its high initial investment cost, but innovative business models for ownership and operation are emerging. These include gas stations adding EV chargers; EV chargers managed and owned by energy retailers, DSOs or charging point operators; and commercial businesses expanding their business by adding EV chargers. Charging stations can be owned by technology companies, utilities, governments, municipalities or other retailers.

WHY Innovative approaches for the ownership and operation of public charging stations will make public charging far more accessible, enabling faster adoption of EVs.

BOX 3.27 | Commercial businesses with EV chargers, advertising on chargers and on-demand charger installation

Kirana Charzer, an Indian start-up, offers a compact charging station that is accessible via a mobile app. The charging station, which is powered by Internet of Things, can be hosted by shops or restaurants, providing them with additional income, while also extending the EV charging infrastructure (Dash, 2020).

Digital billboards on Volta chargers throughout the United States provide extra revenue to offset the cost of infrastructure and charging (Volta, 2022).

On its website, the city of Saint Etienne, France, asks drivers where they want public chargers; this enables the city to install chargers where they are most likely to be used, thereby strengthening its business case further.

MODELS TO ENABLE EV DEPLOYMENT

34 A single bill for EV charging at home and on the go

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
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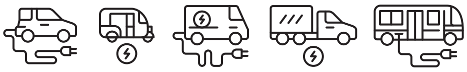
WHAT Single-bill business models allow EV owners to pay for public charging on their home electricity bills. The service works by combining a standard domestic supply contract with a roaming package that detects the use of public charging points and bills for such use upon agreement with charging point operators. However, it may require removing regulations inhibiting the use of home or business electricity contracts at other locations.

WHY Having a single bill for EV charging at home and on the go simplifies electricity payments for EV drivers, eliminating one more barrier to the greater use of EVs.

MODELS TO ENABLE EV DEPLOYMENT

35 Battery swapping

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●●●○	●●●○	

WHAT Instead of charging the battery in a vehicle, battery swapping replaces empty battery packs with fully charged packs. For swapping to work, battery packs must be easily accessible and replaceable. Swapping also is easiest when batteries are lightweight, as in electric two- and three-wheelers. For heavier vehicles, battery swapping is more complicated, requiring a mechanic's assistance.

The battery swapping model requires the removed battery packs to be recharged. This greatly increases the number of battery packs that must be in circulation, raising the overall costs.

WHY Battery packs are the most expensive component of EVs, representing about one-third of the total cost of the vehicle, and they degrade over time. Outsourcing batteries' maintenance and replacement can therefore reduce costs for EV drivers and owners. In some cases, it also replaces potentially long charging times with quick swaps, which could be especially useful for fleet managers. Providers, meanwhile, can realise revenues not only from swap customers, but also from the services offered to the grid using the batteries stored at swapping points.

BOX 3.28 | Battery swapping for two- and three-wheelers in Taiwan and Ample, a US-based battery swapping start-up

Gogoro, a Taiwanese manufacturer, and Panasonic have made portable lithium-ion batteries for two- and three-wheelers that are available for swapping in vending machines in Asia. The business model includes a fee for using the swapping stations (Gogoro, 2022).

Ample, a San Francisco-based start-up, plans to outfit vehicles with its modular battery packs, which can be swapped at dedicated stations, which are fully automated and can identify the exact location of the battery module to be swapped. Their batteries can be scaled easily based on "Lego-like" modules, which makes it possible for the company to expand rapidly (ample, 2022).

BOX 3.29 | Battery swapping pilot project for heavy trucks in China

As part of the National Energy Group's "electric heavy truck green transportation pilot project", two battery swapping stations, which can serve 100 heavy trucks, were built. The green electricity generated by distributed photovoltaic in this project directly provides power supply to the battery swapping stations. Vehicles can realise automatic battery swapping within 3-5 minutes. The project is expected to reduce the regional transport logistics cost by 5-10%, cause annual average carbon dioxide emission reductions of 137 000 tons and lead to a decrease of 1 730 tons in emissions.

Source: (CHN Energy, 2022).

SECTION II

POWER TO HEAT AND COOLING

CHAPTER 4

ELECTRIFICATION OF HEATING AND COOLING

STATUS AND PACE OF PROGRESS

Heating and cooling accounts for about half of the global final energy consumption. It is the largest source of energy end use, ahead of electricity (20%) and transport (30%), and is responsible for more than 40% of global energy-related carbon dioxide emissions.

The majority of heat generation comes from fossil fuels (coal, oil and natural gas), with some from the unsustainable use of biomass. The share of fossil fuels in heat generation has, nevertheless, been declining (from 91% in 2010 to 75% in 2021) (IEA, 2022a). Meanwhile, the buildings (residential and commercial) and industrial sectors account for approximately 95% of global heating demand.

The global energy demand for cooling is expected to increase by 45% by 2050 compared with 2016 levels (from 7 to 12 exajoules [EJ]) (IEA, 2018). One reason for this is that only a third of the global population currently living in hot climates possesses cooling appliances (Camarasa *et al.*, 2022). Another reason is that global temperatures are rising, with an increase of 1.5°C or more over pre-industrial levels expected by 2035 (IPCC, 2018). Both reasons are likely to cause an increase in the demand for cooling appliances, especially with rising standards of living in developing countries. For example, the number of cooling units in China and India increased by more than 60% between 2010 and 2020, and is expected to increase threefold in the current decade (Green Cooling Initiative, 2022).

Space cooling, mostly in buildings, is responsible for roughly half of the energy used for cooling. The rest of the energy is used for industrial and commercial refrigeration (Green Cooling Initiative, 2022). Since cooling is already predominantly powered by electricity, decarbonisation gains will be linked to smart electrification strategies rather than greater electrification, as in the case of heat.

Electrification, primarily of heating, is the key strategy for decarbonising heating and cooling (and meeting the 1.5°C target by 2050).[1] IRENA's 1.5°C Scenario shows that by 2050, electricity would power 73% of the total demand in buildings, up from the current 34%. This will require putting 793 million heat pump units into operation by 2050, a 14-fold increase from today's 58 million units. In the industrial sector, some industrial processes, such as steel industry furnaces, are difficult to electrify. Nonetheless, by 2050, electricity should account for 27% of total final energy consumption in industry (IRENA, 2023). Figure 4.1 shows the projections for 2030 and 2050 under IRENA's 1.5°C Scenario.

The heating (and cooling[2]) sector is divided into two end uses, buildings and industry, since industry often requires much higher temperatures (>150°C) than buildings (<100°C). Residential and commercial buildings can also be divided into those with small-scale heating and cooling systems or large-scale district heating systems. Each end use has a different current status and pace of progress and will thus require different innovations.

For example, district heating and cooling (DHC) systems still predominantly rely on fossil fuels (90% of the total heating supply), even though they could switch to renewable sources, waste heat streams or other sources (IEA, 2019). The use of district heating has increased 32% since 2010, accounting for 16 EJ of heating world-wide in 2021. District cooling (now only 1-2% of the entire European cooling market) is expected to increase by 3.5% annually over the next five years (Research and Markets, 2022).

For all buildings globally, 62% of heating was supplied by fossil fuels in 2020, with the remainder coming from traditional uses of biomass (26%) and modern renewables (12%).[3] The renewables share is expected to increase rapidly.

The industrial sector uses both low-temperature heat (for example, food and chemicals require less than 100°C) and high-temperature heat (steel, cement and glass industries require temperatures above 1 000°C), and predominantly relies on fossil fuels (89% in 2020). High-temperature processes (those that require temperatures above the range of heat pumps', greater than 150°C) are difficult to electrify directly at high efficiencies. These processes can alternatively be indirectly electrified using "green" hydrogen (see Section III).

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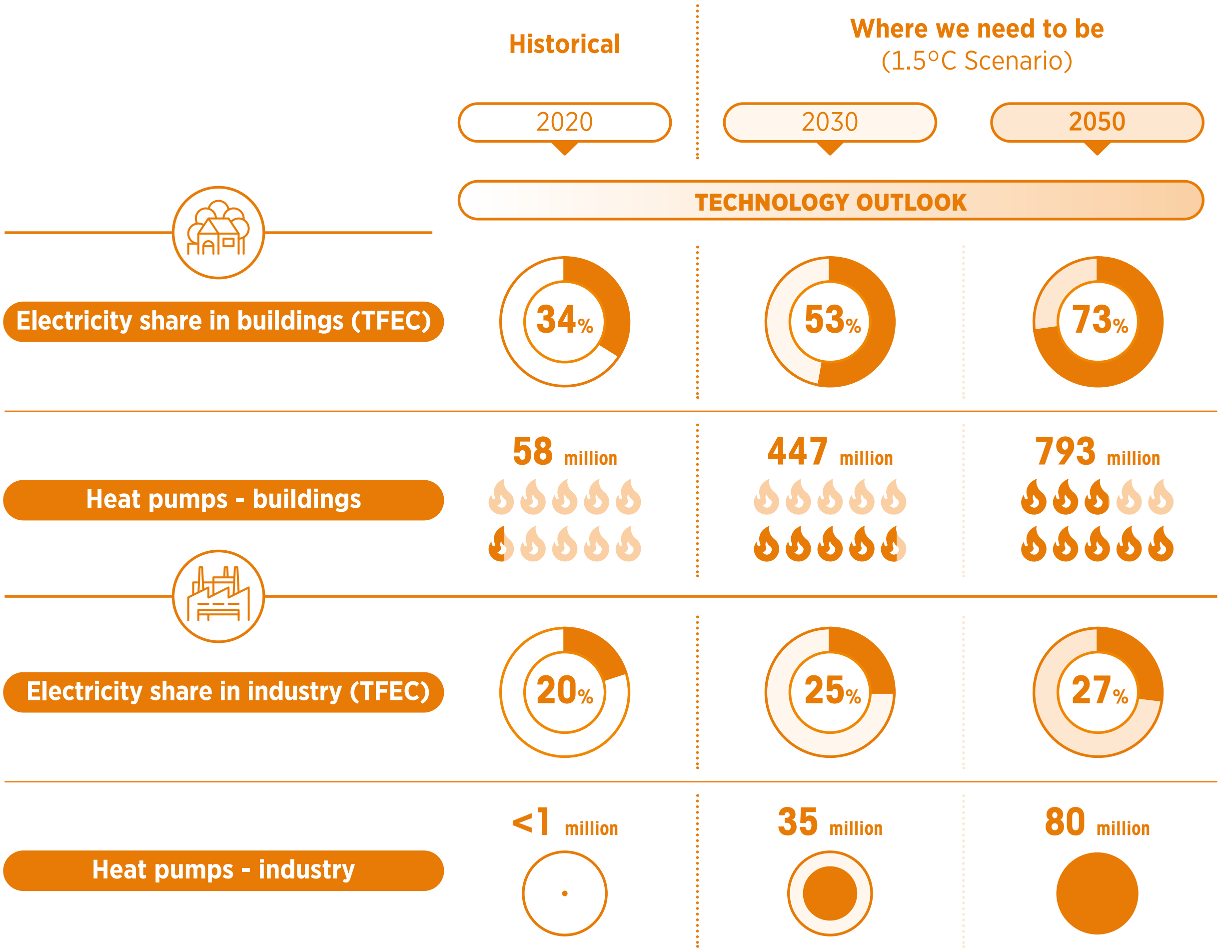
[1] *Here, the phrase "electrification of the sector" refers to a significant increase in the rate of electrification of the heating sector but not a 100% electrified sector. According to the future 2050 scenarios consulted, electrification should be combined with other clean sources, including biofuels and waste heat recovery. The indirect electrification of heat via hydrogen is addressed in Section III.*

[2] *We use the term "power to heat" as a generalisation for both transformations, that is, power to heat and power to cooling. However, of the two options, "power to heat" is generally more relevant due to the size of the heating sector.*

[3] *Modern renewables exclude traditional uses of biomass. Heat production from modern renewables covers the direct and indirect final consumption (e.g. through district heating) of bioenergy, solar thermal and geothermal energy, as well as renewable electricity for heat based on an estimate of the amount of electricity used for heat production and on the share of renewables in electricity generation (IRENA, 2020a, 212).*

FIGURE 4.1 | Electricity shares and market roll-out of heat pumps under IRENA's 1.5°C Scenario for the industry and buildings sectors



Source: (IRENA, 2023).

Note: TFEC = total final energy consumption.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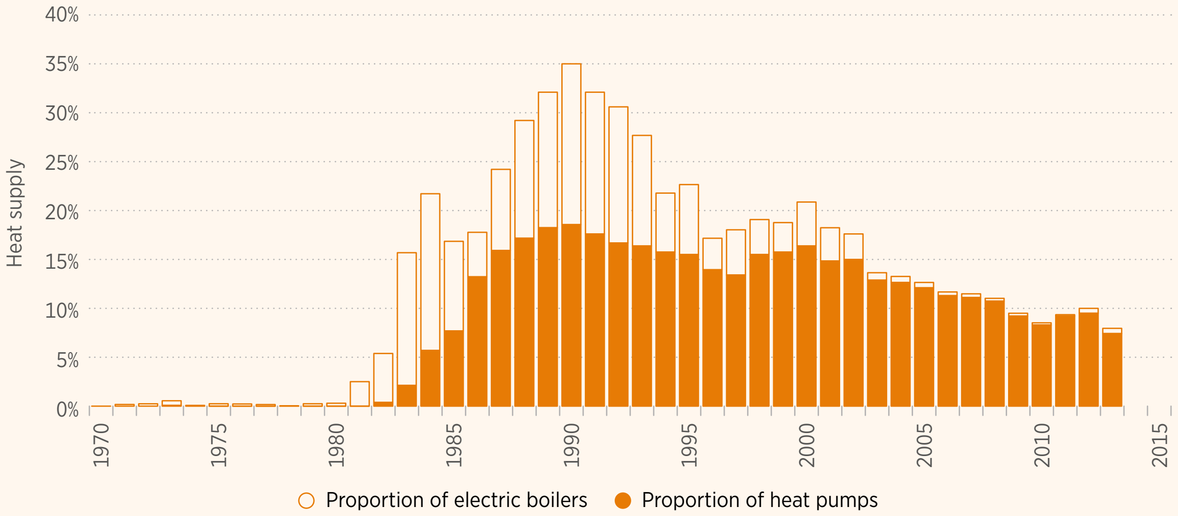
BOX 4.1 | Success factors for the deployment of large-scale heat pumps: The Swedish case

Sweden's electricity generation far exceeded demand, thanks to its extensive hydropower resources and the construction of nuclear power plants in the 1970s and 1980s. The surpluses could not be exported, however, due to the limited transmission capacity with neighbouring countries. To use some of the surplus electricity, Sweden developed district heating systems with large heat pumps, installing a total capacity of 1527 MW in the 1980s. Eighty percent of that capacity is still in use.

FIGURE 4.2 | Annual proportion of heat supplied to Swedish district heating systems from electric boilers and heat pumps, 1970-2013



After 2000, however, combined heat and power plants became more cost-competitive with heat pumps due to higher electricity prices and taxes. This led to a decline in the share of heat from heat pumps (Figure 4.2). Nevertheless, the Swedish example includes valuable operational and maintenance experience, including the adoption of new refrigerants and the expansion of the use of heat pumps to a larger range of temperatures and applications, especially in the industrial sector.

Source: (Averfalk *et al.*, 2017).

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4.1 Importance of smart electrification for future heating and cooling systems

The smart electrification strategies discussed in this report seek to create heating and cooling systems that are more efficient, effective, reliable and secure. They make it possible to integrate more renewable sources, reduce peak loads and congestion, and, ultimately, sharply reduce the dependence on fossil fuels, while also reducing costs and environmental impacts. They can also add flexibility to the power system, making it more efficient, avoiding investments in additional generation capacity in transmission or distribution grids.

Smart electrification strategies are heavily context dependent, since there is no simple guaranteed solution that works for all. The initiatives listed below are examples of successful cases that support smart electrification strategies in different countries:

- **Smart electrification via remote-controlled heating and cooling systems:** Predictive and adaptive algorithms make it possible to adjust heating, ventilation, cooling or refrigeration based on real-time power market conditions and consumers' needs, thus ensuring comfort at lower prices. As an example, in France, BeeBryte is already selling such remote-control services (BeeBright, n.d.).

- **Thermal storage** makes it possible to integrate more renewable sources. Storing just one cubic metre (m^3) of water-based heat can facilitate a 55-70% increase in the share of cooling demand that can be met by solar photovoltaic (PV) (Laine *et al.*, 2019). In Nigeria, for example, proposed ice-based energy storage with solar PV-powered refrigeration can reduce energy consumption by up to 40% in cooling-as-a-service models (Koolboks, 2020).

- **Aggregating decentralised distributed energy resources** enables them to provide flexibility services to grids. For example, in Belgium, demand-response operations using 40 000 residential heat pumps can provide 100 MW of upward reserve[4] at a cost of EUR 0-14/MWh, much lower than the local historical price of EUR 32/MWh (Georges *et al.*, 2017). The refrigeration units in supermarkets also offer several megawatts of flexible load. Because they can adjust cooling load by 60-80% very quickly, they can provide grid-balancing services (Danfoss, 2017). In another example, Japanese manufacturer Daikin and Next Kraftwerke, a German aggregator, have demonstrated that air-conditioning systems with cold storage tanks can be aggregated into virtual power plants (NEDO, 2018).

- **Smart electrification of industrial heating demand:** Pilot projects have demonstrated that the heat demand of aluminium smelting plants could be modulated up or down by 25% for up to 48 hours. This flexibility, coupled with on-site wind generation, has increased the share of renewable energy used in smelter plants by up to 50% (TRIMET, 2021).

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[4] *Upward reserve refers to the possibility of reducing energy consumption based on the flexibility available at end use (i.e. heat pumps + thermal storage). It helps power systems to reduce the use of fossil fuel–based generation sources. The economic benefit derives from fluctuating electricity prices.*

- **Waste heat recovery:** Reuse of industrial waste heat has enabled an Irish dairy product factory to reduce its energy consumption by 12%, helping it to save EUR 150 000 annually. This has also enabled a chocolate factory in the Netherlands to cut energy use by 6%. Another source of useful heat is city sewage systems. Cologne, Germany, recovered 600 MWh of thermal energy from its sewage system in 2017 (5% of the total city demand) (Celsius, 2020).

- **Natural cooling sources:** According to Enware, the company owning and operating Toronto's deep lake water cooling (DLWC) system, this Canadian city saves 90 TWh of electricity annually by using cold water from the depths of Lake Ontario to cool more than 100 buildings. These savings are equivalent to the electricity consumption of a town of 25 000 inhabitants (City of Toronto, 2021).

4.2 Blind spots for policy makers

Electrification of the heating sector presents challenges that are widely known but have not yet been overcome. To begin with, homeowners and other small-scale end users have been reluctant to transition away from traditional fossil fuel–based heating technologies, such as gas boilers. In addition, users are not always aware of the benefits of smart electrification strategies, such as lower energy costs for homes or businesses.

Other barriers are the initial investment costs and the reluctance to share energy assets (such as solar facilities or thermal storage) or information (such as behind-the-meter data). Some areas may have a shortage of practitioners with the know-how to guarantee installations' quality and consistency. Manufacturers may also be reluctant to produce high-quality electricity-related goods that compete with their existing fossil fuel–based products.

In industry, companies are reluctant to change their processes unless there are guarantees that the quality of their finished products will remain unaffected, or unless the economic benefits are large enough to warrant the time, effort and cost of replacing existing equipment and technologies.

The smart electrification of heating and cooling is also being hindered by misconceptions and blind spots. Seven blind spots are identified:

Temperature is the critical variable in designing a smart electrification strategy.

→ The high efficiency of heat pumps, which can produce three units of heat per unit of input electricity or more, makes them a cost-effective alternative for homes and commercial buildings, even though their upfront investment costs are higher than those of fossil fuel–based alternatives such as gas boilers, except for air-to-air heat pumps in some markets (IRENA, 2022c; IEA, 2022a; Chapter 4). However, current heat pumps[5] can provide temperatures of only up to 150°C, which is not sufficiently high for many industrial processes. An effective electrification strategy must therefore include a careful assessment of temperature requirements.

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[5] *Research and development efforts are focusing on increasing the temperature range of heat pumps with solutions that can provide heat at the level of 200°C.*

Hybrid heat pumps offer an interim solution to rapidly introduce heat pumps in buildings with existing gas infrastructure.

→ Combining heat pumps with in-place gas-fired boilers can minimise efficiency drops in heat pumps in colder weather and, more importantly, increase users' confidence in transitioning to an electrified heating supply. Hybrid heat pumps will supply most of the heat, generating immediate savings in energy costs. Hybrid pumps also reduce the need to increase the peak electricity load on the grid, which might otherwise be required to power heat pumps during severe cold spells, when heat pumps are less efficient. In addition, the ability to switch between two energy carriers adds resilience to the energy system and can reduce costs when using smart controls that factor in energy prices. Over time, the remaining gas use could be replaced with decarbonised fuels, such as renewable biogas.

Thermal energy storage has significant potential to increase the power system's flexibility.

→ Thermal energy storage adds flexibility to the power system, leading to greater utilisation of renewable sources and reduction of operational costs. Its many advantages include its lower investment costs than other options, such as batteries, no requirement of additional infrastructure and its ability to provide flexibility over time scales that range from hours to entire seasons. It can thus be well matched to heating and cooling demands, which vary by season. It also can also be scaled easily, making it practical, since it offers flexibility for both individual households and large DHC networks. Whether aggregated across multiple households or used directly in DHC systems, thermal energy storage can provide balancing services, increase the security of supply, integrate a larger share of variable renewable energy sources, and generate additional revenue for homeowners and district heating operators.

Digitalisation is at the core of a smart approach.

→ Digitalisation leverages smart devices and sensors – along with data on past operations, accurate forecasting and artificial intelligence – to control heating and cooling loads in ways that improve overall operations. It is vital for integrating greater shares of renewable sources, adding flexibility and resilience, lowering both energy supply and heating and cooling costs, creating value and new business models, and avoiding over-investment in building equipment and the electricity grid. At the same time, digitalisation can enable the actors involved to co-operate more effectively. A digitalised heating and cooling system will help policy makers to make better regulations, enable new business and inform end users to support better decisions.

Cooling demand is growing and should be considered in energy planning.

- The increase in cooling demand offers another strong argument for widespread heat pump adoption since reversible heat pumps supply cooling at low additional costs. Reversible heat pumps also make thermal networks more efficient and profitable because they can provide services throughout the year. Furthermore, considering peak cooling demands and peak solar energy occur simultaneously, the growing cooling demand can be coupled with solar PV, making it easier to increase solar PV's penetration. In addition, cooling enables the use of ambient heat and cold sources that might otherwise not be used. However, effective energy planning measures are required to meet the greater cooling demand in the most cost-effective ways.

Building codes offer important incentives for a smart heating strategy in the residential sector.

- Building codes can increase the use of smart heating and cooling solutions and help tap the smart electrification potential within the buildings sector, which is still unrealised. A relevant example of how building codes can help shape an electrified and efficient heating supply is found in the United States. California is proposing to ban gas furnaces in homes by 2030. Similar bans in the building codes of other states and countries could dramatically increase the uptake of heat pumps. In addition, building codes could promote new business models such as peer-to-peer green energy trading and the creation of local energy markets.

Energy efficiency and waste heat/cold recovery should be a key part of smart electrification strategies.

- Greater energy efficiency and the reuse of waste heat are effective measures for reducing the total electricity load for generating heating/cooling. Energy efficiency lies at the foundation of any decarbonisation pathway for the heating and cooling sector. The reduction of demand via energy efficiency measures limits the need for additional renewable capacity or the reinforcement of the electricity grid. Regarding waste heat/cold, large amounts of energy flows produced by thermal processes are still released to the environment. Despite the adoption of an increasing number of measures to reduce those energy streams, they hold significant potential for use. Waste heat from data centres are examples of how waste heat can be used to meet nearby heating demand.

CHAPTER 5

TOOLBOX FOR SMART ELECTRIFICATION OF HEATING AND COOLING

An effective smart strategy depends on multiple variables, such as the degree of flexibility in the power system or grid capacity, but benefits are both large and clear in any context.

Smart electrification of heating and cooling requires innovations in business models, market design and regulation, and system planning and operation, along with advancements in heating and cooling generation technologies. It also requires breaking down silos between stakeholders, including utility companies, power grid operators, district heating and cooling (DHC) companies, and building and industrial energy managers.

This report identifies 35 key innovations in three demand segments: district heating and cooling, the buildings sector and the industry sector. Table 5.1 lists the main differences between the segments. They vary, for example, in the temperatures required for each application and in the scale of the demand.

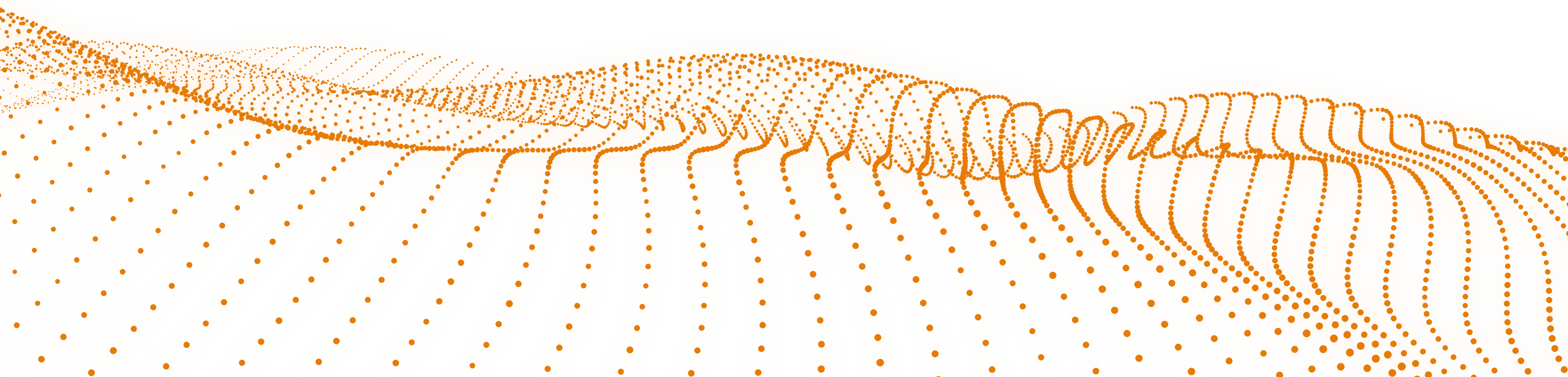


TABLE 5.1 | Differences between heating/cooling customers that affect the choice of a smart electrification strategy

Segment	Temp	Scale	Use case	Technologies	Stakeholders	Main characteristics for electrification strategies
District heating and cooling	>0°C <100°C[a]	Medium/ large	Space heating, space cooling, water heating[b]	Large-scale low-temperature heat pumps (ground sourced), large-scale electric boilers, thermal storage	Local municipalities, residential homeowners, commercial shops, supermarkets, university campuses, hospitals, data centres, real estate developers, among others	Urban and infrastructure planning required, high upfront investments, suitable for new urban areas, weather-dependent demand
Buildings sector	>0°C <100°C	Small	Space heating and cooling, water heating	Single small-scale low-temperature heat pumps (air and ground sourced), small-scale electric boilers	Residential homeowners, commercial shops, real estate developers, hotels, sports centres, hospitals, among others	Aggregation required for TSO/DSO strategies, user behavioural changes, financial capacity for investing in power-to-heat solutions, weather-dependent demand
Industry sector	<150°C	Medium/ large[c]	Various industrial processes	High-temperature heat pumps (air and ground sourced or waste heat sourced) for auxiliary or process heating, large-scale electrode boilers	Industries such as petrochemicals, refining, cement, mining, food and beverages, steel, data centres, pharma, pulp and paper	Large-scale use cases, TSO/DSO involvement, demand dependent on industrial processes and needs, not weather-dependent applications, behavioural changes not a source of flexibility
	>150°C	Medium/ large	Petrochemical industries such as ammonia, methanol and ethylene/ propylene	High-temperature electric heating to achieve the required process temperatures of above 150°C or even above 1 000°C (*i.e.* electric resistance furnaces, induction furnaces, electric arc furnaces, or e-cracking furnaces)	Industrial operators, technology licensors, equipment vendors	Specific applications that traditionally rely on fossil fuel–based technologies, temperatures above 1 000°C required in many cases, flexibility does not play a main role, no weather dependency

[a] In early generation DHC systems, pressurised hot water with temperatures above 100°C was used in some cases.

[b] For the new generation of DHC systems, the water heating demand is met by a backup system, which helps reach the desired temperature (*i.e.* booster heat pump).

[c] Subject to the requirements of a specific industrial application.

Notes: DSO = distribution system operator; TSO = transmission system operator.

Table 5.2 lists the 35 innovations that are briefly explored below and in greater detail in Chapter 6.

TABLE 5.2 | Innovation toolbox for smart electrification of heating and cooling

TECHNOLOGY AND INFRASTRUCTURE

Conversion technologies

- **1** Low-temperature heat pumps
- **2** Hybrid heat pumps
- **3** High-temperature heat pumps
- **4** Waste heat-to-power technologies
- **5** High-temperature electricity-based applications for industry

Thermal storage

- **6** Low-temperature thermal energy storage
- **7** Medium- and high-temperature thermal energy storage

District heating and cooling systems

- **8** Fourth-generation DHC systems
- **9** Fifth-generation DHC systems

Digitalisation

- **10** Internet of Things for smart electrification
- **11** Artificial intelligence for forecasting heating and cooling demands
- **12** Blockchain for enabling transactions
- **13** Digitalisation as a flexibility enabler

MARKET DESIGN AND REGULATION

Electricity market

- **14** Dynamic tariffs
- **15** Flexibility provision by thermal loads
- **16** Flexible power purchase agreement

Sector regulations and incentives

- **17** Standards and certifications for heating and cooling equipment
- **18** Energy efficiency programme for buildings and industry
- **19** Building codes for power-to-heat/cooling solutions
- **20** Streamlining permitting procedures for thermal infrastructure

SYSTEM PLANNING AND OPERATION

Integrated planning

- **21** Holistic planning for cities
- **22** Heating and cooling maps
- **23** Coupling cooling loads with solar generation

Smart operation

- **24** Smart operation with thermal inertia
- **25** Smart operation with seasonal thermal storage
- **26** Smart operation of industrial heating
- **27** Combining heating and cooling demands in district systems

BUSINESS MODELS

Services for the power system

- **28** Aggregators
- **29** Distributed energy resources for heating and cooling demands
- **30** Heating and cooling as a service

Waste heat recovery models

- **31** Waste heat recovery from data centres
- **32** Eco-industrial parks and waste heat recovery from industrial processes
- **33** Circular energy flows in cities – booster heat pumps

Models to enable deployment

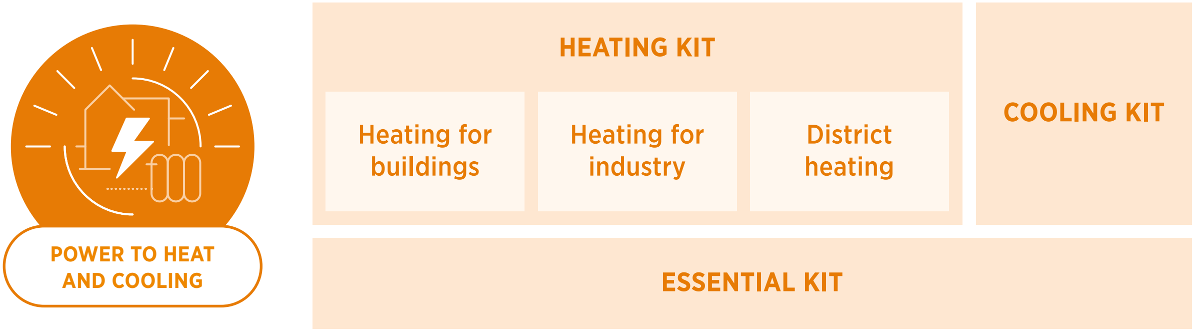
- **34** Community-owned district heating and cooling
- **35** Community-owned power-to-heat assets

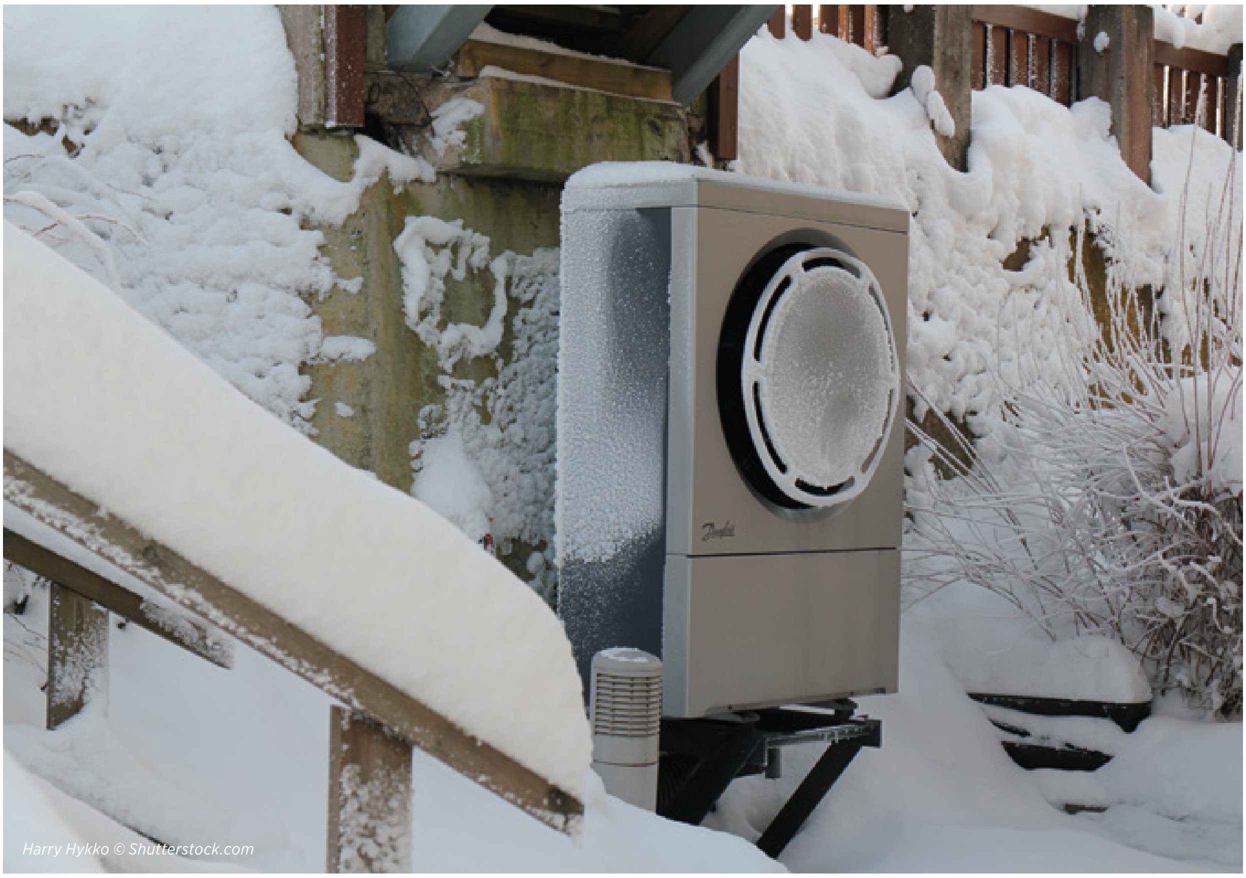
5.1 Guidelines for implementation

Creating an innovative smart electrification strategy requires leveraging the synergies among different innovations across four dimensions: technology, markets and regulation, business models, and system planning and operation. It must also consider the available capabilities and potentials of current energy systems. For instance, Sweden's substantial hydropower resources make it possible to deploy large-scale heat pumps.

To guide policy makers in formulating smart electrification strategies, we propose a toolBox with three kits: the essential kit, which should be implemented in any situation, followed by the heating kit and then the cooling kit, based on the needs. The heating kit is further divided into kits for buildings, industry and district heating (Figure 5.1).

FIGURE 5.1 | Implementation guidance for smart electrification in the heating and cooling sector

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Essential kit

The essential kit includes cross-cutting innovations such as heat pumps and thermal storage, along with innovations in market design, system planning and business models, such as smart tariffs and aggregation. The innovations are listed in Table 5.3 and discussed in detail later in this section.

TABLE 5.3 | The essential kit for the heating and cooling sector

ESSENTIAL KIT			
TECHNOLOGY AND INFRASTRUCTURE	**MARKET DESIGN AND REGULATION**	**SYSTEM PLANNING AND OPERATION**	**BUSINESS MODELS**
• **1** Low-temperature heat pumps • **6** Low-temperature thermal energy storage • **13** Digitalisation as a flexibility enabler	• **14** Dynamic tariffs • **17** Standards and certification for heat pumps • **18** Energy efficiency programmes • **20** Streamlining permitting procedures for thermal infrastructure	• **21** Holistic planning for cities	• **28** Aggregators

Heating kit

The heating-for-buildings kit includes additional innovations to the essential kit that are specific to the smart electrification of heating in the residential sector (Table 5.4). Hybrid heat pumps offer an intermediate step between fossil fuel–based heating and 100% electric heating, for example, while thermal storage and the matching of solar resources with demand offer major gains in flexibility and overall system efficiency.

The heating-for-industry kit includes the innovations needed to electrify heating in the industry sector. Industries are profit driven and typically operate continuously at high-capacity factors. Innovations may thus encounter resistance if they significantly affect operations. On the other hand, innovations such as high-temperature heat pumps (see Box 5.1) and waste heat recovery (Table 5.5) have the potential to significantly increase the efficiency of operations while also reducing emissions from fossil fuel use.

TABLE 5.4 | The heating-for-buildings kit

HEATING KIT

HEATING FOR BUILDINGS

TECHNOLOGY AND INFRASTRUCTURE	MARKET DESIGN AND REGULATION	SYSTEM PLANNING AND OPERATION	BUSINESS MODELS
• **2** Hybrid heat pumps • **10** Internet of Things for smart electrification • **11** Artificial intelligence for forecasting heating and cooling demand • **12** Blockchain for enabling transactions	• **15** Flexibility provision by thermal loads • **16** Flexible power purchase agreement • **19** Building codes for power-to-heat/ cooling solutions	• **23** Coupling cooling loads with solar generation • **24** Smart operation with thermal inertia	• **29** DERs for heating and cooling demands • **35** Community-owned power-to-heat assets

Note: DERs = distributed energy resources.

TABLE 5.5 | The heating-for-industry kit

HEATING KIT

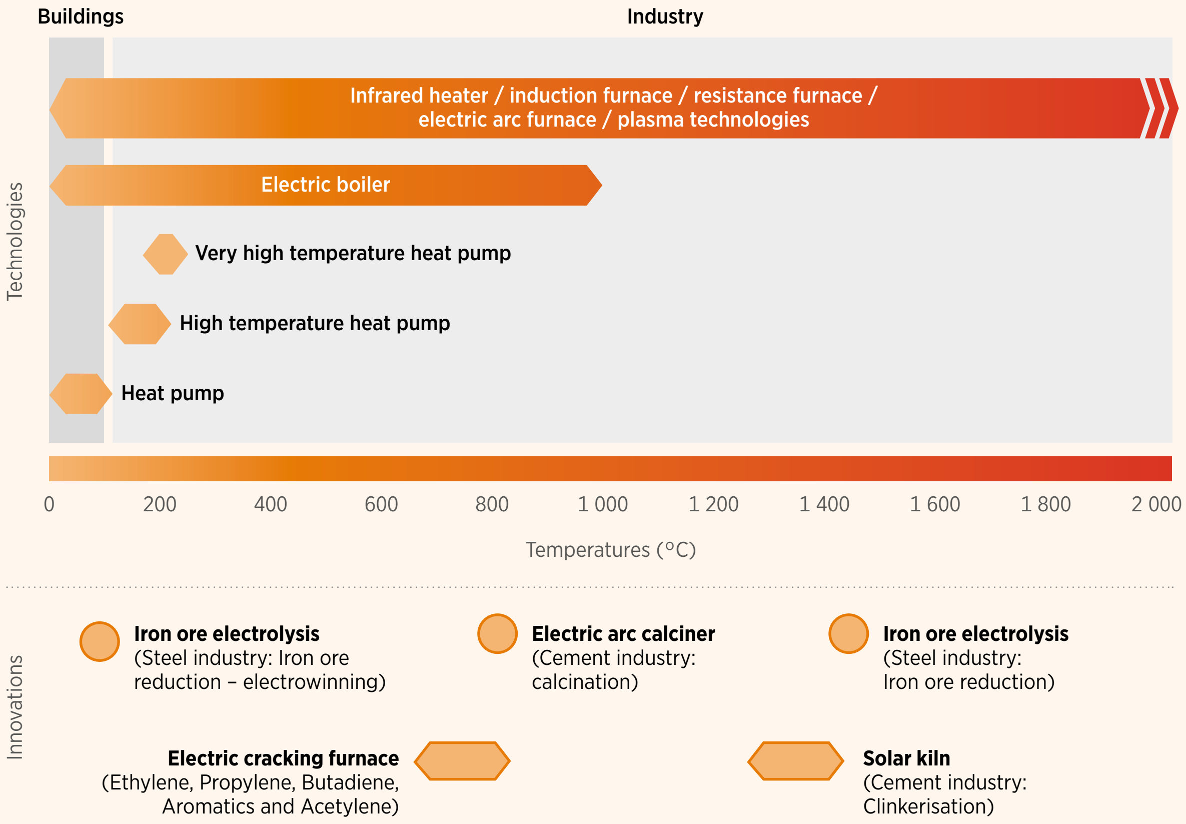
HEATING FOR INDUSTRY

TECHNOLOGY AND INFRASTRUCTURE	MARKET DESIGN AND REGULATION	SYSTEM PLANNING AND OPERATION	BUSINESS MODELS
• **3** High-temperature heat pumps • **4** Waste heat-to-power technologies • **5** High-temperature electricity based applications for industry • **7** Medium- and high-temperature thermal storage	• **15** Flexibility provision by thermal loads • **16** Flexible power purchase agreement	• **26** Smart operation of industrial heating	• **30** Heating and cooling as a service • **32** Eco-industrial parks and waste heat recovery from industrial processes

BOX 5.1 | Industrial high-temperature requirements

Industrial processes require a wide range of temperatures. No singular technology can thus meet all industrial energy needs. Figure 5.2 shows how different technologies can provide the required temperatures, which can go above 1 000°C in specific sectors.

FIGURE 5.2 | Temperature ranges and technologies for industry sectors



Based on: (Arpagaus *et al.*, 2018; Madeddu *et al.*, 2020; Keller *et al.* 2022; and Somers, 2022).

For some uses, electricity can be used directly in electric furnaces, electric boilers, heat pumps or other electrolytic processes. One innovation still under development is the high-temperature heat pump, which can deliver heat at up to 150°C (Arpagaus *et al.*, 2018). When commercially available, these pumps could be used for applications such as injection moulding in the plastic industry or many drying processes, adding significant energy savings, as shown successfully in the EU DryFiciency project (DryFiciency, 2016).

Three main industrial sectors – chemical, cement and steel – are the most challenging to electrify, but promising solutions are being developed. For the chemical industry, electric crackers (e-crackers) are in the pilot phase. The cement industry is working on new kilns where heat is provided via plasma generators (Somers, 2020). The steel sector is piloting new electrolytic reduction processes. In addition, these industries might be electrified indirectly through renewable fuels like green hydrogen.

The district heating kit aims to shape the smart electrification strategy for thermal grids and includes the fourth and fifth generations[6] of thermal grids and waste heat-to-power technologies (4GDH and 5GDG). Waste heat-to-power technologies are not included in the buildings kit because they require significant volumes to become profitable. However, the market innovations and business models are the same or similar across building and district heating (Table 5.6).

TABLE 5.6 | The district heating kit

HEATING KIT			
DISTRICT HEATING			
TECHNOLOGY AND INFRASTRUCTURE	**MARKET DESIGN AND REGULATION**	**SYSTEM PLANNING AND OPERATION**	**BUSINESS MODELS**
• **2** Hybrid heat pumps • **4** Waste heat-to-power technologies • **8** Fourth-generation DHC systems • **9** Fifth-generation DHC systems • **10** Internet of Things for smart electrification • **11** Artificial intelligence for forecasting heating and cooling demand • **12** Blockchain for enabling transactions	• **15** Flexibility provision by thermal loads • **16** Flexible power purchase agreement	• **21** Holistic planning for cities • **22** Heat and cold mapping • **23** Coupling cooling loads with solar generation • **25** Smart operation with with seasonal thermal storage storage • **27** Combining heating and cooling demands in district systems	• **30** Heating and cooling as a service • **31** Waste heat recovery from data centres • **33** Circular energy flows in cities – booster heat pumps • **34** Community-owned district heating and cooling

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[6] *Here, we consider that 5GDH aims at combined heating and cooling with a joint supply network, whereas 4GDH focuses on dedicated heating and cooling supply networks (Lund et al., 2021). Here, we consider that 5GDH aims at combined heating and cooling with a joint supply network, whereas 4GDH focuses on dedicated heating and cooling supply networks (Lund et al., 2021).*

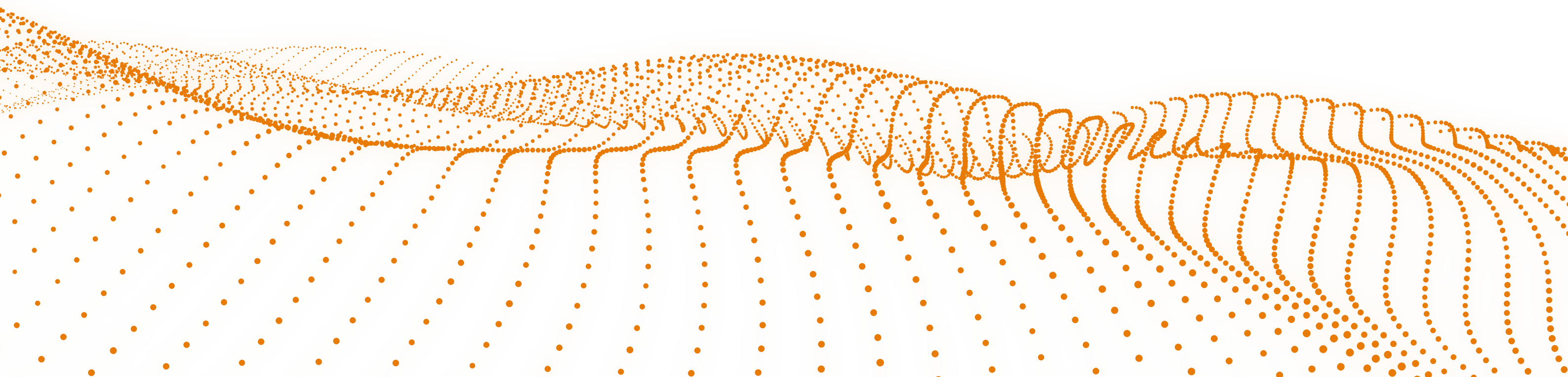
Cooling kit

Cooling strategies are different from heating strategies due to three reasons: First, cooling is already electricity powered for the majority of applications. Further, the cooling demand is much lower than the heating demand in the Northern Hemisphere. In addition it often overlaps the times of solar generation. Furthermore, the key innovation in the heating kit, heat pumps, also plays a central role in cooling since most heat pumps can be reversed to provide cooling. 5.2 Case studies7 shows the innovations in the cooling kit.

TABLE 5.7 | The cooling kit

COOLING KIT

TECHNOLOGY AND INFRASTRUCTURE	MARKET DESIGN AND REGULATION	SYSTEM PLANNING AND OPERATION	BUSINESS MODELS
• **10** Internet of Things for smart electrification • **11** Artificial intelligence for forecasting heating and cooling demand • **12** Blockchain for enabling transactions	• **15** Flexibility provision by thermal loads • **16** Flexible power purchase agreement • **19** Building codes for power-to-heat/cooling solutions	• **22** Heating and cooling maps • **23** Coupling cooling loads with solar generation • **24** Smart operation with thermal inertia • **27** Combining heating and cooling demands in district systems	• **29** Distributed energy resources for heating and cooling demands • **30** Cooling as a service • **33** Circular energy flows in cities • **34** Community-owned district heating and cooling assets



5.2 Case studies

Two case studies show how this report's toolBox can be used to create smart electrification strategies.

Smart electrification in district heating and cooling – Taarnby, Denmark

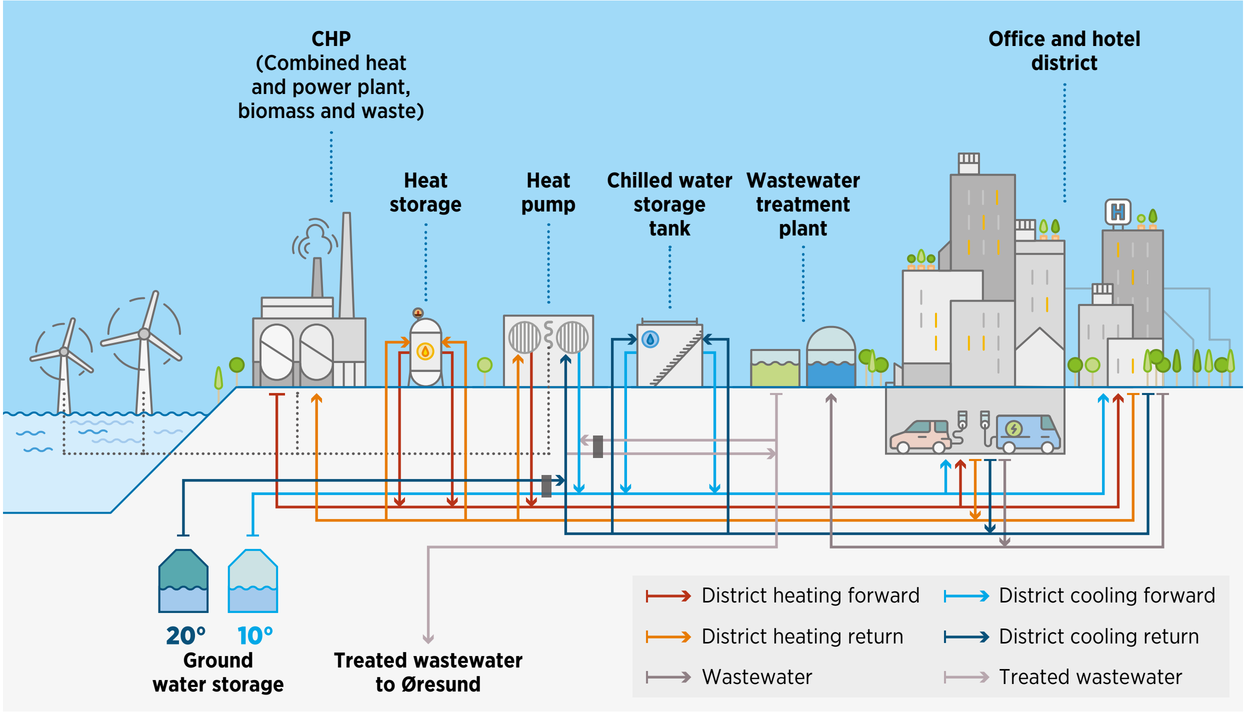
Taarnby, Denmark, put a new DHC system into operation in 2020. The system is considered to be the smartest DHC system in the world, and it integrates heating, cooling and electricity generation, while also taking advantage of heat and cold from water storage and wastewater treatment.

The DHC system has three main sources of heating and cooling (Figure 5.3):

- Four large reversible water-to-water heat pumps extract heating and cooling from groundwater, with a total capacity of 4.5 MW for cooling and 6.5 MW for heating.
- Waste heat from the water treatment plant provides another 4 MW of heat capacity.
- A storage tank holds 2 000 m^3 of chilled water, providing 2.5 MW of cooling. The water storage increases the system's peak cooling capacity, stabilises the heat pumps' operation and acts as a 13 MWh "virtual battery".

The city also plans to add an aquifer thermal energy storage system by 2025, which will allow about 5 000 MWh of cooling to be stored in the winter for use during the summer.

FIGURE 5.3 | **Layout of the Taarnby DHC system**



Source: (Ramboll, 2022).

The most innovative features of the system are as follows:

- In winter, the heat pumps not only supply heat to buildings, they also cool the groundwater by extracting heat from it. The cold storage then provides free cooling during summer.
- Heat from the water treatment plant is no longer wasted.
- The thermal storage systems reduce costs by storing energy when electricity prices are low and supplying energy when they are higher. They also add flexibility to the grid, making it possible to integrate more variable renewable energy and avoid overinvestments in the electricity grid or in battery storage.
- Co-producing heating and cooling is more efficient than producing each separately.
- Stricter building codes ensure that the 11 buildings connected to the DHC grid are highly efficient, while individual smart meters for each customer provide real-time data and enable the utility to control energy use remotely.
- Seasonal tariffs increase efficiencies and lower costs, while bonuses or penalties reward or penalise customers depending on the temperature of the air they return to the system. For cooling, for example, high temperatures (above 16°C) make the system more efficient.

Pavlo Glazkov © Shutterstock.com

Table 5.8 shows the combination of innovations adopted by the Taarnby DHC system. It combines innovations from the essential kit and the strategy for the thermal grid under the classification proposed in the section "Guidelines for Implementation".

TABLE 5.8 | The smart electrification strategy for district heating and cooling in Taarnby, Denmark

TECHNOLOGY AND INFRASTRUCTURE	MARKET DESIGN AND REGULATION	SYSTEM PLANNING AND OPERATION	BUSINESS MODELS
ESSENTIAL KIT			
• **1** Low-temperature heat pumps • **6** Low-temperature thermal energy storage	• **14** Dynamic tariffs • **18** Energy efficiency programmes	• **21** Holistic planning for cities	
HEATING KIT: DISTRICT HEATING			
• **4** Waste heat-to-power technologies • **8** Fourth-generation DHC systems • **9** Fifth-generation DHC systems • **10** Internet of Things for smart electrification • **11** Artificial intelligence for forecasting heating demand	• **15** Flexibility provision by thermal loads	• **25** Smart operation with seasonal storage • **27** Combining heating and cooling demands in district systems	• **30** Heating as a service • **33** Circular energy flows in cities – booster heat pumps • **34** Community-owned district heating

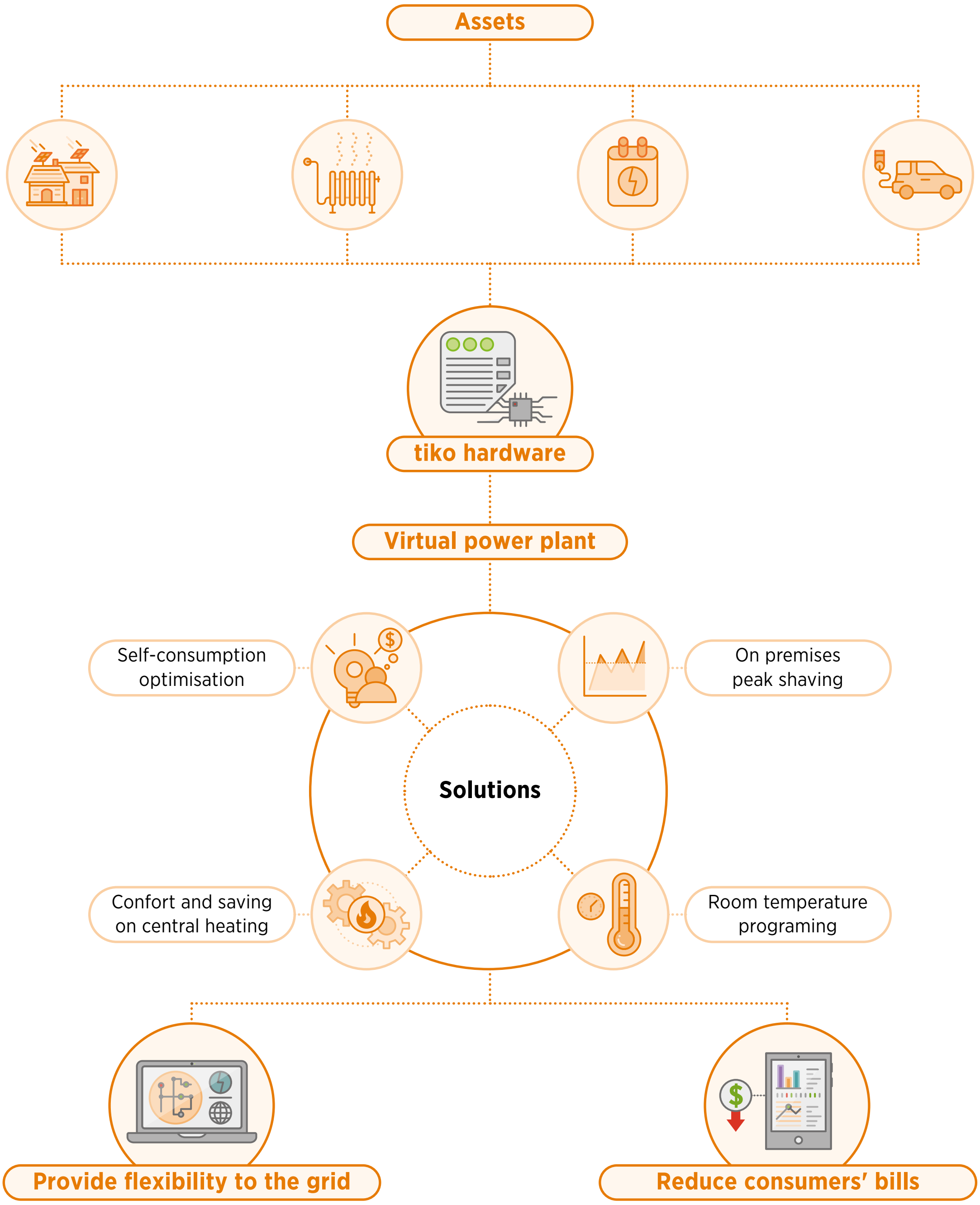
Note: DHC = district heating and cooling.

The sector coupling, thermal storage and the many opportunities for flexibility enable the DHC system to integrate a remarkably large share of renewables (91%) and optimise system operations in real time. Taarnby's case is thus a flagship example of smart sector integration, demonstrating the synergies among transport, district heating and cooling, water infrastructure and the electricity system. More generally, the EU research project *Heat Roadmap Europe* has identified DHC as a key solution for reaching climate, energy efficiency and security goals.

Smart electrification in the residential sector – aggregator platform

A Swiss start-up, tiko, has aggregated refrigerators, heat pumps and other electrical appliances owned by many customers (more than 7 000 households) to create what is now the largest virtual power plant in Europe (tiko Energy, 2022). The company's digital platform controls these appliances to shift or reduce the peak demand. This provides valuable flexibility to the grid, while also reducing users' bills (Figure 5.4). In addition, the platform couples the power consumption of appliances with private electricity generation, such as rooftop PV, to reduce bills even further.

FIGURE 5.4 | Layout of the platform



Source: (tiko Energy, 2022).

tiko's virtual power plants have a total capacity of 100 MW, making the company a key player in the integration of variable renewable energy, distributed power generation, electrification of heating and cooling, and the digitalisation of energy systems in Switzerland (Swisscom Energy Solutions AG, 2018).

Table 5.9 presents the innovation elements that are combined in the tiko pilot case, which includes elements from all four dimensions of the essential kit, including innovative elements such as heat pumps, digitalisation or aggregators. In addition, it brings innovative elements from the buildings kit since buildings is its market segment. It also incorporates the cooling dimension via the coupling of PV with the cooling demand.

TABLE 5.9 | The smart electrification strategy of heating for residential sector in the residential sector in Switzerland – tiko case study

TECHNOLOGY AND INFRASTRUCTURE	MARKET DESIGN AND REGULATION	SYSTEM PLANNING AND OPERATION	BUSINESS MODELS
ESSENTIAL KIT			
• **2** Low-temperature heat pumps • **2** Hybrid heat pumps • **13** Digitalisatian as a flexibility enabler	• **14** Energy efficiency programmes	• **21** Holistic planning for smart cities	• **28** Aggregators
STRATEGY FOR BUILDINGS			
• **4** Waste heat-to-power technologies • **8** Fourth-generation DH systems • **9** Fifth-generation DH systems • **10** Internet of Things for smart electrification • **11** Artificial intelligence for forecasting heating demand	• **15** Flexibility provision by thermal loads	• **23** Smart operation with thermal inertia • **25** Smart operation with seasonal storage	• **29** Distributed energy resources for heating and cooling demands
STRATEGY FOR COOLING			
		• **23** Coupling cooling loads with solar photovoltaic	

Note: DH = district heating

CHAPTER 6

INNOVATION LANDSCAPE FOR SMART ELECTRIFICATION OF HEATING AND COOLING

This chapter presents an overview of 35 innovations for smart electrification of heating and cooling by answering two main questions for each innovation:

WHAT What is the innovation about?

WHY Why is the innovation important for smart electrification?

The chapter also groups the innovations into four main dimensions: technology and infrastructure, markets and regulation, business models, and system planning and operation.

For each innovation, the icons in Table 6.1 are used to describe its readiness level, the impact on the electrification of end uses (*e.g.* heat pump uptake) and the impact on smart electrification (*e.g.* how much this innovation contributes to demand response and to increased flexibility of the power system). Further, Table 6.2 shows the status and impacts of the innovations across all four dimensions.

TABLE 6.1 | Implementation guidance for smart electrification in district heating and cooling in Taarnby, Denmark

INNOVATION READINESS LEVEL	IMPACT ON	
	Electrification of end-use sector	**Smart electrification**
●○○○ Innovation is in an early stage, with a few demonstration projects	●○○○ Low	●○○○ Low
●●○○ Innovation is in early commercialisation stage, with a few pilot projects	●●○○ Medium	●●○○ Medium
●●●○ Innovation is already implemented in a few countries	●●●○ High	●●●○ High
●●●● Innovation is mature and deployed at a large scale in some regions	●●●● Very high	●●●● Very high

TABLE 6.2 | Overview of the status and impacts of innovations for smart electrification of heating and cooling sectors

Dimension	Category	Innovation	Innovation readiness level	Impact on electrification of end uses	Smart electrification
TECHNOLOGY AND INFRASTRUCTURE	**CONVERSION TECHNOLOGIES**	**1** Low-temperature heat pumps	●●●●	●●●●	●●○○
		2 Hybrid heat pumps	●●●●	●●●●	●●○○
		3 High-temperature heat pumps	●○○○	●●●●	●●○○
		4 Waste heat-to-power technologies	●●●●	●○○○	●●○○
		5 High-temperature electricity-based applications for industry	●○○○	●●●○	●○○○
	THERMAL ENERGY STORAGE	**6** Low-temperature thermal energy storage	●●●○	●●○○	●●●●
		7 Medium- and high-temperature thermal energy storage	●●○○	●●○○	●●●●
	DISTRICT HEATING AND COOLING SYSTEMS	**8** Fourth-generation district heating and cooling systems	●●●○	●●○○	●●●●
		9 Fifth-generation district heating and cooling systems	●○○○	●○○○	●●●●
	DIGITALISATION	**10** Internet of Things for smart electrification	●●●○	●○○○	●●●●
		11 Artificial intelligence for forecasting heating and cooling demands	●●●○	●●○○	●●●●
		12 Blockchain for enabling transactions	●●○○	●○○○	●●○○
		13 Digitalisation as a flexibility enabler	●●○○	●●○○	●●●●
MARKET DESIGN AND REGULATION	**ELECTRICITY MARKET DESIGN**	**14** Dynamic tariffs	●●●○	●●○○	●●●●
		15 Flexibility through thermal loads	●●●○	●●○○	●●●●
		16 Flexible power purchase agreement	●●○○	●●○○	●●●○
	END-USE SECTOR REGULATION AND INCENTIVES	**17** Standards and certifications for improved predictability of heat pump operation	●●●○	●●●○	●○○○
		18 Energy efficiency programmes for buildings and industries	●●●●	●●○○	●●●○

●●●● Very high ●●●○ High ●●○○ Medium ●○○○ Low

Dimension	Category	Innovation	Innovation readiness level	Impact on electrification of end uses	Smart electrification
MARKET DESIGN AND REGULATION	**END-USE SECTOR REGULATION AND INCENTIVES**	• **19** Building codes for power-to-heat/cooling solutions	●○○○	●●●○	●●○○
		• **20** Streamlining permitting procedures for thermal infrastructures	●●○○	●●●●	●○○○
SYSTEM PLANNING AND OPERATION	**INTEGRATED PLANNING**	• **21** Holistic planning for cities	●●●○	●●●○	●●○○
		• **22** Heating and cooling maps	●●●○	●○○○	●●○○
		• **23** Coupling cooling loads with solar generation	●●●●	●●○○	●●●●
	SMART OPERATION	• **24** Smart operation with thermal inertia	●●○○	●○○○	●●●●
		• **25** Smart operation with seasonal thermal storage	●●○○	●○○○	●●●●
		• **26** Smart operation of industrial heating	●●●○	●●○○	●●●●
		• **27** Combining heating and cooling demand in district systems	●●○○	●○○○	●●○○
BUSINESS MODELS	**SERVICES FOR THE ENERGY SYSTEM**	• **28** Aggregators	●●●●	●○○○	●●●●
		• **29** Distributed energy resources for heating and cooling demand	●●●●	●●○○	●●●●
		• **30** Heating and cooling as a service	●●●○	●●○○	●●●○
	WASTE HEAT RECOVERY MODELS	• **31** Waste heat recovery from data centres	●●●●	●●○○	●●●●
		• **32** Eco-industrial parks and waste heat recovery from industrial processes	●●●○	●○○○	●●○○
		• **33** Circular energy flows in cities – booster heat pumps	●●●●	●○○○	●●●○
	ENERGY COMMUNITIES	• **34** Community-owned district heating and cooling	●●●○	●○○○	●●○○
		• **35** Community-owned power-to-heat assets	●●○○	●●○○	●●●●

●●●● Very high ●●●○ High ●●○○ Medium ●○○○ Low

6.1 Technology and infrastructure

Technology innovations are typically at the base of the systemic innovation approach. They make it possible to implement innovations in other dimensions and create new revenue streams. Here, the technology innovations are divided into four broad categories: conversion technologies, thermal energy storage (TES), new generations of district heating and cooling (DHC) systems and digitalisation (Figure 6.1).[7]

FIGURE 6.1 | **Innovations in technology and infrastructure for power to heat and cooling**

TECHNOLOGY AND INFRASTRUCTURE	**CONVERSION TECHNOLOGIEST**	**1** Low-temperature heat pumps
		2 Hybrid heat pumps
		3 Medium- and high-temperature heat pumps
		4 Waste heat-to-power technologies
		5 High-temperature electricity-based applications for industry
	THERMAL ENERGY STORAGE	**6** Low-temperature thermal energy storage
		7 Medium- and high-temperature thermal energy storage
	DISTRICT HEATING AND COOLING SYSTEMS	**8** Fourth-generation district heating and cooling systems
		9 Fifth-generation district heating and cooling systems
	DIGITALISATION	**10** Internet of Things for smart electrification
		11 Artificial intelligence for forecasting heating and cooling demands
		12 Blockchain for enabling transactions
		13 Digitalisation as a flexibility enabler

Notes: AI = artificial intelligence; DHC = district heating and cooling; IoT = Internet of Things.

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[7] *Digitalisation can be defined as the innovative use of information and communications technologies, converting data into value through various applications they can have in a sector. Since it requires the presence of equipment to make use of such information, digital technologies are considered an important innovation in infrastructure.*


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Conversion technologies

CONVERSION TECHNOLOGIES ① **Low-temperature heat pumps**

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●●	●●●●	●●○○	🏠 🏢 🏭

WHAT Electrically-driven heat pumps are the most promising technology for the electrification of the heating and cooling sector. They efficiently transfer thermal energy from many different possible sources, including outdoor air, underground heat, water or waste heat from industry sewage treatment to indoor spaces or processes where the heat is needed. Heat pumps are already a mature technology for efficiently supplying heat at temperatures up to 100°C (even from ambient air with temperatures below 0°C as a source). They also now exclusively use refrigerants that do not deplete the ozone layer; refrigerants with high global warming potential are being phased out.[8]

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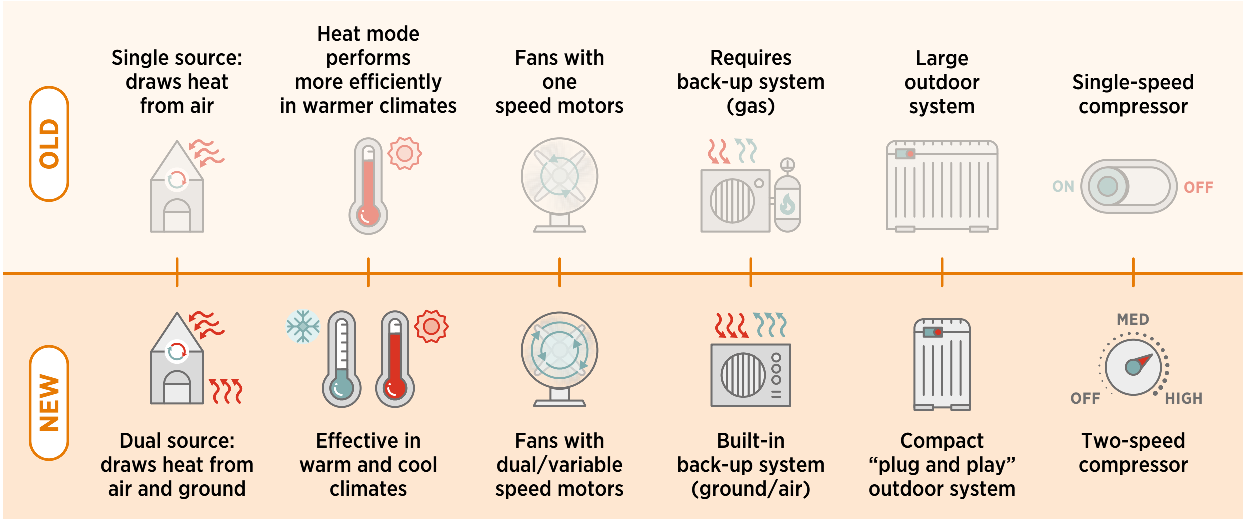
[8] *In Europe, heat pump manufacturers have the challenge of moving towards "fourth-generation" refrigerants with low global warming potential as part of the EU phase-down of currently used hydrofluorocarbon refrigerants by 2030 (EU Regulation 517/2014).*

Heat pump technology is also advancing rapidly (Figure 6.2). New innovations include:

FIGURE 6.2 | Advances in heat pump technology



Based on: (McSurdy, 2019).

- Increased efficiency through use of more than one source, for example, air and ground.
- Increased ability to produce heat efficiently and economically in cold weather (the central goal of the US Department of Energy's "Cold Climate Heat Pump Technology Challenge").
- Built-in backup systems that allow switching to another source of heat or cooling (*e.g.* ground instead of air) rather than relying on backup systems using fossil fuels.
- Compact plug-and-play systems, which are simpler and can be installed inexpensively.
- Dual- or variable-speed compressors to increase efficiency, reduce noise and enable more control for demand-response services.
- More efficient and silent fan designs.
- Improved integration into buildings' energy systems and more control of the balance between heat pump and backup system operation (thus allowing monovalent or monoenergetic operation) (McSurdy, 2019).

WHY Low-temperature heat pumps are the most important technology for decarbonising[9] heating and cooling end uses. They also offer major improvements in the overall energy efficiency of the buildings sector.

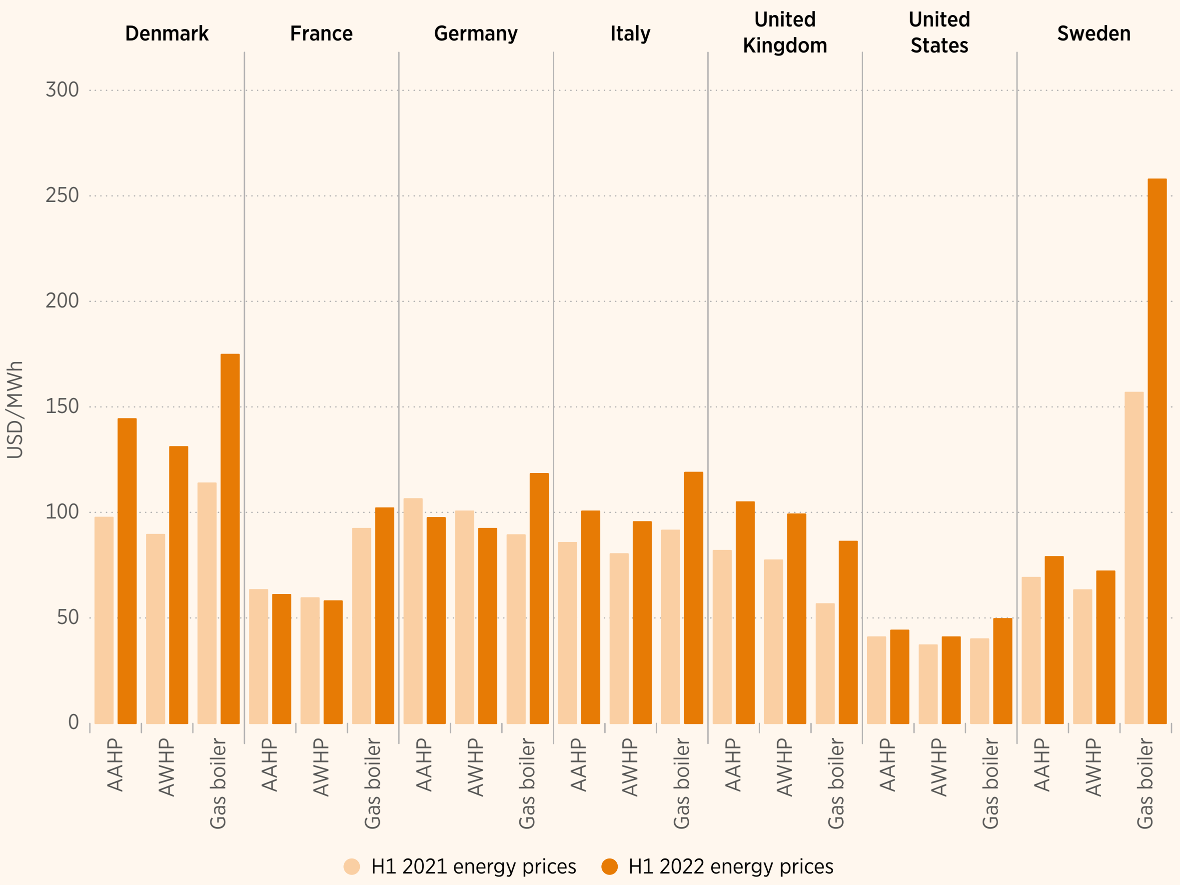
BOX 6.1 | The economics of heat pumps

Heat pumps have been used most often in countries with comparatively low electricity prices, such as Sweden, which has large amounts of hydro and nuclear power. Elsewhere, heat pump adoption has, until recently, been hindered by lack of awareness and confidence, and by the perception of higher upfront investment costs compared with fossil fuel–based alternatives as well as the misperception that heat pumps cannot deliver comfortable levels of heat for residential use in cold-weather climates.

In fact, in countries like Sweden or Denmark, heat pumps are already cost competitive with their biggest competitor, gas-condensing boilers. In other countries, such as the United Kingdom, heat pumps are slightly costlier. Figure 6.3 shows the marginal costs of air-to-air heat pumps, air-to-water heat pumps and gas boilers for selected countries.

Recently, heat pumps have become much more economically attractive due to the European energy crisis, and soaring gas prices. If gas prices were to remain as high as they were in 2022, then market conditions would strongly favour heat pumps over gas boilers. The challenge then lies in creating the right incentives to accelerate the shift from gas boilers to heat pumps.

FIGURE 6.3 | Marginal cost of heating with residential heat pumps and gas boilers under different energy cost assumptions in selected countries between H1 2021 and H1 2022



Source: (IEA, 2022b).

Notes: AAHP = air-to-air heat pump; AWHP = air-to-water heat pump; H1 = the first half of the fiscal year; MWh = megawatt hour.

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[9] *In this statement, it is assumed that the CO_2 intensity factor of the electricity is lower than that of the equivalent fossil fuel–based heating generation, i.e. boilers.*

CONVERSION TECHNOLOGIES

2 Hybrid heat pumps

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●●	●●●●	●●○○	

WHAT Hybrid heat pumps combine a heat pump with a backup technology (*e.g.* a gas boiler), which supplies heat when conditions are not optimal for the heat pump's operation. Those conditions could include periods of extreme cold weather or times of high electricity prices. Under extremely low outdoor temperatures, the backup system can supply either part of the energy demand, allowing the heat pump to operate at high efficiencies, or all the demand by switching off the heat pump. The system can be operated at maximum efficiencies and lowest costs by controlling the balance between the heat pump's and the backup technology's operation. The backup technology is typically a gas or biomass boiler, but solar technologies or even micro combined heat and power units can be used.

Hybrid heat pumps are suitable for both large- and small-scale residential, industrial and district heating systems (Beccali *et al.*, 2022). They do require an effective control system that factors in weather, comfort and market conditions. They can thus support the use of new innovative control management systems, including artificial intelligence (AI) techniques.

WHY While the hybridisation of heat pumps with gas boilers may not be the optimal solution for rapidly decarbonising the energy system, hybrid heat pumps can speed up the market roll-out of heat pumps by addressing some of the concerns about heat pump-only systems and allowing users to install heat pumps on top of their existing systems. Hybrid heat pumps can also accelerate the adoption of smart electrification strategies and the use of additional clean technologies, such as solar or geothermal energy. Hybrid heat pumps should thus be viewed as a transitional innovation.

CONVERSION TECHNOLOGIES

3 High-temperature heat pumps

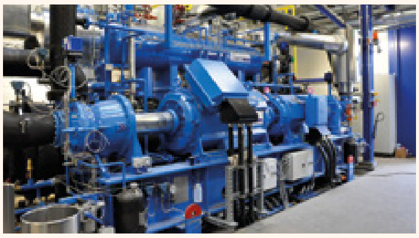
Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●○○○	●●●●	●●○○	

WHAT High-temperature heat pumps (HTHPs) can deliver heat at temperatures between 90°C and 150°C (Arpagaus *et al.*, 2018), although there is no consistent definition of an HTHP.[10] Research efforts are currently underway to increase HTHPs' temperature range to up to 200°C (de Boer *et al.*, 2020).

WHY It is crucial to make HTHPs commercially available because that will allow electrifying many more applications, especially in industry. Since many industrial processes require temperatures above 100°C, heat pumps that can deliver heat above 100°C will be able to electrify a large share of the industrial demand. In Europe, for example, industry would be able to meet 26% of the total EU process heat demand (or 508 terawatt hours/year) using heat pumps (de Boer *et al.*, 2020). Figure 6.4 shows the industrial processes that might be electrified using heat pumps. For many processes, such as pasteurisation and drying, electrification also leads to important energy savings. So far, however, HTHP technology is not considered mature and only a limited number of suppliers exist.

BOX 6.2 | Marienhütte steel and rolling mill

The Austrian steel and rolling mill Marienhütte in Graz, Austria, installed two large heat pumps that can supply heat at up to 95°C with a heating capacity of 6-11 MW. As a source, the pumps utilise the mill's waste heat at a temperature of 30°C to 35°C, using energy that would otherwise be dissipated to the environment. The heat pumps enable the mill to avoid using 46 GWh each year from fossil fuels, thereby reducing annual CO_2 emissions by 11 700 tonnes (de Boer *et al.*, 2020).



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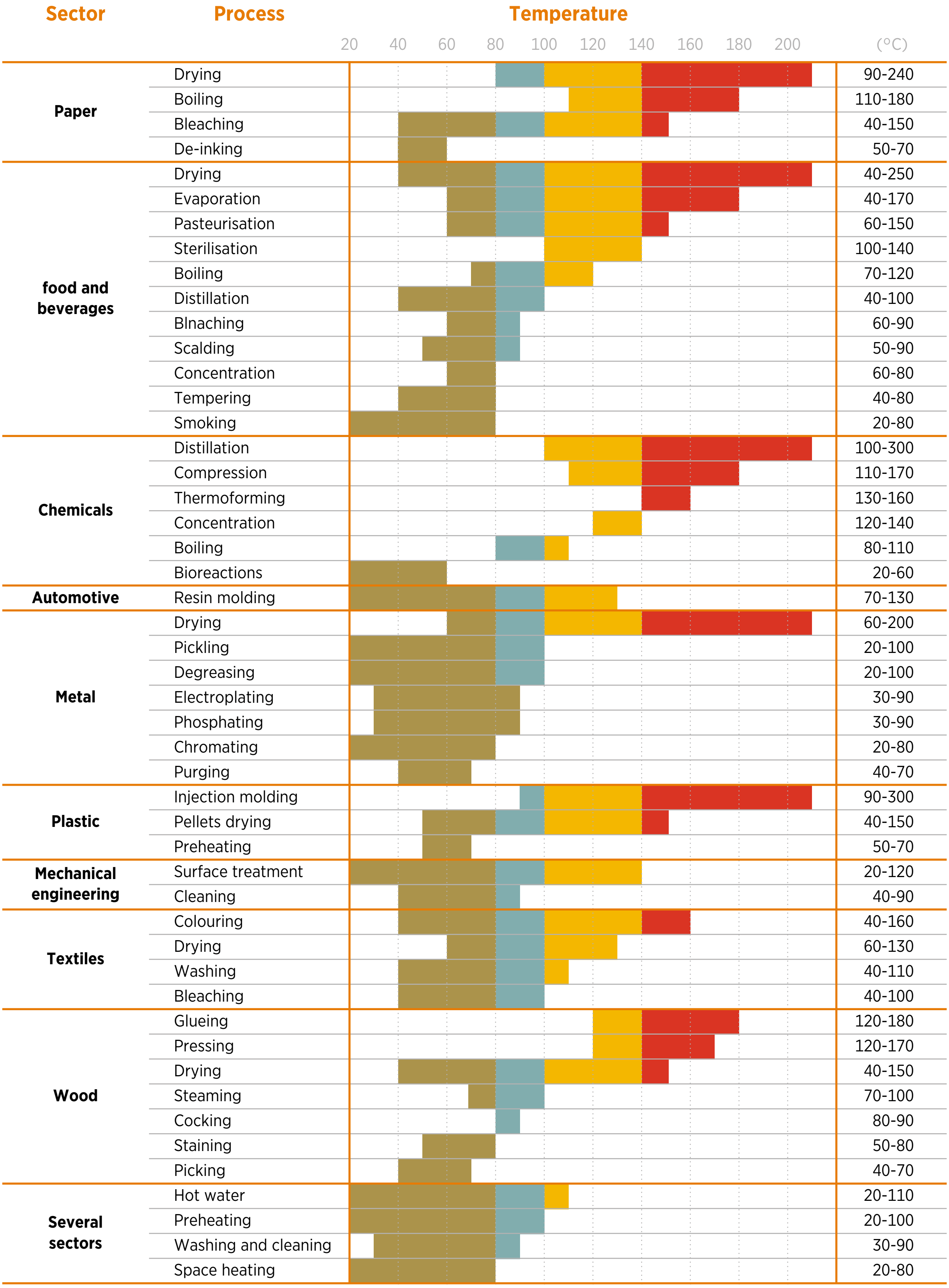
[10] *Generally, 100°C is seen as the lowest threshold temperature for labelling a heat pump as an HTHP. Some authors include a new heat pump category, very-high-temperature heat pumps (VHTHPs), for those heat pumps that provide heat sink temperatures up to 150°C.*

FIGURE 6.4 | Temperature ranges for different industrial processes and heat pumps



Sector	Process	(°C)
Paper	Drying	90-240
	Boiling	110-180
	Bleaching	40-150
	De-inking	50-70
food and beverages	Drying	40-250
	Evaporation	40-170
	Pasteurisation	60-150
	Sterilisation	100-140
	Boiling	70-120
	Distillation	40-100
	Blnaching	60-90
	Scalding	50-90
	Concentration	60-80
	Tempering	40-80
	Smoking	20-80
Chemicals	Distillation	100-300
	Compression	110-170
	Thermoforming	130-160
	Concentration	120-140
	Boiling	80-110
	Bioreactions	20-60
Automotive	Resin molding	70-130
Metal	Drying	60-200
	Pickling	20-100
	Degreasing	20-100
	Electroplating	30-90
	Phosphating	30-90
	Chromating	20-80
	Purging	40-70
Plastic	Injection molding	90-300
	Pellets drying	40-150
	Preheating	50-70
Mechanical engineering	Surface treatment	20-120
	Cleaning	40-90
Textiles	Colouring	40-160
	Drying	60-130
	Washing	40-110
	Bleaching	40-100
Wood	Glueing	120-180
	Pressing	120-170
	Drying	40-150
	Steaming	70-100
	Cocking	80-90
	Staining	50-80
	Picking	40-70
Several sectors	Hot water	20-110
	Preheating	20-100
	Washing and cleaning	30-90
	Space heating	20-80

Technology readiness level (TRL):

- ● Conventional HP <80°C, established in industry
- ● Commercial available HP <80°C, established in industry
- ● Prototype status, technology development, HTHP 100-140°C
- ● Laboratory research, functional models, proof of concept, VHTHP >140°C

Source: (Arpagaus *et al.*, 2018).

Notes: HP = heat pump; HTHP = high-temperature heat pump; VHTHP = very-high-temperature heat pump.

CONVERSION TECHNOLOGIES

4 Waste heat-to-power technologies

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●●	●○○○	●●○○	🏢 🏭

WHAT Waste heat-to-power technologies recover energy from waste heat and convert it into electricity. However, the temperatures of waste heat streams are generally too low to generate electricity using traditional steam turbine technology. Alternative technologies include organic Rankine cycles, which use organic fluid to recover low-temperature waste heat, and the Kalina cycle, which takes advantage of the different boiling points of ammonia and water in a working fluid that mixes the two substances.

WHY Conversion of waste heat into power increases energy efficiency by capturing energy that would otherwise be lost. Although technologies converting low-temperature heat into power themselves are inefficient compared with conventional steam turbines, they also reduce costs because the waste heat is free, and they produce no additional CO_2 emissions. In addition, the electricity generated can be used on site or traded in the electricity market, providing additional flexibility to the grid especially during peak hours. Even though industries have their heat integration site plans to use as much energy as possible and reduce waste heat streams, the potential to expand waste-to-power technologies is still large.

CONVERSION TECHNOLOGIES

5 High-temperature electricity-based applications for industry

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●○○○	●●●○	●○○○	🏭

WHAT Seventy percent of the final energy consumed by European industry in 2015 came from burning fuels, primarily to supply heat (Madeddu *et al.*, 2020). One alternative is to use electricity directly by switching to electric furnaces, electric boilers or other electrolytic processes. Promising solutions are already being developed for the three most difficult-to-decarbonise sectors: chemicals, cement and steel. For the chemical industry, electric crackers (e-crackers) are in the pilot phase. For the cement industry, kilns heated by plasma generators are in the proof-of-concept stage. Meanwhile, the steel industry is piloting electrolytic reduction processes. Finally, as discussed later in this report, these industries could also be electrified indirectly using renewably produced fuels. See Box 5.1 for an overview of power-to-heat technologies, temperature ranges and sectors they can cover.

6

5

WHY Replacing fossil fuels with electricity in industry significantly reduces CO_2 emissions when this electricity is produced from renewables. The benefits would be substantial, since industry now consumes about 38% of the total energy used worldwide. While full electrification is challenging, the adoption of mature and ready-to-use solutions (such as low-temperature heat pumps) can significantly increase industry's electrification rate outside of the difficult-to-decarbonise sectors.1

BOX 6.3 | E-cracking furnace experimental unit

Shell and Dow have installed an electricity-powered experimental heat steam cracker furnace unit at the Energy Transition Campus in Amsterdam (the Netherlands). This is a key milestone in the effort to decarbonise one of the most carbon-intensive processes of petrochemical manufacturing. The solution could be scaled up by 2025 if tests in 2023 show that it can successfully replace today's gas-fired steam cracker furnaces.

Source: (Shell, 2022).

BOX 6.4 | Electrification project of the steel industry in Chenzhou, China

As part of efforts to electrify the Chinese steel industry, a Chenzhou-based casting company is planning to add two additional electricity-based production lines to add capacity. The company plans to adopt the electricity-based production lines instead of the traditional gas-based production line to reduce carbon dioxide emissions.

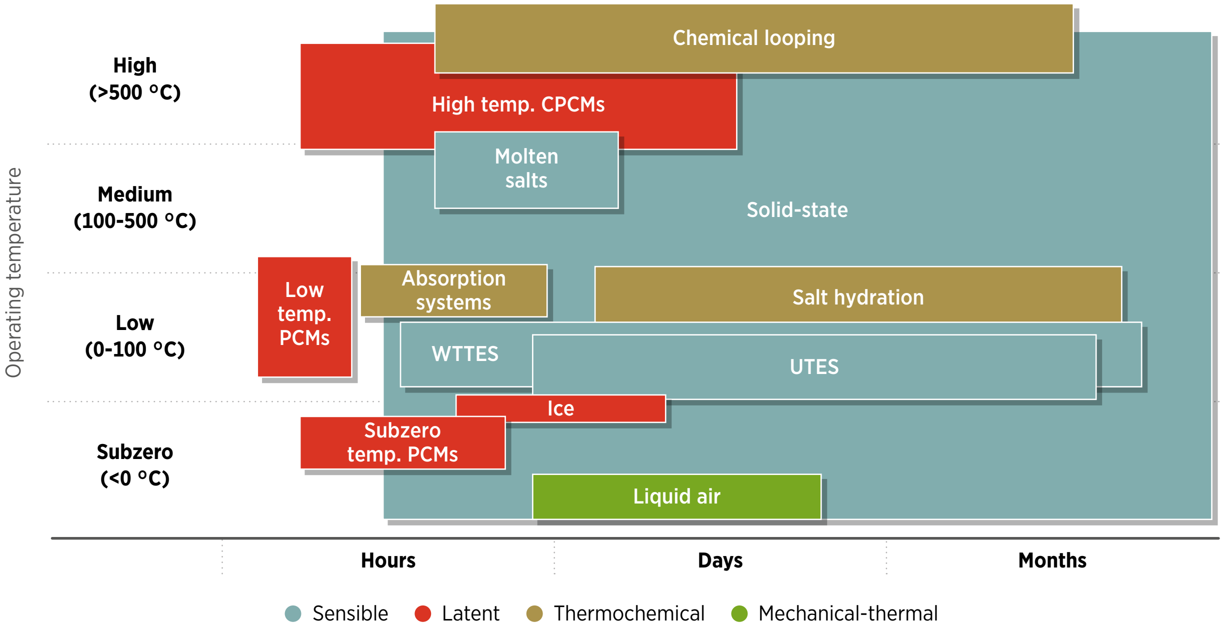
The project plans to build six energy-saving medium-frequency furnaces and eight resistance furnaces with a total power of 31.2 MW. The annual steel output will increase from 30 000 to 50 000 tonnes, with the annual steel output value increasing to about USD 43 million (CNY 300 million). The annual profit is expected to be approximately USD 10 million (CNY 70 million), with 60 GWh of newly increased electricity consumption. Also, 390 000 tonnes of carbon dioxide and 1 110 tonnes of nitrogen oxide emissions are supposed to be reduced annually.

Source: (CEPRI, 2022).

Thermal storage

TES makes it possible to decouple heating or cooling demand from power generation. Such decoupling offers many important benefits, including greater efficiency, flexibility, security and reliability in energy supply, while also reducing costs and greenhouse gas emissions. As described in this section, thermal energy can be stored at low or high temperatures,[11] or at short or long time scales using the alternatives shown in Figure 6.5 (IRENA, 2020b).

FIGURE 6.5 | Operating temperature ranges and time scales for TES technologies



Source: (IRENA 2020b).

Notes: CPCM = composite phase-change material; PCM = phase-change material; TES = thermal energy storage; UTES = underground thermal energy storage; WTTES = water tank thermal energy storage.

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[11] *Sub-zero storage is not considered.*

THERMAL ENERGY STORAGE

6 Low-temperature thermal energy storage

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●○○	●●●●	

WHAT Low-temperature TES accumulates heat (or cooling) over hours, days, weeks or months and then releases the stored heat or cooling when required in a temperature range of 0-100°C. Storage is of three fundamental types (also shown in Table 6.3):

- Sensible storage of heat and cooling uses a liquid or solid storage medium witht high heat capacity, for example, water or rock.
- Latent storage uses the phase change of a material to absorb or release energy.
- Thermochemical storage stores energy as either the heat of a reversible chemical reaction or a sorption process.

TABLE 6.3 | Low-temperature technological alternatives for TES

Storage type	Segment	Efficiency (%)	Range	Storage period	Cost (EUR/kWh)	Technology	TRL
Sensible	–	50-90	<0°C to 100°C	Hours to months	0.1-30	· Water tank TES · Underground TES · Solid-state thermal storage (*e.g.* ceramic bricks, rocks, concrete, packed beds)	Medium-high
Latent	–	75-90	<0°C to >100°C	Hours	50-200	· Ice thermal storage · Sub-zero temperature · Phase-change materials (PCMs), low-temperature PCMs	Medium-high
Thermochemical	–	50-65	0°C to 100°C	Hours to month	15-130	· Sorption, salt hydration, absorption and adsorption systems	Medium

Based on: (IRENA 2020b).

Notes: EUR/kWh = euros per kilowatt hour; TES = thermal energy storage; TRL = technology readiness level.

WHY By decoupling heating and cooling demands from electricity consumption, thermal storage systems allow the integration of greater shares of variable renewable generation, such as solar and wind power. They can also reduce the peak electricity demand and the need for costly grid reinforcements, and even help in balancing seasonal demand. Thermal storage can add increasing benefits to the grid the longer the heat can be stored. The economics are difficult, however, due to the limited number of cycles and the decline in the prices of competing battery storage (Box 6.5). TES systems, therefore, must be low cost.

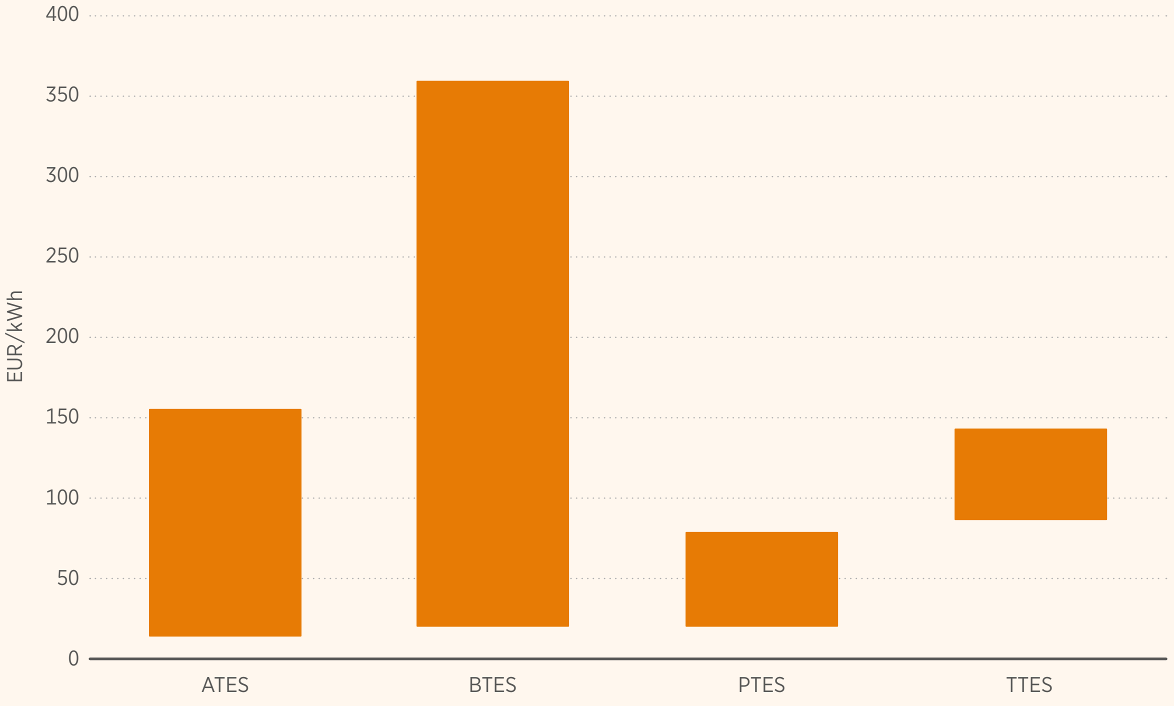
BOX 6.5 | Seasonal aquifer storage of Stockholm's airport

Stockholm's Arlanda Airport has the world's largest aquifer storage unit. It contains 200 million m^3 of groundwater and can store 9 GWh of energy. One section holds cold water (at 3-6°C), while another has water heated to 15-25°C. The system works like a giant seasonal thermos: during summer, cold water is pumped to provide cooling for the airport's district heating and cooling system. The water is returned to the aquifer at a temperature of 20°C. Warm water is then used in winter to preheat the ventilation air in the buildings and melt snow on aircraft parking areas.

BOX 6.6 | Economics of thermal storage

The economics of thermal storage depends on multiple factors, including energy prices, the energy demand served by the storage, the specific storage technologies and storage size (with costs decreasing as storage volumes increase). Figure 6.6 shows the levelised cost of heat (LCoH) for different seasonal storage technologies. Some of the technologies have a wide range of LCoHs, showing the high dependence of costs on specific project conditions. However, the average cost of small-scale hot water thermal storage is approximately USD 100/kWh (Lund *et al.*, 2016), which is still considerably lower than the average cost of battery storage, despite the rapid decline in battery costs from almost USD 3 000/kWh in 2014 to USD 850/kWh in 2021 (IRENA, 2022d).

FIGURE 6.6 | Levelised cost of heat for seasonal thermal storage technologies



Source: (Yang *et al.*, 2021).

Notes: ATES = aquifer thermal energy storage; BTES = borehole thermal energy storage; EUR/kWh = euros per kilowatt hour; PTES = pit thermal energy storage; TTES = tank thermal energy storage.

THERMAL ENERGY STORAGE

7 Medium- and high-temperature thermal energy storage

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●●○○	●●●●	

WHAT In high-temperature TES, energy is stored at temperatures ranging from 100°C to above 500°C. High-temperature technologies can be used for short- or long-term storage, similar to low-temperature technologies, and they can also be categorised as sensible, latent and thermochemical storage of heat and cooling (Table 6.4).

TABLE 6.4 | High-temperature TES technologies

Storage type	Segment	Efficiency (%)	Range	Storage period	Cost (EUR/kWh)	Technology	TRL
Sensible		50-90	150°C to 1 000°C	Hours to months	0.1-25	· Solid-state thermal storage (*e.g.* ceramic bricks, rocks, concrete, packed beds)	Medium-high
Latent		75-90	50°C to 850°C	Hours to days	60-120	· High-temperature PCMs	Medium
Thermochemical	–	75-100	500°C to 900°C	Hours to seasonal	80-160	· Chemical looping (calcium looping), salt hydration, absorption and adsorption systems	Low-medium

Notes: EUR/kWh = euros per kilowatt hour; PCM = phase-change material; TES = thermal energy storage; TRL = technology readiness level.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WHY High-temperature storage offers similar benefits to low-temperature storage (*e.g.* providing flexibility and lowering costs). However, high-temperature storage is especially useful for smart electrification of heating and cooling in industry, given that many industrial processes either require high temperatures or produce high-temperature heat. Meanwhile, in many cases, industry has relatively steady heat demand over the day; storage would thus play only a small role in meeting demand peaks. Instead, energy could be stored when its prices are low and then discharged when prices are high; this will enable industry players to leverage fluctuating prices and provide valuable demand-response services to the energy system.

BOX 6.7 | World's first Carnot battery stores electricity in heat: Third-life storage plant

The Carnot battery is a promising new concept in electricity storage. It uses heat pumps to convert wind- and solar-generated electricity into heat, which is stored in salts and converted back into electricity using a steam engine generator. Storage temperatures in molten salt can range from 200°C to more than 500°C (Vecchi *et al.*, 2022).

The world's first Carnot battery prototype is being built in Stuttgart at the Institute of Engineering Thermodynamics within the German Aerospace Centre (DLR) together with the European CHESTER consortium (Compressed Heat Energy Storage for Energy from Renewable Sources).

The battery is based on the CHEST (compressed heat energy storage) process and uses a patented double-ribbed tube heat exchanger to move heat between the heat pump and the heat engine. It can achieve high round-trip efficiencies of over 50% with low energy losses as it converts electricity into heat and back into electricity (Smallbone *et al.*, 2017). A Carnot battery with a capacity of 1 000 MWh could provide a stable energy supply to a city the size of Stuttgart, while facilitating the coupling of heat and electricity. Further, since Carnot batteries use simple, affordable materials (water and salt), they are more environmentally friendly than conventional batteries. However, achieving high efficiencies requires the maturation of high-temperature heat pump technologies. (German Energy Solutions Initiative, 2020).

District heating and cooling systems

DISTRICT HEATING AND COOLING SYSTEMS

8 Fourth-generation DHC systems

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●○○	●●●●	

WHAT DHC systems date back to the late 19th century but have undergone considerable changes and improvements since then. Many of the newest DHC systems are known as "fourth-generation" systems. They work at lower temperatures than the earlier generation systems, making them more efficient and lowering the related supply costs, because they can use lower-quality (lower-temperature) heat sources.

For a district heating system to be classified as a fourth-generation (4GDH) system, it must use smart integration to maximise the overall efficiency as well as the use of locally available renewable energy sources. A key feature of 4GDH systems is that they supply heat or cooling at temperatures as close as possible to the actual temperatures required by end users – a maximum of 60-70°C. Such relatively low supply temperatures (for heating) reduce losses in the district heating system and facilitate greater integration of waste heat sources (*e.g.* excess heat from data centres) than is possible using third-generation systems. 4GDH systems also use large-scale heat pumps of much higher efficiency to further exploit low-temperature waste heat sources or ambient heat. They may also use heat or cold storage to support the smart operation of heat pumps (Lund *et al.*, 2021).

WHY 4GDH systems add major benefits; for example, they lead to low overall energy consumption and add flexibility to the power system. Compared with earlier generation systems, they have reduced grid losses by 6%, primary energy consumption by 4.5% and total costs by 2.7%.

BOX 6.8 | Districlima, Barcelona, Spain

One of the largest district heating and cooling systems in Spain is in the city of Barcelona. Now a fourth-generation system, it continues to expand across the city. The system has two primary production plants with a total cooling capacity of 113 MW and heating capacity of 79 MW. It also has a 40 MWh water storage tank and a 120 MWh ice storage tank. The system supplies heating and cooling to a 20.2 km network.

Most of the heating and part of the cooling are produced using the steam generated by a nearby urban waste incinerator. Cold generation is assisted by industrial electric chillers cooled with seawater.

Storage systems allow the city to supply heating and cooling during periods of high demand and reduce costs by storing energy when demand is low. The network expansion has resulted in the growth of annual carbon dioxide emissions reductions from 10 654 tonnes in 2009 to 29 792 tonnes in 2019.

Source: (European Commission, 2021).

DISTRICT HEATING AND COOLING SYSTEMS

9 Fifth-generation DHC systems

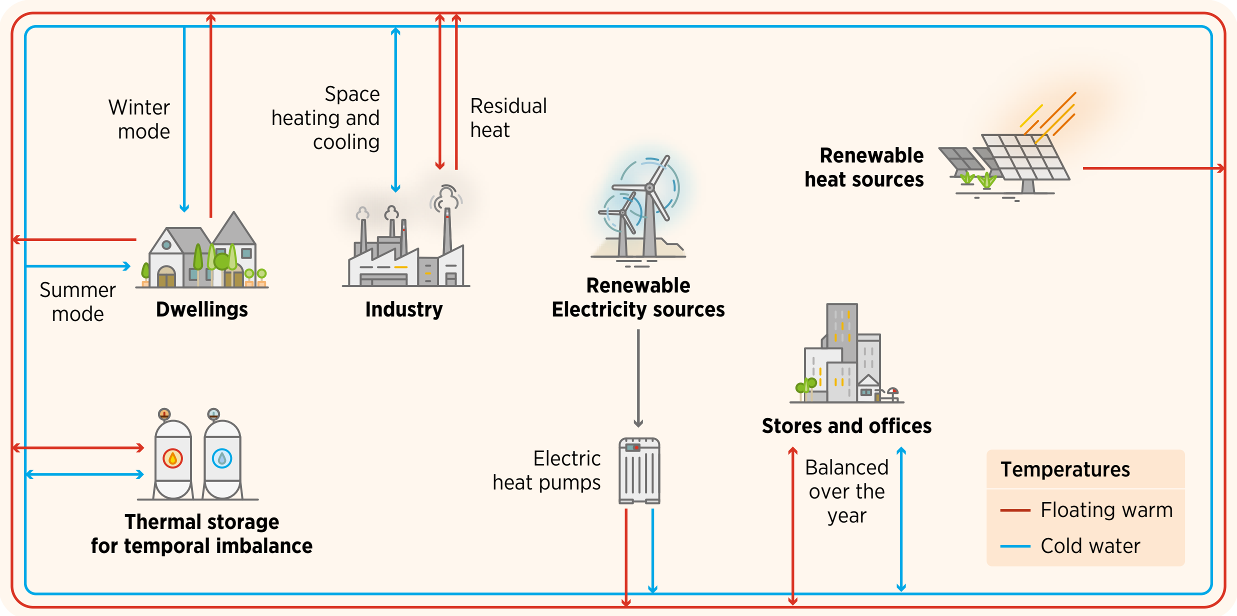
Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●○○○	●○○○	●●●●	

WHAT Fifth-generation district heating systems distribute heat at even lower temperatures than 4GDH systems. This requires end users to boost temperatures using additional distributed heat pumps (Lund *et al.*, 2021). Users can thus function as customers (by extracting heat from the network) or generators (by injecting heat into the network). The same principle applies for cooling.

5GDH, which is also known as a neutral loop, should not be seen as a sequential generational advancement over 4GDH, but as a variation of 4GDH or "sibling" (Lund *et al.*, 2021). 5GDH is especially suitable for applications where cooling and heating demands are of similar size, making it an important innovation as the global cooling demand rises.[12] 5GDH, which is also known as a neutral loop, should not be seen as a sequential generational advancement over 4GDH, but as a variation of 4GDH or "sibling" (Lund *et al.*, 2021).

Fifth-generation systems use bi-directional pipes and a modern control and communications infrastructure (Figure 6.7) to allow users to consume or generate heat, or exchange it among themselves (E.ON, 2022; Kensa Heat Pumps, 2022). Meanwhile, the use of distributed heat pumps allows lower temperatures on the network, thereby reducing transmission heat losses and radically lowering the costs of installing distribution circuits.

FIGURE 6.7 | Illustration of a fifth-generation DHC system



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[12] *While the temperature ranges of 4GDH and 5GDH systems are not formally distinguished, the latter focus on collective networks operating close to ambient temperature levels as common heat sources or sinks for building-level heat pumps (Lund et al., 2021).*

WHY Fifth-generation systems can offer benefits beyond fourth-generation systems especially when the levels of heating and cooling demands are similar. They boost efficiency, encourage greater use of renewable sources and can lower overall costs.

BOX 6.9 | Fifth-generation district heating and cooling system in the Netherlands

The Mijnwater district heating and cooling system in Heerlen, the Netherlands, used to be a local district heating and cooling network using a flooded coal mine as a low-temperature geothermal source. However, it is a modern urban fifth-generation district heating and cooling system now. The upgraded system uses a backbone of bi-directional pipes to exchange heating and cooling among a data centre, supermarket refrigerators, small-scale industrial processes and connected buildings. It currently serves a building floor area of over 200 000 square metres. New users can easily connect to the bi-directional pipeline with basement heat exchangers, making it easy to expand the system.

By maximising the use of waste heat and renewable energy sources, the upgraded system has cut energy use by 30% compared with the conventional supply system. Other similar pilot projects are being developed in Paris-Saclay (France), Bochum (Germany), Heerlen and Brunssum (the Netherlands), and Glasgow and Nottingham (United Kingdom) (Boesten *et al.*, 2019; Brummer and Bongers, 2019; Bonger and Marini, 2020).

Digitalisation

DIGITALISATION **10 Internet of Things for smart electrification**

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●○○○	●●●●	🏘 🏢 🏭

WHAT Internet of Things (IoT) refers to physical devices that use electronics, sensors and software to connect and exchange data with other devices over the Internet. These devices are also called “connected devices” and “smart devices”, and they support remote monitoring and control through cloud-based control systems. For example, these tools and devices can adjust the energy consumption of loads such as heat pumps or water heaters in response to price signals or grid conditions to reduce energy costs, optimise operations and provide demand-response flexibility to the grid.

WHY IoT is a key tool for enabling the smart coupling of the power and heat sectors. Its use will help save energy, reduce costs and carbon emissions, and maximise the use of renewable sources by enabling automation.

BOX 6.10 | A ubiquitous IoT in China’s electric power system

The concept of a ubiquitous IoT in an electrical power system was first proposed by China in 2019, and its construction is to be completed by 2024. Such an IoT uses advanced communication technology to realise the full interconnection of power systems. In addition, it allows the integration of additional sectors such as heating and cooling as well as decentralised energy sources like photovoltaics. The system, once implemented, will be able to control the on-line operation status of equipment and fully utilise multiple complementary energy sources, such as power grid, electric vehicles and energy storage to improve comprehensive energy utilisation efficiency, save energy costs and reduce carbon emissions.

Source: (SGCC, 2019).

DIGITALISATION

11 Artificial intelligence for forecasting heating and cooling demands

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●○○	●●●●	

WHAT AI adds intelligence to the data and communications among the different components of IoT. One particularly promising use of AI is developing predictive energy consumption models for buildings that factor in the buildings’ thermal characteristics and architecture, meteorological conditions, solar irradiance, wind velocity and direction, outdoor and indoor temperatures and user behaviour. Recent research shows that novel data-driven AI- or artificial neural network–based approaches can improve the accuracy of these predictions and enable predicting short-term fluctuations, a capability essential for control applications (Bünning *et al.*, 2020; Petrichenko *et al.*, 2017; Saloux and Candanedo, 2018).

WHY By forecasting heating and cooling demands better, and then controlling loads to optimise their operation, AI enables greater flexibility in the energy system and facilitates increased use of variable renewable energy sources. Data-driven approaches using AI techniques such as deep learning also add significant energy savings. For example, the majority of buildings are mostly empty (more than 60% of the time), yet they maintain air temperatures of 21-23°C inside. AI methods can detect when a building is completely empty and then lower temperature setpoints in winter or raise them in summer during those periods. Further, AI can help size heating and cooling storage facilities better.

DIGITALISATION

12 Blockchain for enabling transactions

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●○○○	●●○○	

WHAT Blockchain technology is a novel distributed, digital ledger for verifying transactions. It provides a shared, secure and transparent environment wherein all transactions are registered, documented and processed. These transactions can include peer-to-peer electricity trading or the sale of excess energy flows in the form of heating, cooling or electricity, without the involvement of a trusted third party (Khan *et al.*, 2019). For 5GDH systems, for instance, blockchain technology can create a common heat production system among district heating companies, energy producers and producer-consumers (prosumers) that helps to optimise the network.

WHY Blockchain systems can help solve data reliability challenges, lower transaction costs, reduce error and fraud, and empower households and energy communities. Combined with smart contracts, blockchain systems can automate processes, helping to integrate renewables in the energy system and increase its flexibility. Potential future uses include enabling cross-sector and cross-border trade and providing tax benefits.

BOX 6.11 | Blockchain for operating virtual power plants in Germany

The ViFlex pilot project, launched by German transmission system operator TenneT and the climate solution provider Viessman, bundles heat pumps together with energy storage to form virtual power plants. The project controls the operation of individual heat pumps to accommodate larger shares of renewable electricity and to prevent grid congestion. This pilot uses the Equigy blockchain crowd-balancing platform with smart contracts, enabling individual customers with flexible assets to participate in energy service markets.

Source: Equigy (2020).

DIGITALISATION

(13) Digitalisation as a flexibility enabler

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●●○○	●●●●	

WHAT Digitalisation makes it possible to set smart strategies. By way of computational programmes or machine learning algorithms, such strategies use the data acquired from metering devices to add valuable flexibility, optimise operations and lower costs. Computational programmes are being implemented in industrial ovens, in systems that use reservoirs for cooling and in induction furnaces for aluminium smelting (Cuvelier, 2020). Metering devices are widely used by industries to monitor the operation and energy use of machinery, furnaces, boilers and various processes. Such devices are increasingly used in buildings, where they inform new business models that reduce consumers' energy bills.

WHY Digitalisation is a key innovation, enabling energy-intensive users in the industry sector, such as aluminium smelters, to increase the flexibility of their electricity consumption, save energy and increase the reliability of their processes. Similarly, digitalisation can help buildings reduce energy costs and can provide flexibility to the energy grid to maximise the use of renewable sources.

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6.2 Market design and regulation

Innovations in market design and regulation are critical to create the right incentives for implementing smart power-to-heat strategies and technologies, which, in turn, will accelerate the electrification of this end-use sector. As Figure 6.8 shows, these vital innovations include everything from smart tariffs and flexible power purchase agreements (PPAs) to improved building codes and permitting procedures. Each innovation is discussed in detail in this section.

FIGURE 6.8 | Innovations in market design and regulation for power to heat and cooling

MARKET DESIGN AND REGULATION	**ELECTRICITY MARKET DESIGN**	• **14** Dynamic tariffs
		• **15** Flexibility provision by thermal loads
		• **16** Flexible power purchase agreement
	END-USE SECTOR REGULATION AND INCENTIVES	• **17** Standards and certification for improved predictability of heat pump operation
		• **18** Energy efficiency programmes for buildings and industries
		• **19** Building codes for power-to-heat/cooling solutions
		• **20** Streamline permitting procedures for thermal infrastructure

Electricity market design

ELECTRICITY MARKET DESIGN | **14 Dynamic tariffs**

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●○○	●●●●	

WHAT Dynamic tariffs vary over time or by location depending on the conditions in the power system, such as the amount of demand or renewable generation. These price signals provide incentives for customers and system operators to optimise both electricity use and energy production and to reduce costs. For example, higher electricity prices during peak consumption hours will encourage customers to use less energy for heating or cooling, thus lowering peak loads. Similarly, low prices when large amounts of renewable energy are available will encourage greater energy use, helping to avoid the curtailment of renewable sources.

WHY The price signals enabled by dynamic tariffs create powerful incentives for consumers and system operators to adjust their use of heating and cooling appliances or storage to reduce energy costs. This process of adjustment, in turn, enhances an energy system's flexibility. Price signals can also encourage consumers to adopt heat pumps and other highly efficient equipment, which will accelerate the decarbonisation of the energy system.

BOX 6.12 | Agile Octopus

In the United Kingdom, the energy supplier Octopus Energy uses dynamic electricity prices to encourage customers to shift their electricity consumption from peak to non-peak hours, for example, by charging electric vehicles or running heaters at night when demand is low. The programme, called Agile Octopus, adjusts prices every half hour based on changes in wholesale prices. Decline in wholesale electricity prices cause savings on energy bills for customers. In unusual situations where electricity surpluses cause prices to turn negative, the programme even pays customers to use more electricity to take energy off the grid. To protect customers from very high wholesale prices, Octopus Agile caps retail prices at GBR 0.55/kWh. The service is fully digitalised, and users can access all services using their smartphones.

Source: Octopus Energy (2022).

ELECTRICITY MARKET DESIGN

15 Flexibility provision by thermal loads

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●○○	●●●●	

WHAT Heat pumps, especially when combined with thermal or even electric storage, can be ramped up or down to provide grid-balancing services to both transmission and distribution system operators without affecting consumers' comfort. Adjustments can be made at intervals as short as a few seconds to regulate frequency, or over minutes to hours to balance supply and demand. Heat pumps combined with storage also offer reserves to cover contingencies over longer periods. These services typically require aggregating the thermal loads of multiple end users to reach a critical volume sufficient to participate in the market. DHC systems are particularly effective at providing flexibility because customers are already aggregated on the thermal grid; also, the network itself provides thermal inertia, and is under central control.

To allow heat pumps or other power-to-heat technologies to provide grid-balancing services, regulations should:

- Lower the minimum capacity requirement for participation in these markets, or allow aggregators to bundle small assets and participate in the market; and
- Allow demand-side participation in the grid-balancing markets.

WHY The ability to control heat pumps and other thermal loads on short or long-time scales offers multiple benefits. Both industrial and residential consumers can reduce their energy costs by adjusting their energy needs as electricity prices change. They can also receive additional revenue by providing flexibility to electricity grids. Meanwhile, the flexibility helps balance the grid and enables the integration of greater shares of variable renewables in the system.

ELECTRICITY MARKET DESIGN

16 Flexible power purchase agreement

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●○○	●●●○	

WHAT PPAs can help companies or grid operators secure the supply or consumption of large amounts of electricity under fixed conditions over a defined time frame. Traditional PPAs, however, lack flexibility and can lock participants into unprofitable or suboptimal situations if prices or markets change. Flexible PPAs (FPPAs) solve this problem by adjusting the agreements' terms when certain specified changes occur. For example, an FPPA could lower electricity prices for purchasers when heating or cooling demand drops or when supplies of variable renewable energy are high. FPPAs thus not only cover purchasers' electricity needs, they also add valuable flexibility, increasing revenues for energy producers and enabling grid operators to control the grid more effectively.

FPPAs are well suited for thermal energy networks. A large DHC system could sign an FPPA with a nearby PV power plant to buy all the electricity from the plant, even when the output varies, for example. A district heating system with combined heat and power could set up an FPPA in which it acts as both an electricity generator and consumer. The best strategy depends on the specific market conditions, but the flexibility inherent in DHC systems enables better agreements.[13]

WHY Flexibility can make PPAs more financially attractive, increasing the incentives for electrifying heating and cooling and installing thermal storage. These agreements thus can accelerate investments in power-to-heat technologies and flexibility sources. They also add another market option for investors and can be combined with less innovative agreements (such as retail tariffs) to diversify financial risks.

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[13] *Small-scale users can also benefit from FPPAs via aggregators (innovation in Figure 6.12). However, DHC systems and industries are of sufficient size to set up individual contracts with distribution system operators.*

End-use sector regulations and incentives

END-USE SECTOR REGULATION AND INCENTIVES

17 Standards and certification for improved predictability of heat pump operation

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●●○	●○○○	🏠

WHAT Standards specify the requirements for the performance, quality and safety of appliances such as heat pumps, while certifications verify that the standards are being met. Together, the right standards and certifications help remove the uncertainties and risks inherent in purchasing new technologies and allow buyers to compare options more easily. The details of the standards are also crucial. For heat pumps, for example, standards should be set for their smart operation both as stand-alone systems and as components in an integrated system. Standards and certifications should also consider how systems are designed and installed, for maximum benefit.

WHY Proper standards and certifications for heating and cooling appliances (and for their smart operation) enable residential and commercial customers to buy and operate them with greater confidence and lower risk, accelerating the electrification of heating and cooling. Standards also incentivise manufacturers to improve their products' efficiency and performance.

END-USE SECTOR REGULATION AND INCENTIVES

18 Energy efficiency programmes for buildings and industry

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●●	●●○○	●●●○	🏠 🏢 🏭

WHAT The buildings and industrial sectors consume more than 65% of the total global energy. Increasing the efficiency of that energy use, therefore, offers major gains. Globally, greater energy efficiency will reduce total greenhouse gas emissions and energy demand, making it easier to supply that energy from renewable sources. For individual building owners and companies, greater energy efficiency will reduce energy costs, improve comfort in buildings and boost competitiveness in industry.

Energy efficiency programmes can be mandated by standards or other regulations, such as building codes. In the Netherlands, for example, corporations that manage social housing must make periodic large-scale renovations, such as adding insulation, to guarantee certain levels of efficiency.

Alternatively, energy efficiency measures can be encouraged with market-based incentives, such as tax credits or interest-free loans. These incentives can help overcome one common barrier to energy efficiency upgrades: the real or perceived high upfront costs of efficiency measures such as additional insulation, improved windows or highly efficient heating systems. Increasing energy efficiency in industry is more challenging than in the buildings sector, where the same approaches can be used across most buildings. In contrast, the industrial sector often requires programmes that are tailor made for specific applications. Many of these may not be cost-effective. Efficiency gains in industry may thus require regulations, market-based incentives or requirements such as the European Union Emissions Trading System, or national initiatives like Netherland's Environmental Management Act (Vreuls, 2017). One useful strategy for improving the overall efficiency is making better use of waste heat; at the same time, improving the energy efficiency of many processes can also reduce the amount of available waste heat.

WHY Energy efficiency programmes can be enormously effective for buildings, reducing the energy demand for heating and cooling by up to 80% (Verbeke and Audenaert, 2018). The many benefits include lower energy costs, increased comfort and higher thermal inertia, which allows greater demand-side flexibility.

In industries, energy efficiency programmes via regulation or market mechanisms can accelerate transformation. However, unaligned regulations in international markets can hinder the competitiveness of industries that have to comply with relatively stringent requirements. Global consensus is essential to harmonise global markets.

BOX 6.13 | Energy efficiency programme for buildings in Paris, France

Paris's Climate Action Plan aims to reduce energy consumption in municipal buildings by 60% by 2050. The plan uses energy performance contracts to provide incentives for building efficiency investments. The contracts allow building operators to pay back the upfront costs of investments using the savings from lower energy costs over a pre-defined period. These contracts have already been used in 240 schools to install new windows, LED (light emitting diode) lighting, insulation upgrades or new boiler systems.

Source: (C40 Knowledge Hub, 2020).

END-USE SECTOR REGULATION AND INCENTIVES

19 Building codes for power-to-heat solutions

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●○○○	●●●○	●●○○	

WHAT Building codes are regulations that govern the design, construction and modification of commercial buildings and homes. As such, they represent powerful tools for accelerating electrification and greater energy efficiency in buildings. For example, they can set minimum efficiency standards for the building envelope; for heating, ventilation and air-conditioning systems; for lighting; and for water heating systems (Rosenberg *et al.*, 2015). They can also support the connection of buildings into DHC networks.

WHY Most building codes do not include standards requiring greater electrification and energy efficiency, and so do not encourage the roll-out of power-to-heat options. Revising building codes, therefore, can accelerate the energy transition while also reducing energy costs and greenhouse gas emissions, increasing comfort and energy system flexibility, and enabling larger shares of renewables. They also offer frameworks for comparing energy supply alternatives.

BOX 6.14 | First building codes requiring heat pumps approved in California

The California Energy Commission voted in 2021 to approve the first building code in the United States requiring heat pumps for either space heating or water heating in most new homes and other buildings (unless these could meet strict energy efficiency requirements in other ways). Greater use of heat pumps will increase resilience in the face of climate-fuelled heat waves, while also reducing the strain imposed on the grid by inefficient air-conditioning systems. Greater use of heat pumps will increase resilience in the face of climate-fuelled heat waves, while also reducing the strain imposed on the grid by inefficient air-conditioning systems (NRDC, 2021).

END-USE SECTOR REGULATION AND INCENTIVES

⑳ Streamlining permitting procedures for thermal infrastructure

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●●●●	●○○○	

WHAT A streamlined permitting process entails clear and transparent procedures that aim to accelerate, guarantee and ensure quality. This is important in the case of thermal infrastructure, such as district heating systems, which require large investments and the participation of multiple actors. Streamlined procedures can make it easier to apply for permits (such as with a one-stop shop), prevent breakdowns in communication and facilitate co-ordination among various decision makers. The procedures should include installation guidelines outlining key steps, requirements, cost calculations and assessments of CO_2 reductions. They will also be most effective when tailored to their various audiences, such as homeowners, renters or commercial installers.

WHY Streamlining permitting procedures for thermal infrastructure would significantly accelerate the deployment of power-to-heat technologies in buildings.

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6.3 System planning and operation

The electrification of heating and cooling sectors requires innovations in system planning. This section describes those innovations, which include heat mapping and joint planning of electricity and DHC networks (Figure 6.9).

FIGURE 6.9 | Innovations in system planning and operation for power to heat and cooling

SYSTEM PLANNING AND OPERATION	**INTEGRATED PLANNING**	**21** Holistic planning for cities
		22 Heating and cooling maps
		23 Coupling cooling loads with solar generation
	SMART OPERATION	**24** Smart operation with thermal inertia
		25 Smart operation with seasonal thermal storage
		26 Smart operation of industrial heating
		27 Combining heating and cooling demands in district systems

Strategic planning

INTEGRATED PLANNING

21 Holistic planning for cities

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●●○	●●○○	

WHAT Half of the energy consumed in cities is for heating and cooling. As this report describes, electrified solutions can bring about significant reductions in consumption, although implementing such solutions requires co-operation at the planning level among all stakeholders from power system operators as well as the heating and cooling sectors, including grid operators, private companies, the public sector, end users, research institutions and regulators. Co-operation is especially critical for capital-intensive infrastructure such as district heating networks and large heat pumps. Policy makers at the national or regional levels would do well to establish long-term climate action plans backed by local authorities to facilitate investments and to provide incentives such as grants to help households connect to existing networks. In addition, industries near urban areas can play a role by providing surplus heat via thermal networks. Meanwhile, local authorities are key for planning and constructing district heating systems, leveraging possible synergies with other urban infrastructure, and facilitating co-ordination between district heating system operators and other stakeholders, such as real estate developers.

WHY Holistic planning of heating and cooling can vastly reduce the investments needed for their electrification. Identifying synergies between different temperature streams and reservoirs (such as wastewater, industrial waste heat or eco districts) will maximise efficiency, as will optimising the use of shared storage facilities that are charged or discharged by different types of users.

INTEGRATED PLANNING

22 Heating and cooling maps

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●○○○	●●○○	

WHAT Heat mapping can be an extremely useful tool for understanding energy use across a city. The idea is to create a map that shows precisely where, and how much, energy is being used in a city, along with types of energy and end uses. The mapping can then be used for many layers of analysis.

WHY Heating and cooling maps can help paint a complete picture of demand and thus inform plans for energy use and infrastructure investments. It can help determine the optimal placement and sizing of heat pumps, for example, while considering the constraints imposed by both heating networks and the electricity distribution network. Such planning will reduce losses in both networks and optimise overall operational costs.

BOX 6.15 | Heat mapping project in Europe

Hotmaps is a European project that has designed an open-source toolbox to support public authorities, energy agencies and urban planners as they plan heating and cooling at local, regional and national levels. It allows users to map cooling and heating demand, as well as supply, for 28 EU Member States, along with renewable energy generation and industrial waste heat potential. It ensures that planned strategies will be in line with EU policies. Hotmaps has been demonstrated and validated in seven European pilots – in Denmark, Romania, Spain, Germany, Switzerland, Ireland and the United Kingdom.

Source: (Hotmaps, 2021).

INTEGRATED PLANNING

23 Coupling cooling loads with solar generation

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●●	●●○○	●●●●	

WHAT Given the close match between the profiles of solar generation and cooling demand, energy planners can help meet cooling demand (especially as it increases) by deploying additional PV systems. In particular, energy planners can identify suitable rooftops or other surfaces for PV systems and ensure that the electricity grid is capable of integrating large numbers of distributed solar PV arrays.

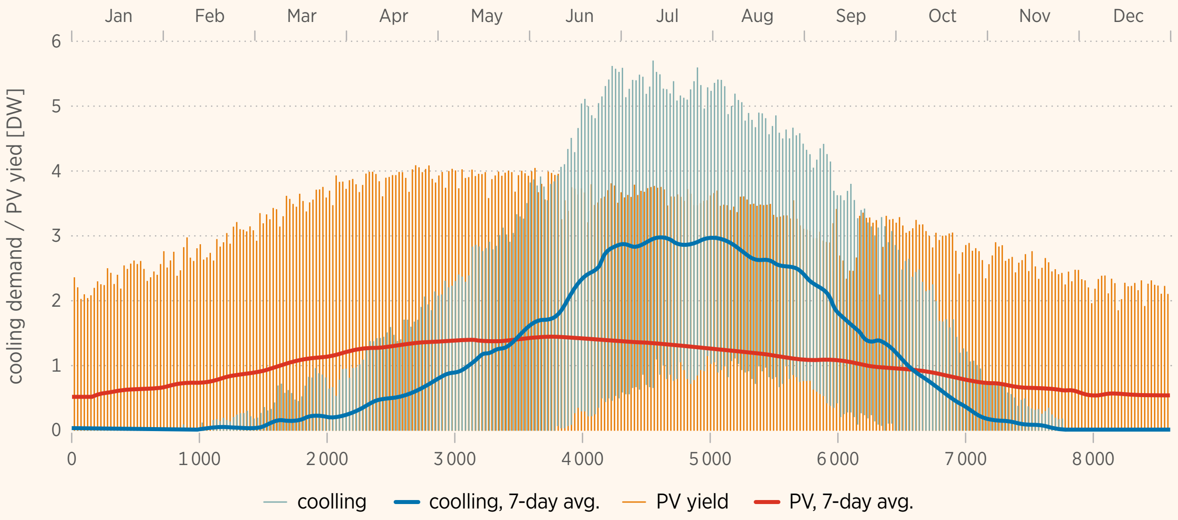
WHY Effective deployment of solar energy would significantly decarbonise the cooling supply. It could also reduce dependence on the grid, increasing resilience and enabling people in remote locations with unreliable grid access to use cooling systems for critical purposes such as refrigerating food or medicines.

BOX 6.16 | Coupling cooling loads and solar PV generation in Arizon

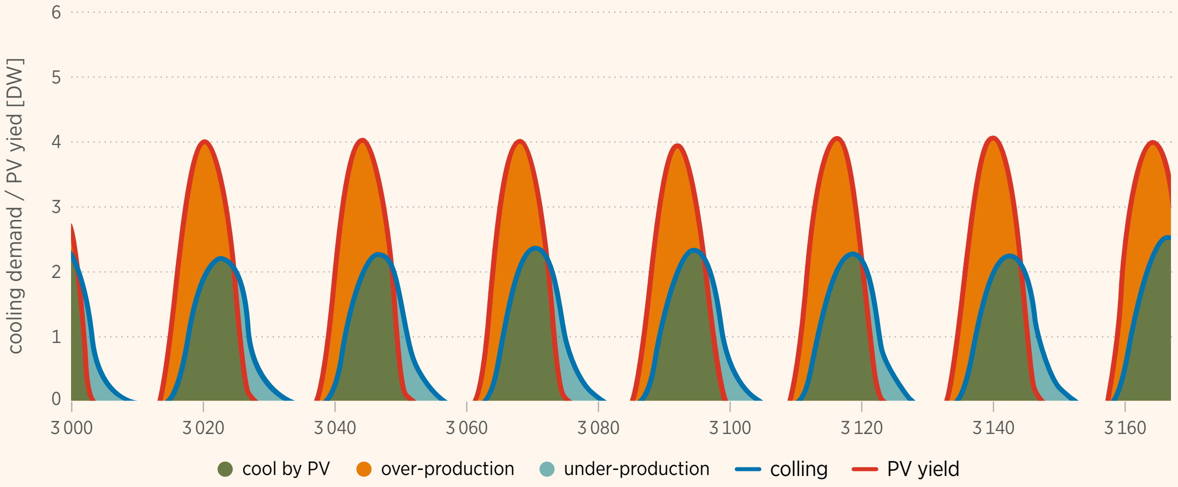
Figure 6.10 shows the correlation between seasonal and daily demands and PV electricity yield in an Arizona county. The Figure illustrates how solar generation can meet 55% of the cooling electricity demand on an hourly basis (Laine *et al.*, 2019). Even more of the demand could be met if buildings were pre-cooled during the sunniest hours, taking advantage of the buildings' thermal storage capabilities.

FIGURE 6.10 | AC demand and PV electricity yield in Maricopa County, Arizona, 2010

Modelled AC demand and PV electricity yield in 2010



Cooling production by PV and PV yield over- and under-production for the second week of May 2010



Notes: AC = alternating current; GW = gigawatt; PV = photovoltaics.

Smart operation

SMART OPERATION

24 Smart operation with thermal inertia

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●○○○	●●●●	

WHAT Building envelopes can store a lot of heat – a property called high thermal inertia. Increasing a building's energy efficiency also increases its thermal inertia. Buildings with higher thermal inertia, in turn, can play a big role in the smart electrification of heating or cooling, since they maintain their temperatures longer when heating or cooling systems are turned off to provide flexibility to the energy system. In other words, buildings with high thermal inertia can shift their demand and ensure comfortable conditions for the people using them.

WHY Thermal inertia can help time-shift energy demand and flatten out demand fluctuations. This saves energy and reduces the peak demand while still providing the same comfort levels. Combined with dynamic tariffs, thermal inertia will reduce energy bills because demand is shifted to lower-cost off-peak hours. The need for fossil fuel–based "peaker" generators will also be reduced, and it will be easier to integrate renewable energy. Thermal inertia also can be aggregated and marketed as a flexibility service to electricity grids.

SMART OPERATION

25 Smart operation with seasonal thermal storage

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●○○○	●●●●	

WHAT Seasonal TES entails storing heat or cold when demand is low and then using it months later when demand is high. Possible storage systems include underground water tanks, underground aquifers, adiabatic compressed air and liquid air. Seasonal storage typically requires considerable planning and co-ordination between end-use demands and energy resources, and it is economically viable only when costs are low, given that the storage systems charge or discharge so infrequently.

WHY Seasonal storages make it possible to meet the seasonal heating or cooling demand with renewable energy sources produced months earlier. This can be especially valuable for meeting the expected increases in winter electricity demand amid the greater adoption of heat pumps in district heating networks, homes and other buildings. The electricity generation capacity of district heating systems is often determined based on the winter heat demand. Seasonal storage allows the system to operate with less generation capacity, lowering costs. For example, Sweden's Arlanda Airport uses seasonal aquifer storage to reduce the energy supply needed from the local district heating system by 10-15 GWh.

6
26 27

SMART OPERATION

26 Smart operation of industrial heating

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●○○	●●●●	

WHAT Industrial heating processes offer many opportunities to shift loads and add flexibility to power grids. Examples include ice storage in the food, beverage and dairy industries, which can release cooling when the demand at an industrial site is below the peak; this will reduce the electricity demand in the power system and enable industrial facilities to both use and produce energy as "prosumers". Similar approaches can be used for heating. To this end, transmission system operators (and, to a lesser degree, distribution system operators) need to co-ordinate with their major industrial clients to identify loads that could be shifted.

WHY Smart operation of industrial heating allows greater use of renewable energy to provide heating and cooling. It also increases the energy efficiency of industrial processes by utilising hot and cold streams that would otherwise have been wasted, and reduces the electricity demand and investments needed in grids.

SMART OPERATION

27 Combining heating and cooling demands in district systems

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●○○○	●●○○	

WHAT While most district energy networks have been created to supply heat, heat pumps make it possible to also meet cooling needs and create integrated networks that simultaneously supply heating and cooling to different end users, such as homes and data centres, increasing the overall network efficiency. In addition, combining heating and cooling with groundwater thermal storage allows heat pumps to cool the water while providing heat in winter. The cold water then provides free cooling in summer.

WHY Global cooling demand is growing due to climate change and higher air quality standards in efficient buildings. Integrating cooling in existing district heating networks will help meet that demand, while also making the networks more efficient and enabling greater integration of renewable energy. It further increases efficiency by enabling the integration of ambient energy and waste cold sources that would otherwise not be used, and has numerous advantages compared with individual distributed chillers – for example, lower costs in dense areas and greater flexibility.

6.4 Business models

Accelerating the electrification of power to heat and cooling will require new and innovative business models. Figure 6.11 shows eight important innovations that will enable smart coupling across sectors and provide new services and business models for both the power and the end-use sector. The innovations are described in detail in this section.

FIGURE 6.11 | Innovations in business models for power to heat and cooling

BUSINESS MODELS	**SERVICES FOR THE ENERGY SYSTEM**	• **28** Aggregators
		• **29** Distributed energy resources for heating and cooling demands
		• **30** Heating and cooling as a service
	WASTE HEAT RECOVERY MODELS	• **31** Waste heat recovery from data centres
		• **32** Eco-industrial parks and waste heat recovery from industrial processes
		• **33** Circular energy flows in cities – booster heat pumps
	ENERGY COMMUNITITES	• **34** Community-owned district heating and cooling
		• **35** Community-owned power-to-heat assets

Services for the energy system

SERVICES FOR THE ENERGY SYSTEM | **28 Aggregators**

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●●	●○○○	●●●●	

WHAT When grouped together, a sufficient number of small-scale consumers or producers of energy for heating or cooling can control both electricity consumption (in distributed heat pumps) or the use of distributed generation (from users' PV production) to lower costs, maximise efficiencies and provide valuable flexibility services to system operators. Aggregators thus create "virtual power plants" with a degree of market power akin to that of a conventional generator.

WHY The flexibility that individual heat pumps or rooftop solar arrays can provide is far too limited to have an impact on the grid. However, aggregating many units together creates a major source of flexibility that can be marketed to grid operators. For example, in Belgium, demand-response operations using 40 000 residential heat pumps can provide 100 MW of upward reserve at a cost of EUR 0-14/MWh, lower than the local historical price of EUR 32/MWh offered by conventional reserves (Georges *et al.*, 2017).

6
29 30

SERVICES FOR THE ENERGY SYSTEM

29 Distributed energy resources for heating and cooling demands

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●●	●●○○	●●●●	🏠 🏢 🏭

WHAT Distributed energy resources (DERs) include rooftop PV on individual homes and a variety of generation sources that can provide electricity to DHC systems anywhere along the DHC infrastructure, including rooftop PV and small-scale solar power plants. These distributed sources are especially suited for powering cooling loads, given the match between solar generation profiles and the timing of cooling demand, but heating loads can also be met by adding thermal storage. Net metering schemes would help accelerate the deployment of DERs.

WHY Across all segments, the on-site generation of renewable power can reduce energy costs and peak energy demand on the grid, while increasing revenues and flexibility.

SERVICES FOR THE ENERGY SYSTEM

30 Heating and cooling as a service

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●●○○	●●●○	🏠 🏢 🏭

WHAT Heating as a service (HaaS) and cooling as a service (CaaS) are business models in which service providers, rather than end users, own and operate users' heat pumps, boilers, chillers or other equipment. The providers charge fees for the services they offer, which can include heat and electricity or also cooling.

WHY Buying services instead of actual equipment lowers the financial risks for consumers by reducing or eliminating upfront costs for purchases and installation. It enables low-income families to make bulk energy purchases, reducing fuel poverty. It also reduces technical risks because service providers are responsible for maintenance. For suppliers, benefits include increased consumer loyalty, access to operational data to improve services, reduced environmental impacts, incentives to increase energy efficiencies and revenues from selling the services.

BOX 6.17 | Heating as a service (HaaS) in Denmark

Suntherm in Denmark offers a service that provides heat pumps in homes with no upfront costs. The company's cloud-based system remotely controls the heat pumps, optimising their operation based on heating needs, consumption patterns and weather forecasts. Suntherm provides all maintenance and repairs and can also connect solar PV. Consumers pay for the services in instalments over ten years.

Source: (Suntherm, 2021).

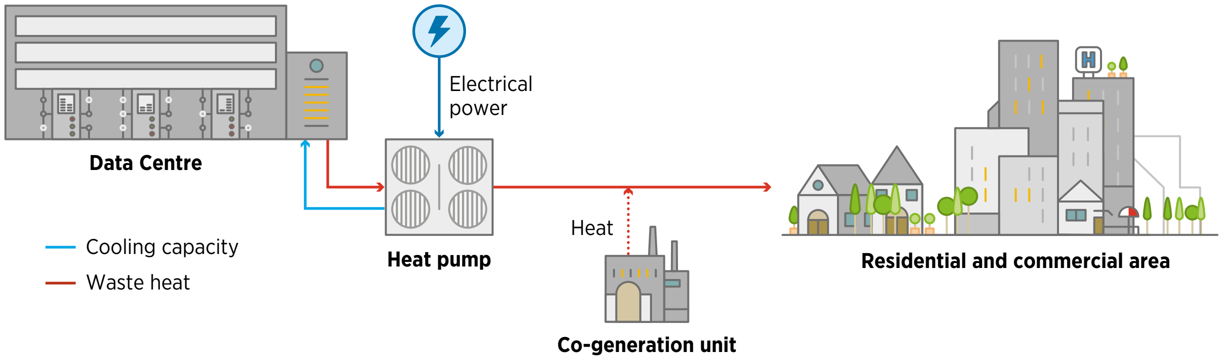
Waste heat recovery models

WASTE HEAT RECOVERY MODELS | **31 Waste heat recovery from data centres**

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●●	●●○○	●●●●	

WHAT One of the most rapidly growing sources of waste heat are data centres, whose use has increased by more than 250% over the last five years (IEA, 2022c). In Germany, for example, data centres now convert more than 13 TWh of electricity per year into heat, typically at temperatures of 25-40°C, most of which is wasted (Goethe Institut, 2020). This heat can be recovered and used as a valuable resource, especially in DHC networks. In addition, there are opportunities to store the larger amounts of waste heat that data centres produce in summer to provide heating in winter (Figure 6.12).

FIGURE 6.12 | **Layout of a waste heat recovery system**



WHY Recovery and use of the waste heat from data centres offer large economic and environmental gains. They reduce the data centres' electricity demand and enable valuable use of heat that would otherwise have been lost for heating homes and other buildings through district heating networks.

BOX 6.18a | Waste heat recovery from the Facebook data centre in Denmark

Facebook's data centre in Odense was located and designed to recover and donate up to 100 000 MWh of waste energy each year. It sends hot water to the city's district heating system, operated by Fjernvarme Fyn, where the water is mainly used for heating with radiators. The data centre is also powered with 100% renewable energy, mainly from a local wind project (Copenhagen Centre of Energy Efficiency, 2023).

BOX 6.18b | Waste heat recovery from a data centre in Tibet, China

In Lhasa, Tibet, a cooling system to utilise the waste heat from a data centre has been implemented to increase the data centre's energy efficiency. To achieve the recycling and reuse of clean energy, the waste heat is recycled to heat the aquaculture and agricultural facilities (Xiong, 2021).

WASTE HEAT RECOVERY MODELS

32 Eco-industrial parks and waste heat recovery from industrial processes

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●○○○	●●○○	

WHAT Eco-industrial parks are communities of businesses, located on a common property, that collaborate to enhance their combined environmental, economic and social performance. One business can use another's waste heat, for example, or peak energy demand can be lowered by leveraging synergies between the different electricity consumption profiles of different industrial processes.

WHY Eco-industrial parks offer win-win strategies for improving efficiency; lowering total energy consumption and costs; reducing peak loads; and providing other benefits through shared heat generation, waste heat recovery and other measures.

BOX 6.19 | Eco-industrial park in Denmark

The Kalundborg Symbiosis is a partnership between 12 public and private companies in Kalundborg, Denmark. Under the partnership, residues of one company become resources for others. For example, Novo Nordisk and Novozymes send their wastewater to a nearby treatment plant, leading to above-average wastewater temperatures. The heat is then used to increase the return water temperature in the district heating network from 55°C to 80°C with the help of a 10 MW heat pump facility, one of the largest in Denmark. The eco-industrial park is the first full realisation of industrial symbiosis created through private initiatives.

Source: (Kalundborg Symbiosis, 2022).

WASTE HEAT RECOVERY MODELS

33 Circular energy flows in cities – booster heat pumps

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●●	●○○○	●●●○	

WHAT Waste heat can be recovered from many sources other than data centres, including sewage water, solar panels, supermarkets, paper mills, industry, hospital chillers, mink coat storage and crematories. Heat can be recovered using thermal exchangers to be transferred to where it is needed, and booster heat pumps can be added to supply the specific temperatures required for each application, such as space heating or hot water in buildings.

WHY Waste heat can supply a significant share of cities' heating and cooling requirements. Utilisation of waste heat has many advantages, including reduction of waste energy and costs, revenue generation and increase of electrification through replacement of fossil fuel use with heat pumps in district heating networks. Cities that now recover heat from sewage water include Vancouver in Canada (SHARC Energy, 2020) and Cologne in Germany (Celsius, 2020).

Models to enable deployment of heating and cooling assets

ENERGY COMMUNITITES

34 Community-owned district heating and cooling

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●●○	●○○○	●●○○	🏢

WHAT DHC networks can be owned by communities in addition to the usual utility ownership model.

WHY Creating new community-owned or hybrid private-public DHC networks can accelerate the scale-up of district energy systems because these models allow all stakeholders to be more involved in building and managing DHC infrastructure. These new business models can make heating or cooling more affordable, reduce greenhouse gas emissions, speed up project development and provide more transparent connection costs and energy tariffs.

BOX 6.20 | Community-owned district heating utility in Denmark

The district heating utility Jaegerspris Kraftvarme in Denmark is 100% owned by consumers and organised as a private co-operative. As the only shareholders, consumers are involved in all major investment and strategic decisions. The investment costs are financed with long-term debt, with a municipal guarantee, and are recovered through heat sales. All profits are passed to consumers in the form of lower tariffs, following the not-for-profit principle in Denmark's Heat Supply Act, and tariffs are increased to cover deficits if any. The goal of this business model is to deliver services to consumers at the lowest price (European Commission Joint Research Centre, 2021)..

ENERGY COMMUNITITES

35 Community-owned power-to-heat assets

Innovation readiness level	Impact on electrification of end use	Impact on smart electrification	Relevant to
●●○○	●●○○	●●●●	🏠

WHAT Communities can own not only district heating systems (innovation #34 in Figure 6.12) but also large heat pumps, thermal storage or PV installations that serve many community residents. Each stakeholder owns a share of the assets and can participate in their management.

WHY Community ownership can increase access to thermal storage or renewable generation and reduce costs. It can thus reduce congestion on transmission and distribution lines, enable a community to recharge thermal storage using low-cost renewable energy, and help promote the adoption of smart electrification and new technologies for residential and commercial heating and cooling.

SECTION III

POWER TO HYDROGEN

CHAPTER 7

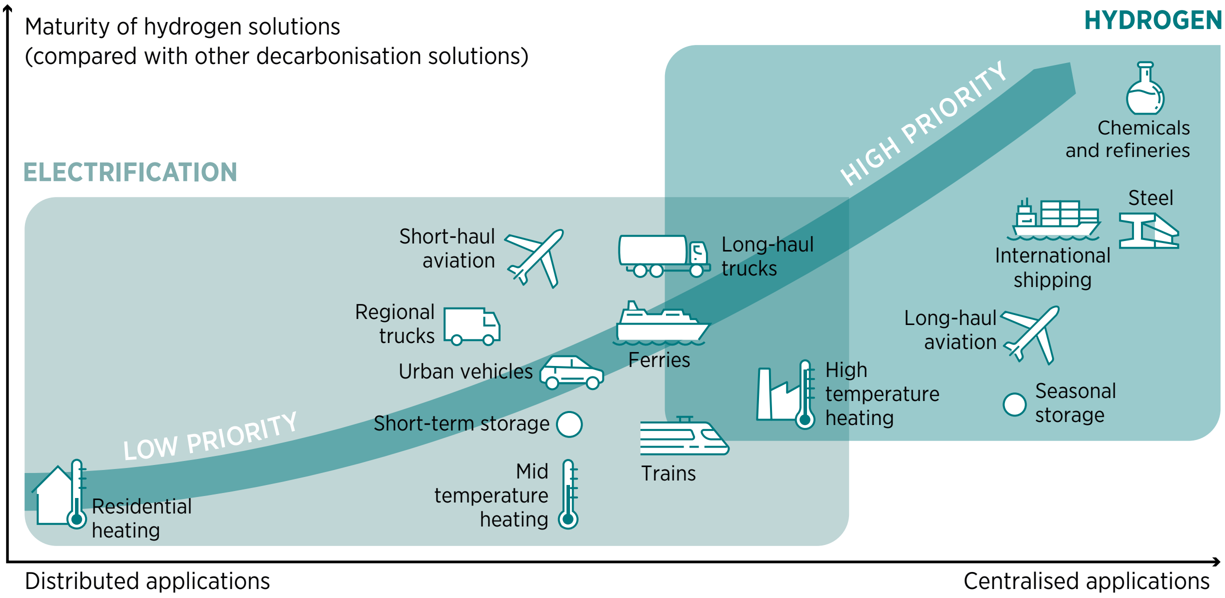
GREEN HYDROGEN

STATUS AND PACE OF PROGRESS

Direct electrification is difficult, if not impossible, in some end-use sectors, including steel-making, chemical production, long-haul aviation and maritime shipping. But there is a viable solution for decarbonising these end uses – "green" hydrogen and other fuels produced from renewable electricity (Figure 7.1) (IRENA, 2022e). IRENA's 1.5°C Scenario projects that by 2050, clean – green and blue – hydrogen production will grow to 523 million tonnes per year by 2050 (IRENA, 2023). Hydrogen can also serve as an excellent energy storage medium.

However, green hydrogen adoption remains low compared with required deployment levels, due to relatively high costs. In Europe, green hydrogen's average levelised cost is between USD 4.5/kg and USD 6/kg. In the United States, the *2022 Inflation Reduction Act* offers a USD 3/kg subsidy, which could bring the levelised cost of hydrogen down below USD 2/kg, making green hydrogen competitive.

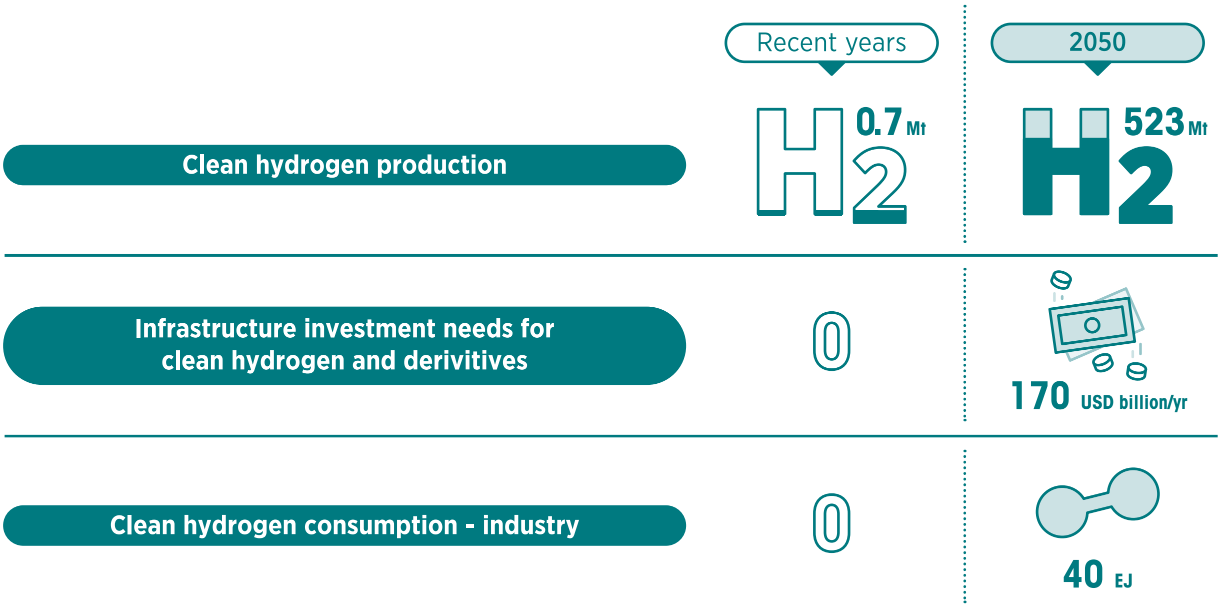
FIGURE 7.1 | End-use applications where clean hydrogen can be an effective alternative for deep decarbonisation: Clean hydrogen policy priorities



Source: (IRENA, 2022g).

In IRENA's 1.5°C Scenario (Figure 7.2), the production of green hydrogen and its derivatives must increase from today's negligible levels to 125 million tonnes of hydrogen (MtH_2)/year by 2030 and 523 MtH_2/year by 2050 (94% of global hydrogen production). Such a significant increase in production will require substantial investments in electrolysers and other technologies to produce, deliver and use green hydrogen fuels; IRENA's 1.5°C Scenario calls for investments of USD 170 billion/year through 2050.

FIGURE 7.2 | Green hydrogen production, investment and consumption in IRENA's 1.5°C Scenario



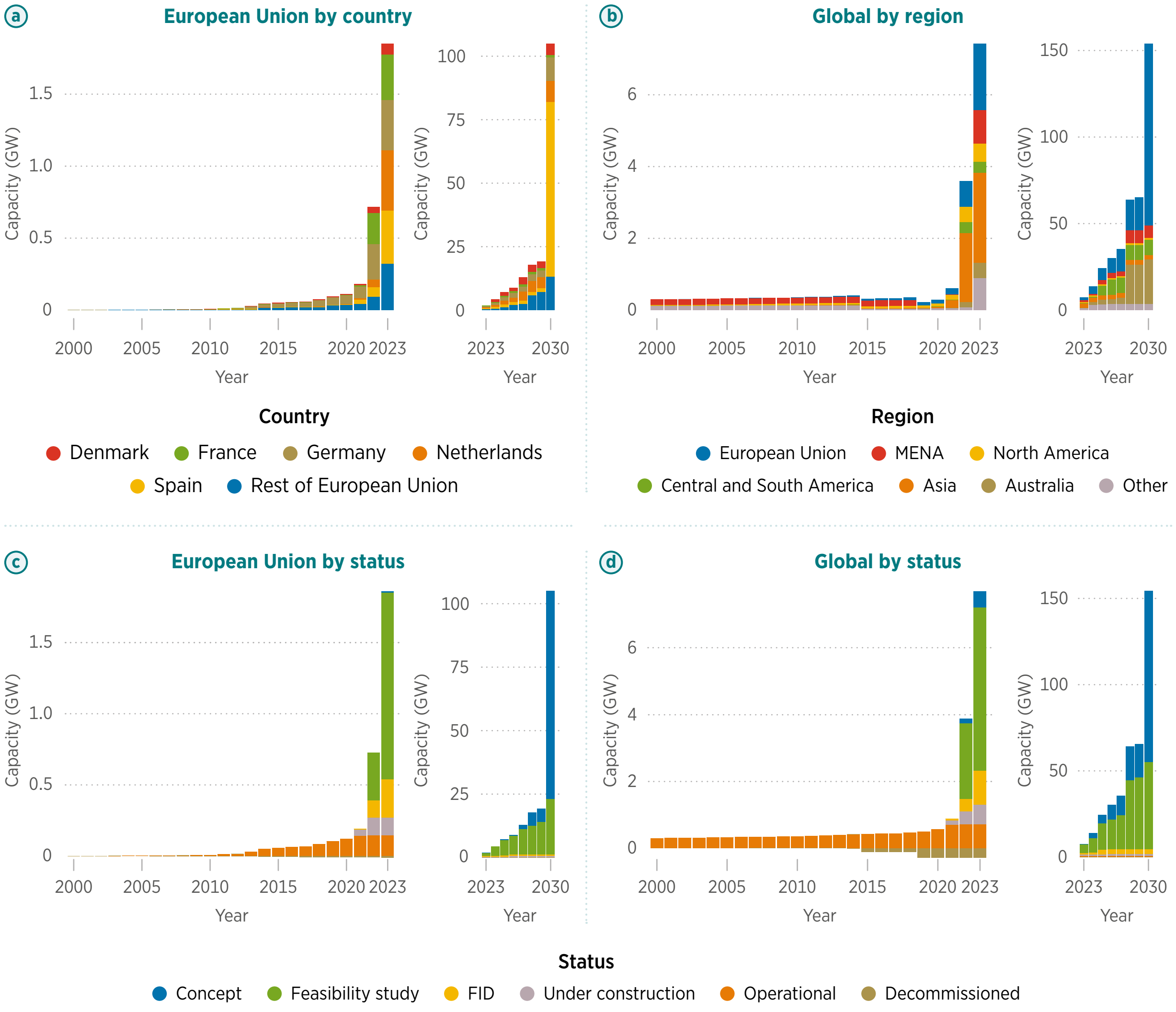
Source: (IRENA, 2023).
Notes: 316.67 Mt = 38 EJ. EJ = exajoule; Mt = million tonnes.

In IRENA's 1.5°C Scenario, by 2050, the industrial sector would use 40 EJ from clean hydrogen per year, particularly in chemicals, and iron and steel, while the transport sector would require 21 EJ from hydrogen and its derivatives (IRENA, 2023). Some of the hydrogen would be converted into chemical derivatives – such as ammonia, methane and methanol – and synthetic fuels, which are known as "Power-to-X" products. These hydrogen-based products can be directly used as transport fuels or chemical feedstocks, or for seasonal energy storage. Green hydrogen also supports the integration of renewables, offers long-term energy storage and can accelerate the growth of clean industries, such as steel in India, ammonia and fertilisers in Egypt and Trinidad and Tobago, or cement in Viet Nam and Indonesia (Cordonnier and Saygin, 2022).

To produce enough green hydrogen and derivatives to meet the climate goals outlined in the Paris Agreement, global electrolyser capacity must grow 6 000 to 8 000 fold from today's negligible 0.5 MW up to 350 GW in 2030 and roughly 5 000 GW in 2050 (Figure 7.3). However, while the number of recent project announcements suggests that capacities will increase exponentially in the coming years, final investment decisions have not yet been made for 80% of the announced capacity (Odenweller *et al.*, 2022). Nevertheless, more than 60 countries have developed, or are in the process of developing, national hydrogen strategies, and many emerging and developing countries have abundant low-cost renewable energy resources, which paves the way for competitive hydrogen markets (IRENA, 2022e). Using these resources to produce green hydrogen would enable these countries to reap major social and economic benefits, such as reduced dependence on imported fossil fuels, increased access to clean energy and creation of new export markets.

FIGURE 7.3 | Historical development and future announcements of electrolysis projects

Projects in the European Union by (a) country and (c) project development status;
Global projects by (b) aggregated region and (d) project development status



Source: (Odenweller *et al.*, 2022).

Notes: Each panel is divided into two parts. The main, left-hand part shows 2000-2023 data, while the smaller right-hand part with a separate axis shows 2023-2030 data. Projects without a specified starting date (accounting for 21 GW in the European Union and 127 GW globally) are omitted in all the panels. Panels a and b have figures corresponding to decommissioned projects omitted. FID = final investment decision; GW = gigawatt; MENA = Middle East and North Africa.

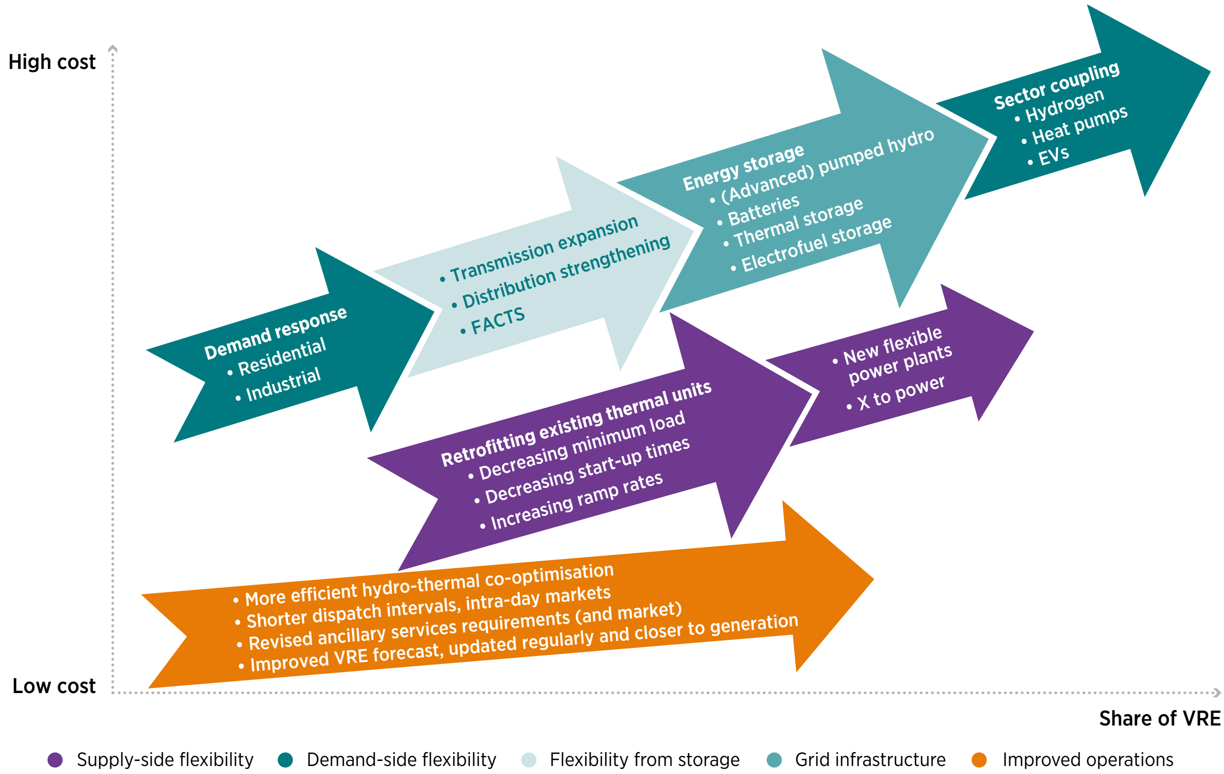
7.1 Importance of smart electrification in the development of green hydrogen

The use of green hydrogen is vital for decarbonising hard-to-abate sectors. How the hydrogen is produced also offers major benefits. For instance, smart and flexible operation of electrolysers (which break down water into hydrogen and oxygen) can provide a range of valuable services. Smart electrification of electrolysers can:

- harness synergies between hydrogen production and renewable generation by increasing production when generation is high and decreasing it when generation drops;
- provide balancing services to the power grid, and earn additional revenues for electrolysers;
- reduce congestion on transmission and distribution networks;
- reduce curtailment in renewable generation; and
- reduce peak loads on grids and peak demand from buildings or industries, especially when coupled with hydrogen storage and fuel cells.

However, hydrogen should be viewed as a last resort option for providing flexibility, given that there are several low-cost alternatives available (see Figure 7.4).

FIGURE 7.4 | Technical alternatives to increase system flexibility



Source: (IRENA, 2018).

Notes: EV = electric vehicle; FACTS = flexible alternating current transmission system; VRE = variable renewable energy.

7.2 Blind spots for policy makers

Realising the promise of green hydrogen requires significant progress across its entire value chain: from research and innovation actions to make green hydrogen competitive, rapidly scale up electrolyser manufacturing and build the infrastructure needed to produce, store and transport hydrogen and its derivates, to new business models that attract new actors, and market design and regulations that allow setting up an international reliable market.

Apart from these main challenges, the development of sound, smart and safe strategies for a green hydrogen economy must navigate some blind spots. The following points may help guide the way forward.

Matching supply and demand can reduce the uncertainties and risks of investing in the hydrogen value chain.

→ Given the uncertainties surrounding future demand for hydrogen, identifying stable demand sources will reduce the risks of building hydrogen production facilities. For example, industrial hubs already have a substantial fuel and feedstock demand, which could be met by hydrogen or its derivatives. The risk associated with investments in on-site electrolysers would therefore be relatively low.

Long-term signals and commitments are necessary to kick-start a clean hydrogen economy.

→ These can include national hydrogen road maps, adequate regulatory frameworks, streamlined permitting, carbon taxes or the removal of fossil fuel subsidies.

Regulatory sandboxes are critical for a new sector like green hydrogen.

→ Regulatory sandboxes allow new innovations to be tested in real-life projects under a regulator's oversight, enabling assessments of not only the technology itself but also of operations, business models and potential regulatory frameworks.

Power and hydrogen markets need to work together to encourage smart electrification and renewables' integration.

→ Creating a hydrogen market will require greater integration and co-operation among gas and power transmission system operators, which needs to begin at a very early stage. A successful green hydrogen strategy requires joint development of strategies for electricity and gas systems, which have historically worked in silos.

Internationally harmonised technical standards and certificates are among the main pillars of the future hydrogen economy.

→ Codes and standards for the construction, operation and maintenance of hydrogen facilities must be developed and implemented internationally. In addition, hydrogen sources must be certified to validate claimed carbon dioxide emissions reductions and allow appropriate renumeration.

Electrolysers will require additional renewable generation capacity, beyond the surplus generation that would otherwise have been curtailed.

→ Electrolysers must be operated for at least 4 000 hours per year to be cost competitive (Ansari *et al.*, 2022). They will thus require diversified renewable generation resources and a well-connected network. One promising approach is combining off-grid electrolysers with PV generators to avoid the expense and complexity of grid connections (Bellini, 2020).

Green hydrogen production requires water resources.

→ Hydrogen requires significant amounts of (pure) water as a feedstock. The electrolysis process uses 9 m^3 (9 000 litres) of purified water to produce a tonne of hydrogen (Collins, 2021). As the effects of climate change continue to exacerbate water stress, a growing number of countries may need to consider whether hydrogen production is suitable in the longer term. However, the projected green hydrogen needed by 2050 in IRENA's 1.5°C Scenario would require around 7-9 billion m^3 of water a year – less than 0.25% of current freshwater consumption (IRENA, 2022e). Regions with water scarcity could increase their water supplies using desalination where economically feasible.

Measures are required to detect and prevent hydrogen leakage.

→ By 2050, green hydrogen production, transportation and storage are expected to become major sources of leakage. Under high-risk scenarios by 2050, leakage rates could represent 5.6%[14] of the hydrogen economy (Fan *et al.*, 2022). Data-driven research and monitoring initiative programmes on hydrogen leakage detection, prevention and mitigation are essential to avoid leakages in a large-scale hydrogen economy.

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[14] *The quantification of leakage rates is subject to uncertainty because of the lack of direct measurement. In many cases, hydrogen leakages are based on the proportion of hydrogen contained in the amount of methane leaked. In other cases, leaked rates are identified in electrolysers and hydrogen refueling stations that are not yet fully commercial which means that their associated leakage rates are expected to decrease as design and operation standardisation take place.*

CHAPTER 8

TOOLBOX FOR SMART GREEN HYDROGEN PRODUCTION

The design of an optimal green hydrogen production strategy is influenced by how the hydrogen will be produced and used, and the energy system's attributes.

This report identifies 30 innovations that can accelerate the indirect electrification of hard-to-decarbonise sectors through the production and use of green hydrogen and its derivatives (Table 8.1). These innovations (described in more detail in Chapter 9) are grouped under four main categories: new electrolyser technologies, smart market designs, improved systems and planning, and new business models.

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TABLE 8.1 | Innovation toolbox for smart electrification of the hydrogen sector

TECHNOLOGY AND INFRASTRUCTURE

Electrolyser technology

- **1** Pressurised ALK electrolyser
- **2** PEM electrolyser
- **3** SOEC electrolyser
- **4** AEM electrolyser

Hydrogen infrastructure

- **5** Compressed hydrogen storage
- **6** Liquefied hydrogen storage
- **7** Hydrogen-ready equipment

Digital technologies

- **8** Digital backbone for green hydrogen production
- **9** Hydrogen leakage detection

MARKET DESIGN AND REGULATION

Power market

- **10** Additionality principle
- **11** Renewable PPAs for green hydrogen
- **12** Cost-reflective electricity tariffs
- **13** Electrolysers as grid service providers

Hydrogen market

- **14** Certificates
- **15** Hydrogen purchase agreements
- **16** Carbon contracts for difference

Standard and regulations

- **17** Regulatory framework for hydrogen network
- **18** Streamlining permitting for electrolyser projects
- **19** Quality infrastructure for green hydrogen
- **20** Regulatory sandboxes

SYSTEM PLANNING AND OPERATION

Strategic planning

- **21** Electricity TSOs, including grid-connected hydrogen facilities in their planning
- **22** Co-locating electrolysers with renewable generators (onshore and offshore)

Smart operation

- **23** Smart hydrogen storage operation and P2P routes
- **24** Long-term hydrogen storage
- **25** Co-operation between electricity and gas operators

BUSINESS MODELS

Primary revenue streams

- **26** Local hydrogen demand
- **27** Hydrogen trade
- **28** Hydrogen industrial hub

Stacking other revenue streams

- **29** Revenues from providing services to the power system
- **30** Sale of electrolysis by-products (oxygen and heat)

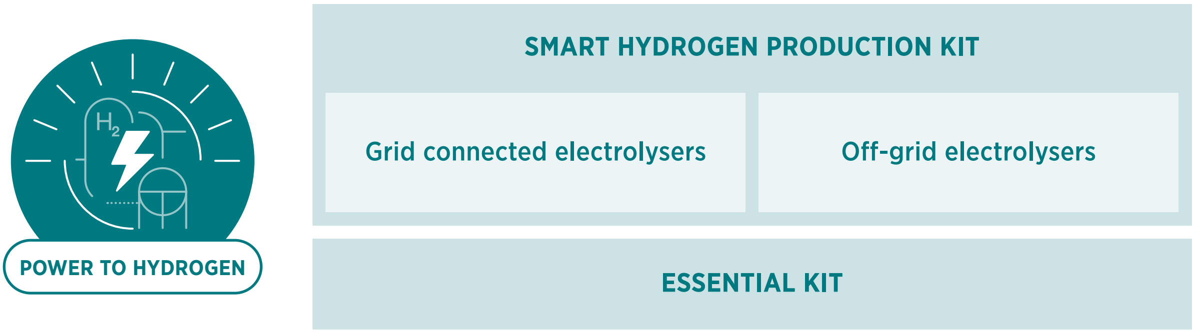
Notes: AEM = anion exchange membrane; ALK = alkaline; PEM = polymer electrolyte membrane; P2P: power-to-power; PPA = power purchase agreement; SOEC = solid oxide electrolyser cell; TSO = transmission system operator.

8.1 Guidelines for implementation

Effective smart electrification strategies will result from the synergies of innovations in technology, markets and regulation, business models, and system planning and operation. In general, these strategies add flexibility to the system and facilitate the integration of larger shares of renewable generation, resulting in "greener" hydrogen production.

To guide policy makers in formulating smart electrification strategies for their own contexts, the following advanced hydrogen economy toolbox is proposed, featuring three individual toolkits.

FIGURE 8.1 | Implementation of smart electrification strategies for hydrogen economies



Essential kit

The innovations in the essential kit lay the groundwork for a hydrogen economy. This kit focuses on technological innovations (*e.g.,* electrolyser technologies) and regulations supporting hydrogen uptake (see Table 8.2).

TABLE 8.2 | The essential kit for smart hydrogen production

ESSENTIAL KIT

TECHNOLOGY AND INFRASTRUCTURE

- **1** Pressurised ALK electrolyser
- **2** PEM electrolyser
- **3** SOEC electrolyser
- **4** AEM electrolyser
- **5** Compressed hydrogen storage
- **6** Liquefied hydrogen storage
- **7** Hydrogen-ready equipment

MARKET DESIGN AND REGULATION

- **14** Certificates
- **15** Hydrogen purchase agreement scheme
- **16** Carbon contracts for difference
- **18** Streamlining permitting for electrolyser projects
- **19** Quality infrastructure for green hydrogen
- **20** Regulatory sandboxes

BUSINESS MODELS

- **27** Hydrogen trade
- **30** Sale of electrolysis by-products (oxygen and heat)

Notes: AEM = anion exchange membrane; ALK = alkaline; PEM = polymer electrolyte membrane; SOEC = solid oxide electrolyser cell.

Smart hydrogen production kit

The smart hydrogen production kit builds on the essential kit to ensure the smart operation of both grid-connected (Table 8.3) and off-grid electrolysers (Table 8.4). For example, the innovations in the smart hydrogen production kit ensure that the power sector sends the right signals for smart electrolyser operation and market creation, and that planning for electrolyser locations accounts for the impacts of new demand on electricity generation and transmission, and assesses the potential use of hydrogen storage.

TABLE 8.3 | Smart hydrogen production kit for grid-connected electrolysers

SMART HYDROGEN PRODUCTION KIT			
GRID-CONNECTED ELECTROLYSERS			
TECHNOLOGY AND INFRASTRUCTURE	**MARKET DESIGN AND REGULATION**	**SYSTEM PLANNING AND OPERATION**	**BUSINESS MODELS**
• **8** Digital backbone for green hydrogen production	• **10** Additionality principle • **11** Renewable PPAs for green hydrogen • **12** Cost-reflective electricity tariffs • **13** Electrolysers as grid service providers • **17** Regulatory framework for a hydrogen network	• **21** Electricity grid-connected TSOs include hydrogen facilities in their planning • **22** Co-locating electrolysers with renewable generators (onshore) • **23** Smart hydrogen storage operation and P2P routes • **24** Long-term hydrogen storage • **25** Co-operation between electricity and gas operators	• **26** Local hydrogen demand • **29** Revenues from providing services to the power system

Notes: P2P = power to power; PPA = power purchase agreement; TSO = transmission system operator.

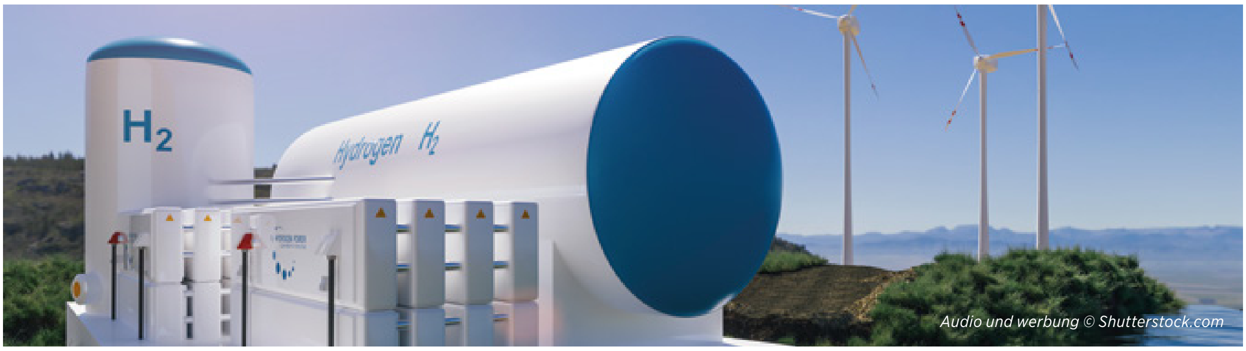


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TABLE 8.4 | **Smart hydrogen production kit for off-grid electrolysers**

SMART HYDROGEN PRODUCTION KIT		
OFF-GRID ELECTROLYSERS		
MARKET DESIGN AND REGULATION	**SYSTEM PLANNING AND OPERATION**	**BUSINESS MODELS**
• **11** Renewable PPAs for green hydrogen	• **22** Co-locating electrolysers with renewable generators (onshore and offshore) • **24** Long-term hydrogen storage	• **28** Hydrogen industrial hub

Note: PPA = power purchase agreement.

8.2 Case studies

Power to Hydrogen – Orkney Islands hydrogen research and development platform in Scotland, United Kingdom

The Orkney Islands, off the north coast of Scotland, are clean energy pioneers. They have adopted a "learning by doing" approach and invested heavily in renewable generation based on abundant renewable resources, such as wind and tidal energy. Since 2013, renewables have supplied more than 100% of the islands' electricity demand.

In fact, the islands have so much wind generation capacity that they often need to shut down wind turbines because there are no transmission lines to the mainland. Part of that capacity is therefore wasted. This has prompted the islands to explore the production of hydrogen using local-grid-connected electrolysers so that surplus renewable power can be used and stored. The objective is to test hydrogen-ready technologies and assess where hydrogen can provide the best solutions in a net zero economy.

TABLE 8.5 | **Smart electrification strategy for the Orkney Islands' hydrogen R&D platform**

TECHNOLOGY AND INFRASTRUCTURE	SYSTEM PLANNING AND OPERATION	BUSINESS MODELS
ESSENTIAL KIT		
2 PEM electrolyser **5** Compressed hydrogen storage		**26** Local hydrogen demand
SMART OPERATION STRATEGY: GRID-CONNECTED ELECTROLYSER		
8 Digital backbone for green hydrogen production	**22** Co-locating electrolysers with renewable generators (onshore and offshore) **23** Smart hydrogen storage operation and P2P routes	

Notes: P2P = power-to-power; PEM = polymer electrolyte membrane.

Table 8.5 lists the innovations included in the project. As part of one project on the island of Eday, the European Marine Energy Centre has integrated a 670 kW PEM electrolyser with hydrogen storage, batteries, and wind and tidal energy generation. The system operates by first using the tidal power and onshore wind power that would otherwise be curtailed to charge the battery system. The battery then provides stable power supply to the electrolyser.

The hydrogen produced by the system is stored and transported on ferries to Kirkwall on the Orkney mainland, where it powers harbour and ferry operations (in part through conversion of the hydrogen back into electricity with a 75-kW fuel cell), along with hydrogen vehicles. Aside from the above, a hydrogen-powered combined heat and power facility is being commissioned at Kirkwall Airport to provide heat and power to the terminal building, and a demonstration project has created synthetic aviation gasoline from hydrogen (EMEC, 2022).

CHAPTER 9

THE INNOVATION LANDSCAPE FOR SMART HYDROGEN PRODUCTION

This chapter discusses 30 innovations for the smart production of hydrogen by answering two main questions for each innovation:

WHAT **What** is the innovation about?

WHY **Why** is the innovation important for smart electrification?

As in the other chapters, we have used a set of icons – outlined in Table 9.1 – to describe each innovation's readiness level, and its impact on the electrification of end uses and on smart electrification strategies. Table 9.2 then provides an overview of the innovations' status and impacts.

TABLE 9.1 | Indicators quantifying the impact of key innovations on end-use sectors' electrification strategies

INNOVATION READINESS LEVEL		IMPACT ON			
		Electrification of end-use sector		**Smart electrification**	
●○○○	Innovation is at an early stage, with few demonstration projects	●○○○	Low	●○○○	Low
●●○○	Innovation is in early commercialisation stage, with a few pilot projects	●●○○	Medium	●●○○	Medium
●●●○	Innovation is implemented already in a few countries	●●●○	High	●●●○	High
●●●●	Innovation is mature and largely deployed in some regions	●●●●	Very high	●●●●	Very high

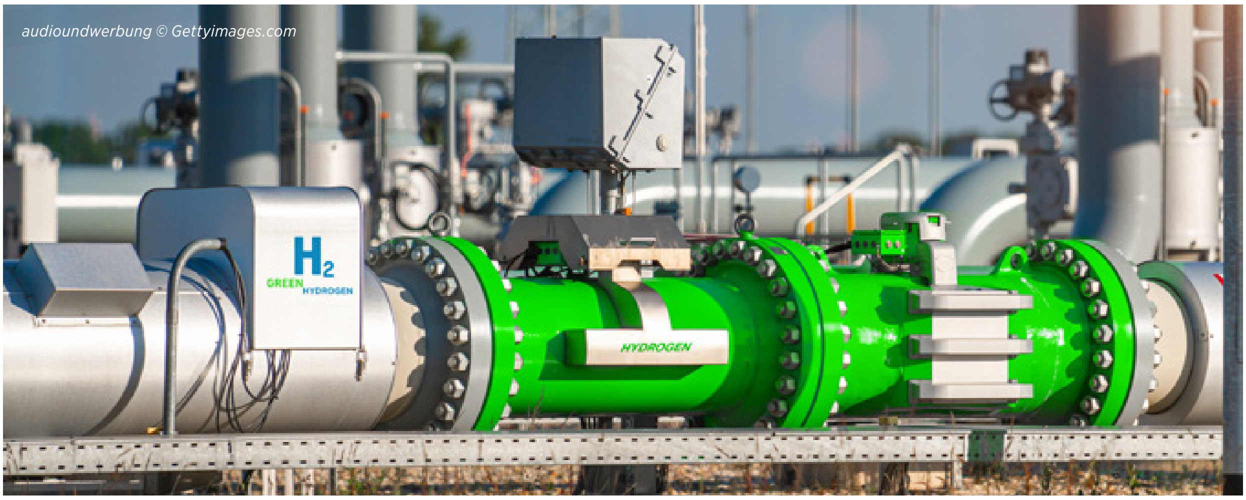
TABLE 9.2 | Overview of the status and impact of innovations in the smart production of green hydrogen

Dimension	category	Innovation	Innovation readiness level	Impact on electrification of end uses	Smart electrification
TECHNOLOGY AND INFRASTRUCTURE	ELECTROLYSER TECHNOLOGY	**1** Pressurised alkaline electrolysers	●●○○	●●●●	●●●○
		2 Polymer electrolyte membrane electrolysers	●●○○	●●●●	●●●○
		3 Solid oxide electrolyser cells electrolysers	●○○○	●●●●	●○○○
		4 Anion exchange membrane electrolyser	●○○○	●●●●	●●●○
	HYDROGEN INFRASTRUCTURE	**5** Compressed hydrogen storage	●●●○	●●●○	●●●●
		6 Liquefied hydrogen storage	●●○○	●●●○	●●●●
		7 Hydrogen-ready equipment	●●●○	●●●○	●○○○
	DIGITAL TECHNOLOGIES	**8** Digital backbone for green hydrogen production	●●●○	●○○○	●●●●
		9 Hydrogen leakage detection	●○○○	●●●●	●○○○
MARKET DESIGN AND REGULATION	ELECTRICITY MARKET DESIGN	**10** Additionality principle	●○○○	●○○○	●●●●
		11 Renewable power purchase agreement for green hydrogen	●●●○	●○○○	●●●○
		12 Cost-reflective electricity tariffs	●●●○	●○○○	●●○○
		13 Electrolysers as grid service providers	●●○○	●○○○	●●●●
	HYDROGEN MARKET	**14** Certificates	●●○○	●●●○	●●●○
		15 Hydrogen purchase agreement scheme	●○○○	●●●●	●●○○
		16 Carbon contract for difference	●○○○	●●●●	●●○○
	STANDARDS AND REGULATION	**17** Regulatory framework for a hydrogen network	●○○○	●●●●	●○○○
		18 Streamlining permitting for hydrogen projects	●●○○	●●●●	●○○○
		19 Quality infrastructure for green hydrogen	●○○○	●●●●	●●●○
		20 Regulatory sandboxes	●●●○	●●●●	●●●○

●●●● Very high ●●●○ High ●●○○ Medium ●○○○ Low

Dimension	category	Innovation	Innovation readiness level	Impact on electrification of end uses	Smart electrification
SYSTEM PLANNING AND OPERATION	**STRATEGIC PLANNING**	**21** Electricity transmission system operators including hydrogen facilities in their planning	●○○○	●●○○	●●●●
		22 Co-locating electrolysers with renewable generators (onshore and offshore)	●●○○	●●●○	●●●○
	SMART OPERATION	**23** Smart hydrogen storage operation and power-to-power routes	●○○○	●○○○	●●●●
		24 Long-term hydrogen storage	●○○○	●○○○	●●●●
		25 Co-operation between electricity and gas operators	●○○○	●●○○	●●●○
BUSINESS MODELS	**PRIMARY REVENUE STREAM**	**26** Local hydrogen demand	●●○○	●●●○	●○○○
		27 Hydrogen trade	●○○○	●●●●	●○○○
		28 Hydrogen industrial hub	●○○○	●●●○	●●○○
	STACKING OTHER REVENUE STREAMS	**29** Revenues from flexibility provided to the power system	●○○○	●○○○	●●●○
		30 Sale of electrolysis by-products (oxygen and heat)	●●○○	●●○○	●○○○

●●●● Very high   ●●●○ High   ●●○○ Medium   ●○○○ Low



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9.1 Technology and infrastructure

Innovations in technology and infrastructure are essential first steps for lowering hydrogen production, storage and transport costs; developing a hydrogen market; and facilitating the smart electrification of end-use sectors with hydrogen and renewable energy. In this context, Figure 9.1 shows nine key innovations grouped into three main categories: electrolyser technology, hydrogen infrastructure (including storage and transport) and digital technologies.

FIGURE 9.1 | **Innovations in technology and infrastructure for power to hydrogen**

TECHNOLOGY AND INFRASTRUCTURE	**ELECTROLYSER TECHNOLOGY**	**1** Pressurised ALK electrolyser
		2 PEM electrolyser
		3 SOEC electrolyser
		4 AEM electolyser
	THERMAL ENERGY STORAGE	**5** Compressed hydrogen storage
		6 Liquefied hydrogen storage
		7 Hydrogen-ready equipment
	DIGITAL TECHNOLOGIES	**8** Digital backbone for green hydrogen production
		9 Hydrogen leakage detection

Notes: AEM = anion exchange membrane; ALK = alkaline; PEM = polymer electrolyte membrane; SOEC = solid oxide electrolyser cell.

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Electrolyser technology

There are four main types of electrolysers: alkaline (ALK), polymer electrolyte membrane (PEM), solid oxide electrolyser cell (SOEC) and anion exchange membrane (AEM). Table 9.3 shows the primary attributes of each type of electrolyser and its development status. The next sections describe the four innovations in more detail, along with their advantages and disadvantages.

TABLE 9.3 | Water electrolysis technologies as of today

	Electrolyser technology	Alkaline	PEM	SOEC	AEM
Technology parameters	**Development status**	Commercial	Commercial	Demonstration	Under research
	Operating temperature (°C)	70-90	50-80	700-850	40-60
	Cell pressure (bar)	< 30	≤ 40	1	< 35
	Voltage efficiency (LHV) (%)	50-68	50-68	75-85	52-67
	Electrical efficiency (system) (kWh/kgH2)	50-78	50-83	40-50	57-69
	Lifetime (stack) (hour)	60 000	50 000-80 000	20 000	5 000
Flexibility	**Load range (%)**	15-100	0-160	20-125	5-100
	Start-up	1-10 min	1 sec to 5 min	< 60 min	
	Ramp up/down	0.2-20% per second	100% per second	A system response time of a few seconds	
	Shutdown	1-10 min	Seconds	Not available	
Cost parameters	**Capital cost (stack) for a minimum 1 MW system (USD/kWel)**	270	400	613-2 000	
	Capital cost (system) for a minimum 10 MW system (USD/kWel)	500-1 000	700-1 400		

Source: (IRENA, 2020c, 2021a; ENTSO-E, 2022b).

Notes: System-level cost data are not available for SOEC and AEM electrolysers, since many of their components are still at a lab scale, and only a few companies are pursuing commercialisation. Load range is the fraction of the full load at which an electrolyser operates. The majority of the equipment has a design factor (an additional 10-20%) that allows the equipment to be run at higher capacity, at the expense of efficiency and lifetime. AEM = anion exchange membrane; kW_e = kilowatt electric; kWh/kgH_2 = kilowatt hours per kilogramme of hydrogen; LHV = lower heating value; MW = megawatt; PEM = polymer electrolyte membrane; SOEC = solid oxide electrolyser cell.

ELECTROLYSER TECHNOLOGY

1 Pressurised alkaline electrolysers

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●●○○	●●●●	●●●○

WHAT ALK electrolysers are the most mature technology and are already at the commercial stage. They have a simple stack system design and are relatively easy to manufacture. Their capital costs are lower than those of other electrolyser technologies (see Table 9.3). While ALK electrolysers can operate at either atmospheric pressures or high pressures (up to 30 bar), high-pressure electrolysers can be ramped up and down much faster (in less than a minute) than those operating at atmospheric pressure, which take several minutes to ramp up or down. High-pressure ALKs are therefore better at following fluctuations in wind and solar generation.

WHY Given that pressurised ALK electrolysers can rapidly follow fluctuations in wind and solar production, its smart integration would facilitate the integration of variable renewable sources. ALK electrolysers also have lower investment costs than other technologies, and have been certified to provide primary reserves to the power system (IRENA, 2020c).

ELECTROLYSER TECHNOLOGY

2 Polymer electrolyte membrane electrolysers

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●●○○	●●●●	●●●○

WHAT PEM electrolysers use cells with a solid polymer electrolyte. The cells typically operate at temperatures between 50°C and 80°C and at pressures between 20 and 40 bar. The benefit of PEM electrolysers lies in their more compact and simple system design, compared with ALK electrolysers, and their ability to function with higher current densities, allowing a smaller carbon footprint. They can also be ramped up and down (and completely stopped and started up) much faster than even pressurised ALK electrolysers (see Table 9.3). However, PEM electrolysers do require titanium-based materials, noble metal catalysts and protective coatings because of their harsh oxidative environment and high voltages. They are thus more expensive than ALK electrolysers (Table 9.3). Research efforts are now focusing on reducing the use of noble materials, such as iridium, to lower the costs of PEM electrolysers. The objective is to reduce the capital costs of a minimum 10 MW system from about USD 700-1 400/kW in 2020, to less than USD 200/kW by 2050.

WHY PEM electrolysers can ramp up or down in seconds, providing tremendous flexibility to power systems. This facilitates greater integration of renewable generation, increases the power grid’s resilience and allows the electrolysers to receive additional revenues from providing grid-balancing services – thus improving the overall economics of a PEM electrolyser facility.

ELECTROLYSER TECHNOLOGY

3 Solid oxide electrolyser cell electrolysers

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●○○○	●●●●	●○○○

WHAT SOEC electrolysers operate at very high temperatures (700-850°C) at atmospheric pressure. Using heat energy as well as electricity, they split water into hydrogen and oxygen. The high temperatures increase the overall electrical efficiency of SOEC electrolysers and enable the use of non-precious metals as catalysts. SOEC electrolysers can also electrolyse carbon dioxide (CO_2) to carbon monoxide (CO) and oxygen. The CO can then be used to produce syngas, a basic building block for the chemical industry. SOEC electrolysers can also be operated in reverse, producing electricity like fuel cells. This functionality increases their hours of operation and keeps them at operating temperature for longer periods. Most current SOEC electrolysers are small, kilowatt-scale demonstration plants, although some projects have already exceeded 1 MW capacity (Neste, 2021). SOEC electrolysers have high capital costs (at more than USD 2 000/kW for 1 MW stacks), although the target for 2050 is to reduce this to less than USD 200/kW.

WHY Considering that SOEC electrolysers are much less flexible than other electrolyser technologies, they are less suited to direct coupling with variable renewable energy production. However, they do have important advantages. Their use of heat in addition to electricity raises their electrical efficiency. Thus, SOEC electrolysers would bring about a significant reduction in overall electricity demand compared with any other electrolyser technology (IRENA, 2020c). In addition, the heat that they require could be supplied by sources such as industrial waste heat streams or concentrated solar power (CSP) plants. This would facilitate the coupling of SOEC electrolysers to heat production technologies. SOEC electrolysers also enable the production of syngas as well as hydrogen, and the potential for reversable operation increases their lifetimes.

THINK A © Shutterstock.com

ELECTROLYSER TECHNOLOGY

4 Anion exchange membrane electrolysers

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●○○○	●●●●	●●●○

WHAT AEM electrolysers are based on the same chemical reaction as ALK electrolysers and use the same materials. The differences are that AEM electrolysers use a polymer membrane, which allows anions but not photons to cross, and they have a simpler, more compact design. Thus, AEM electrolysers do not require noble catalysts or titanium (like PEM electrolysers) and can be used in smaller-scale projects than ALK electrolysers. This makes AEM electrolysers the only modular variety. Nevertheless, further innovation is needed to overcome the primary issues with AEM electrolysers, such as the fact that complex and unstable polymer chemistry, performance inefficiencies and instabilities that can shorten lifetimes. Improvements are also required to increase their power range. The technology is still at an early stage, so current costs are unknown.

WHY AEM electrolysers combine the less harsh conditions of ALK electrolysers (and the resulting lack of requirement for expensive materials) with the simplicity and efficiency of a PEM electrolyser. As a result, they have a considerable potential cost advantage over PEM electrolysers, while also offering a high degree of flexibility and short response times, thus enabling greater integration of renewable generation sources.

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Hydrogen infrastructure

HYDROGEN INFRASTRUCTURE

5 Compressed hydrogen storage

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●●●○	●●●○	●●●●

WHAT Compressed hydrogen is a storage form whereby hydrogen gas is kept under pressure to increase the storage density. It is the most widely used hydrogen storage option. It is based on a well-established technology that offers high rates of charge and discharge. However, because of hydrogen's low volumetric value – three times less than methane under standard conditions – the high-pressure requirements (350-700 bar) leave roughly 15% of the hydrogen energy content to be consumed. Compressed hydrogen can be stored in cylindrical vessels made with materials that resist diffusion and embrittlement (see Box 9.1 for example projects). In addition, purified and compressed gaseous hydrogen can be stored in underground salt caverns (Vattenfall, 2022).

WHY The ability to store and transport hydrogen decouples its production from its supply and use. Storage is crucial for securing supply for end users, such as industry clusters, and for the creation of a global hydrogen market (see Box 9.1 for an example from Norway). Storage also adds flexibility to renewable power generation, beyond that provided by electrolysers, since it allows short- and long-term storage of hydrogen (over entire seasons) produced during periods of high renewable power levels for use when renewable generation and hydrogen production are low. In the long term, large-scale hydrogen storage facilities must be in place to realise the full value of the green hydrogen economy.

BOX 9.1 | Examples of compressed hydrogen storage projects

The Los Angeles Department of Power and Water's Intermountain Power Project (United States) plans to replace coal as the fuel for a 1800 MW power plant in Delta, Utah, first with natural gas and then with a mix of gas and green hydrogen, with the share of hydrogen increasing to 100% by 2045. The plant has access to abundant wind and solar power, and any surplus hydrogen produced by on-site electrolysers will be stored in a large geologic salt dome under the plant for use later (even a whole season later) when electricity demand is high. The repowered plant is expected to enter operation in 2025 and begin burning a mixture with 30% green hydrogen in 2026 (Maloney, 2019; Los Angeles Department of Water & Power, 2020).

The Green Hydrogen Hub (Denmark) intends to be the first project using large salt caverns to couple large-scale green hydrogen production with both underground hydrogen storage and compressed air energy storage. By 2030, the project expects to have an installed electrolyser capacity of 1 GW, 400 GWh of hydrogen storage and a 320 MW compressed air energy storage plant (Green Hydrogen Hub, 2022).

The Deep Purple Project (Norway) combines offshore wind turbines, offshore electrolyser units and storage tanks on the seabed for storing pressurised green hydrogen (Lee, 2019).

The Hypster Project (France) aims to store hydrogen in salt caverns for use in industry and transportation. The project, which was launched in 2021, uses a 1 MW electrolyser to produce 400 kg of hydrogen per day and will initially be able to store 3 tonnes of hydrogen for several months or years in underground caverns. The project will help determine the cost of hydrogen storage, the quality of hydrogen extracted from caverns and the role and importance of underground storage in the hydrogen ecosystem (Hypster Project, 2020).

HYDROGEN INFRASTRUCTURE

6 Liquefied hydrogen storage

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●●○○	●●●○	●●●●

WHAT An alternative to compressed hydrogen storage is storing liquefied hydrogen or converting to hydrogen carriers. Conversions require additional energy, however, and some forms (ammonia and liquid hydrogen) require continuous cooling. Promising storage or transport options include:

- Liquefying hydrogen by cooling it to cryogenic temperatures (below -252.8°C) and storing or transporting it in tanks or other containers.
- Converting hydrogen into liquid ammonia, which has greater density than hydrogen, and can thus be easier to store or transport in containers.
- Converting hydrogen into organic liquids or semi-solids called liquid organic hydrogen carriers (LOHCs), which are particularly useful for transporting hydrogen over long distances.

Liquefied hydrogen storage has a much higher density compared to compressed hydrogen storage. This higher density also increases the volumetric energy density. Liquefied storage needs to be kept at temperatures below -252.8°C. It is estimated that 30-40% of the hydrogen energy content is used for the liquefication process (compared to 15% in the case of compressed gas storage). In addition, the low temperatures needed to store and transport hydrogen require that all related mechanical elements such as valves or tanks resist hydrogen embrittlement. Ships transporting liquefied hydrogen storage either assume significant levels of evaporation due to the cold and lightness of the fluid or improve the insulation of the load or even invest in complex cryogenic systems.

As an alternative to liquefied hydrogen storage and transport, LOHCs, such as benzyl toluene, can help reduce the technical requirements described above. Last, hydrogen derivatives (e-methane or e-methanol) represent alternatives to transport hydrogen to consumption hubs. Ammonia is an even cheaper option (Liebreich, 2022; Usman, 2022).

WHY The ability to store and transport hydrogen offers flexibility to the energy system and allows supply to be connected to demand. The location of supply and demand centres will determine the suitability of liquefied hydrogen storage. Liquefied hydrogen via ammonia or LOHCs is easier to store in large quantities and transport over long distances than electricity. Therefore, these two options are suitable for international hydrogen trade.

HYDROGEN INFRASTRUCTURE

⑦ Hydrogen-ready equipment

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●●●○	●●●○	●○○○

WHAT Hydrogen-ready equipment refers to energy-related infrastructure that can cope with hydrogen, such as meters, junctions, recompressing facilities and pipelines. Liquefied natural gas (LNG) terminals are good examples of infrastructure ready to host or become green hydrogen hubs. The existing infrastructure cannot cope with pure hydrogen due to the tiny size of hydrogen molecules (in the case of storage tanks), and its potential embrittlement capacity that weakens metal structures and causes leaks. However, LNG terminals can move hydrogen in the form of ammonia. According to some estimates, the cost of turning LNG terminals into ammonia ones is 15% of the cost of building a completely new facility. Yet, if the final goal is to produce pure hydrogen, the energy cost of getting this pure hydrogen from ammonia is high, which implies a large amount of clean power to guarantee green hydrogen as an output.

WHY At infant stages of a hydrogen economy, hydrogen-ready equipment can serve as a transitional technology or proof-of-concept for the integration of a small amount of hydrogen in the energy system. Adapting current infrastructure to the use of hydrogen can bring costs down and bring new innovations (technological and business oriented) into the market, thus serving to trigger the hydrogen economy.

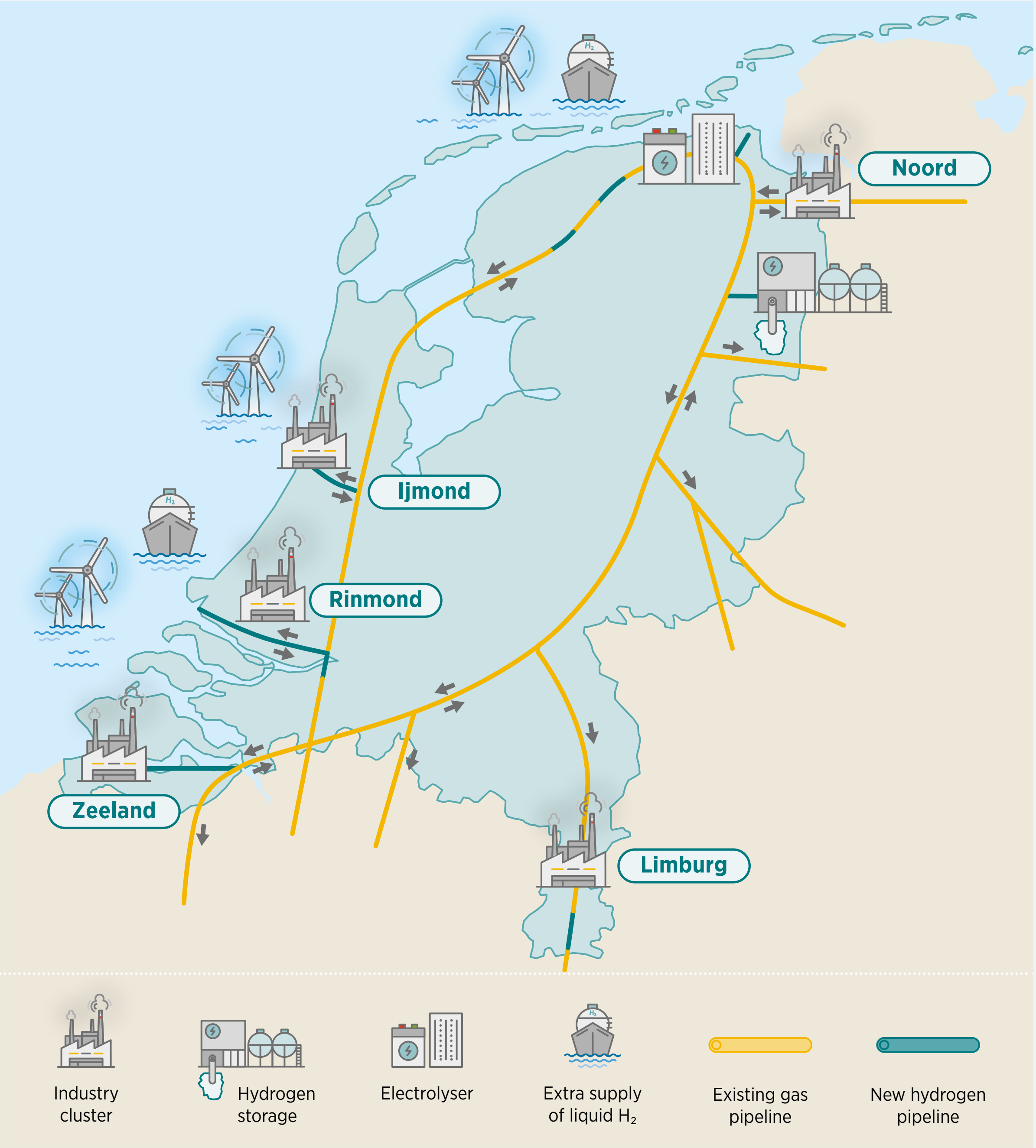
Bim © Gettyimages.com

BOX 9.2 | Hydrogen backbone projects in the Netherlands

The country's first project to heat homes with 100% green hydrogen began in June 2019 in Rozenburg, Rotterdam. The project is a joint initiative of network operator Stedin, the municipality of Rotterdam, DNV GL, Remeha, Bekaert Heating and the housing co-operative Ressort Wonen. The hydrogen will be produced locally with a green-electricity-powered electrolyser and transported over an existing gas pipeline to the apartment complex's boiler. Stedin also plans a similar project that will supply 100% hydrogen to 550 homes over a repurposed natural gas grid in the southern Netherlands by 2025. The hydrogen will be produced by eight anion exchange membrane electrolysers supplied by Enapter.

In addition, Gasunie, the gas transmission system operator in the Netherlands, is planning to build a national hydrogen network that will connect five industrial clusters to hydrogen storage facilities (Figure 9.2). Approximately 85% of the network will be repurposed natural gas pipelines (Gasunie, 2022).

FIGURE 9.2 | Plans for the hydrogen backbone project in the Netherlands for 2030



Source: (Gasunie, 2022).

Digital technologies

DIGITAL TECHNOLOGIES | ⑧ **Digital backbone for green hydrogen production**

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●●●○	●○○○	●●●●

WHAT The Internet of Things (IoT) refers to physical devices that use electronics, sensors and software to collect and exchange large volumes of data over the Internet or across communication networks. This makes it possible to monitor, control and optimise the operation of electrolysers and other key elements of the hydrogen ecosystem. The use of big data and artificial intelligence (AI), for example, can improve supply and demand planning, and provide more accurate forecasts of variable renewable power generation or energy demand.

Roughly, electricity accounts for 70% of total hydrogen production costs (H2GreenSteel, 2022). This means that a data-driven operation is key. Forecasting tools for renewable resource availability, production planning or software for the optimisation of storage capacity and electrolyser operation can support the deployment of the green hydrogen economy.

WHY Building and operating the future hydrogen economy will require substantial data analysis. From the very beginning, for instance, it is vital to use data on the renewable energy potential in various regions, the potential constraints for hydrogen transport, the expected levels and locations of hydrogen demand, and local and international hydrogen prices (including country-specific taxes) to determine the best locations for hydrogen production plants or the most effective transport network designs.

Then, as the hydrogen economy expands, these digital technologies offer major benefits. They enable greater integration of variable renewable generation into the power system and more efficient coupling of electrolysers with generation sources. They facilitate increased automation and improve the forecasting of everything from renewable energy production to hydrogen demand, making it possible to improve the overall efficiency of the green economy.

BOX 9.3 | HyAI (Hydrogen Artificial Intelligence) project

The HyAI project entailed the development of AI's use for hydrogen production and storage. It was a partnership among H2GO Power, the European Marine Energy Centre (EMEC) and Imperial College London, and was funded by Innovate UK and the Sustainable Innovation Fund. The project began in October 2020 and was completed in July 2021. The pilot project integrated weather data, electricity prices and energy data from EMEC's hydrogen production plant in Orkney, Scotland, and then used AI algorithms to predict future power costs and user demand; the aim was optimising hydrogen production and storage. The first results showed that HyAI could improve the cost-effectiveness of hydrogen production and reduce power grid stress, allowing increased shares of renewable energy. A follow-on HyAI 2.0 project, begun in March 2022, is deploying the AI platform at the EMEC facility to control hydrogen production in real time.

Source: (EMEC, 2022).

BOX 9.4 | H_2 Green Steel optimisation software

The Swedish firm H_2 Green Steel champions a digital hydrogen economy based on the data-driven optimisation of processes across the entire hydrogen value chain. This digitalisation can enable the cost-effective production of a wide range of products including green steel, ammonia and methanol. The company is developing two optimisation software tools in hopes of achieving the lowest-cost hydrogen production possible, regardless of the location of operations. It has also developed software to plan the optimal configuration of hydrogen plants in a modular way, making the design process more time and cost efficient, and informed by real-world experiences.

Source: (H2GreenSteel, 2022).

DIGITAL TECHNOLOGIES

9 Hydrogen leakage detection

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●○○○	●●●●	●○○○

WHAT Hydrogen has a very broad flammability range – 4-74% concentration in air. Leakage detection technologies are thus critical to guarantee safety, as well as to mitigate any possible impacts on climate change (the GWP_{100} is 11 and GWP_{20} is 33, respectively[15] (Ocko and Hamburg, 2022). Despite both safety and environmental effects, sensor technologies are not at the maturity level that a hydrogen economy would require. New generations of leak detection sensors should be developed and researchers would do well to explore solutions based on acoustic, laser scanning, optical fibre sensors, infrared if a natural gas/hydrogen (NG/H_2) mix considered, odourised molecules or strain gauge. Innovations should also focus on improving the existing solution regarding measuring range, tolerance, temperature and pressure ranges or response times.

WHY Effective monitoring and control of possible hydrogen leakages across the entire value chain will, in the first place, lower the cost of hydrogen served at consumption hubs. Equally important, it will raise user confidence. Last, growing the knowledge on leakages and hydrogen losses will also help improve equipment like pipes, valves, compression units and so on.

BOX 9.5 | Hydrogen and NG/H_2 leak detection for continuous monitoring and safe operation of future hydrogen or NG/H_2 networks

The European Commission acknowledges the need for advancing technologies that can effectively detect hydrogen leakages to boost a safe hydrogen economy. With this goal, it opened a call for proposals in 2022 with a budget of EUR 180 million. The call is expected to help research that focuses on developing and validating reliable leak-sensing services and leak detection sensor technologies for hydrogen and NG/H_2 mixtures. The proposed research work should start at TRL (technology readiness level) 3 and end at TRL 5 or higher.

Source: (European Commission, 2022).

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[15] GWP_{100} is the global warming potential in 100 years, and GWP_{20} in 20 years. These values are central estimates. It should be noted that hydrogen maximum GWP takes place seven years after the pulse of emission, decreasing afterwards. Hydrogen, thus, is a short-term forcer compared to CO_2, which is a long-term forcer that remains in the atmosphere 100 years after its pulse.

9.2 Market design and regulation

Innovative regulations in power and gas markets are required to integrate electrolysers in the power system, support the flexible and smart operation of electrolysers and accelerate the uptake of green hydrogen (Figure 9.3).

FIGURE 9.3 | Innovations in market design and regulation for power to hydrogen

MARKET DESIGN AND REGULATION	**ELECTRICITY MARKET DESIGN**	• **10** Additionality principle • **11** Renewable PPAs for green hydrogen • **12** Cost-reflective electricity tarrifs • **13** Electrolysers as grid service providers
	HYDROGEN MARKET	• **14** Certificates • **15** Hydrogen purchase agreements • **16** Carbon contracts for difference
	STANDARDS AND REGULATIONS	• **17** Regulatory framework for hydrogen network • **18** Streamlining permitting for electrolyser projects • **19** Quality infrastructure for green hydrogen • **20** Regulatory sandboxes

Note: PPA = power purchase agreement.

Electricity market design

ELECTRICITY MARKET DESIGN | **(10) Additionality principle**

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●○○○	●○○○	●●●●

WHAT Green hydrogen needs to be produced with renewable electricity. The additional demand from green hydrogen production might reduce renewable energy available for other sectors, delaying the overall decarbonisation of the energy sector. "Additionality" for grid-connected green hydrogen means that the production is accompanied by an additional source of renewable energy capacity, and implies that there is a degree to which this additional capacity needs to be matched in space (geographical correlation) and time (temporal correlation).

WHY The additionality principle is very important to ensure that increasing renewable electricity demand for renewable hydrogen production will not compete with the renewable electricity that should go into the direct electrification of other processes across the economy. This principle aims to ensure that the generation of renewable hydrogen incentivises an increase in the volume of renewable energy available to the grid compared to what exists already. In this way, hydrogen production will be supporting decarbonisation and complementing electrification efforts, while avoiding pressure on power generation.

BOX 9.6 | The European Commission's Delegated Act on renewable hydrogen, February 2023

The European Commission has proposed detailed rules to define what constitutes renewable hydrogen in the European Union, with the adoption of two Delegated Acts required under the Renewable Energy Directive. The first Delegated Act defines under which conditions hydrogen can be considered green. The Act clarifies the principle of "additionality" for hydrogen. Electrolysers to produce hydrogen will have to be connected to new renewable electricity production.

While initial electricity demand for hydrogen production will be negligible, it will increase towards 2030 with the massive roll-out of large-scale electrolysers. The European Commission estimates that around 500 TWh of renewable electricity is needed to meet the 2030 ambition, which corresponds to 14% of total EU electricity consumption in 2030. This ambition is reflected in the Commission's proposal to increase the 2030 target for renewables to 45%.

The Delegated Act sets out different ways in which producers can demonstrate that the renewable electricity used for hydrogen production complies with additionality rules. The primary requirement is that the hydrogen production unit must be directly connected to a renewable generating asset that did not come into operation more than 36 months before the hydrogen plant.

If an electrolyser is connected to the main grid, it has three options for considering the hydrogen produced as green:

- If the proportion of renewable power exceeds 90% over the previous calendar year in the bidding zone where the electrolyser is operating.
- Hydrogen production takes place in a bidding zone where the carbon intensity of the grid is lower than 18 grams of carbon dioxide per megajoule (gCO_2/MJ). The electrolyser must acquire a renewable power purchase agreement, with temporal and geographical consideration.
- Power supply can be considered renewable if taken from the grid during an imbalance period (when there is downward re-dispatchment of renewables).
- A renewable power purchase agreement where the principles of additionality, temporal and geographical correlation apply. Temporal correlation is considered to be always met if the hydrogen production occurs within the one-hour period when the clearing price for power resulting from the day-ahead market is lower than or equal to EUR 20/MWh, or lower than 0.36 times the EU Emissions Trading System.

Source: (European Commission, 2023; Stones, 2023).

ELECTRICITY MARKET DESIGN

11 Renewable power purchase agreements for green hydrogen

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●●●○	●○○○	●●●○

WHAT Power purchase agreements (PPAs) can include provisions specifying that the electricity being supplied to a purchaser will be generated from renewable sources. A grid-connected electrolyser, therefore, could use a renewable PPA to ensure that the hydrogen it produces is fully renewable. However, tackling the challenge of renewable power intermittency might require new and more complex forms of PPAs. To fulfil their need for more stable and predictable power than individual renewable power facilities could typically supply, green hydrogen projects could sign renewable PPAs that include supply from multiple generating resources across a wider geographic region (if grid connections are available). This would avoid additional costly capacity that may often go unused.

WHY Renewable PPAs for electrolysers ensure that the hydrogen they produce will be "green". Such PPAs also help resolve an existing issue. Under many current PPAs, hydrogen producers are most likely to use electricity during periods of low renewable power supply; this increases the need for fossil fuel–based generation and overall system emissions. Renewable PPAs, however, provide a powerful incentive for both increasing the renewable power supply and producing hydrogen only when there is sufficient renewable generation, thus eliminating emissions without affecting electricity prices (Parkes, 2022).

ELECTRICITY MARKET DESIGN

12 Cost-reflective electricity tariffs

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●●●○	●○○○	●●○○

WHAT Cost-reflective tariffs are tariffs that vary over time or by location to match electricity production costs. Time-varying tariffs send price signals to electrolysers, giving them incentives to adjust hydrogen production to minimise electricity costs. Since electrolysers can respond quickly to changing prices, cost-reflective tariffs are an effective tool for reducing costs and adding flexibility to the power grid. Meanwhile, tariffs that vary by location provide incentives to build electrolysers in locations with large renewable generation capacities and thus lower prices.

WHY Cost-reflective tariffs are key for greater flexibility and higher demand response. In the case of hydrogen production, their effectiveness can be reduced when the electrolyser does not have enough flexibility to shift or reduce the production time. Moreover, the electrolyser's operation may not be driven by the prices of electricity, but by the mere fact that renewable electricity is available so that the hydrogen is certified as "green hydrogen". However, in principle, dynamic tariffs allow electrolyser operators to lower their production costs by taking advantage of periods of lower-cost electricity.

ELECTRICITY MARKET DESIGN

13 Electrolysers as grid service providers

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
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WHAT Electrolysers can ramp production up and down quickly, offering a flexible load that provides valuable grid-balancing and stability services. Three electrolyser technologies – PEM, ALK and AEM – can participate in existing primary, secondary and tertiary grid-balancing markets.

Taking advantage of this flexibility, however, may require new market designs that open up the system services market to new actors, such as electrolysers, or that reward hydrogen producers for specific services, such as providing fast reserves or managing overgeneration from renewable sources (IRENA, 2021b).

WHY Enabling electrolysers to provide grid-balancing services will not only make the energy system more adaptable, but also enable hydrogen producers to gain additional revenues, potentially reducing the final price of green hydrogen.

BOX 9.7 | Electrolysers' capability to provide ancillary services

Commercially viable electrolyser technologies could, in principle, provide a wide range of frequency and non-frequency ancillary services as well as congestion management. It is worth noting that the role for power-to-hydrogen projects in providing flexibility will ultimately depend on their competitiveness compared to other storage technologies. If these alternatives (*e.g.* batteries) can provide flexibility at lower cost, the need for power-to-hydrogen capacity may be significantly reduced.

Table 9.4 summarises the flexibility capability of alkaline (ALK), polymer electrolyte membrane (PEM) and solid oxide electrolyser cell (SOEC) electrolysers and which ancillary services they are able to currently provide.

TABLE 9.4 | Flexibility capacity and services of three types of electrolyser

		ALK	PEM	SOEC
Flexibility capability	**Load range (%)**	15-100	0-160	20-125
	Start-up	1-10 min	1 sec to 5 min	< 60 min
	Ramp up/down	0.2-20% per second	100% per second	A system response time of a few seconds
	Shutdown	1-10 min	Seconds	Not available
Ancillary services	**Frequency containment reserves**	Yes with limits	Yes with limits	No
	Automatic frequency restoration reserves	Yes with limits	Yes	No
	Manual frequency restoration reserves	Yes	Yes	No
	Reserve restoration	Yes	Yes	No
	Voltage control	Electrolysers can provide reactive power if they are equipped with self-commutated rectifiers		
	Congestion management (through re-dispatch and curtailment)	Yes	Yes	No

Source: (IRENA 2020c, 2021a; ENTSO-E, 2022b).

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BOX 9.8 | An electrolyser providing ancillary services in Germany

In Germany, the participation of small electrolysers in the market is made possible by aggregating them into virtual power plants (IRENA, 2021b). Tests with an alkaline electrolyser owned by thyssenkrupp in Duisburg show that it can ramp production up and down fast enough to enter the market for primary reserve, where the entire service offering has to be fully delivered within a maximum of 30 seconds and be continuously available for at least 15 minutes (thyssenkrupp, 2020).

Hydrogen market

HYDROGEN MARKET | **14 Certificates**

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●●○○	●●●○	●●●○

WHAT Certification is an essential element of any industry, especially a nascent one such as hydrogen. Certificates for hydrogen and its derivatives contain information on compliance with standards and regulatory requirements, and enable verification through data on sustainability criteria, such as the carbon footprint and renewable energy content, thereby allowing differentiation from other less green products. To be effective, certificates must use a strong and reliable tracking system across the entire value chain, and be consistent, accurate and accepted by all market participants. They will typically be managed by non-profit organisations or other official entities, with industry backing.

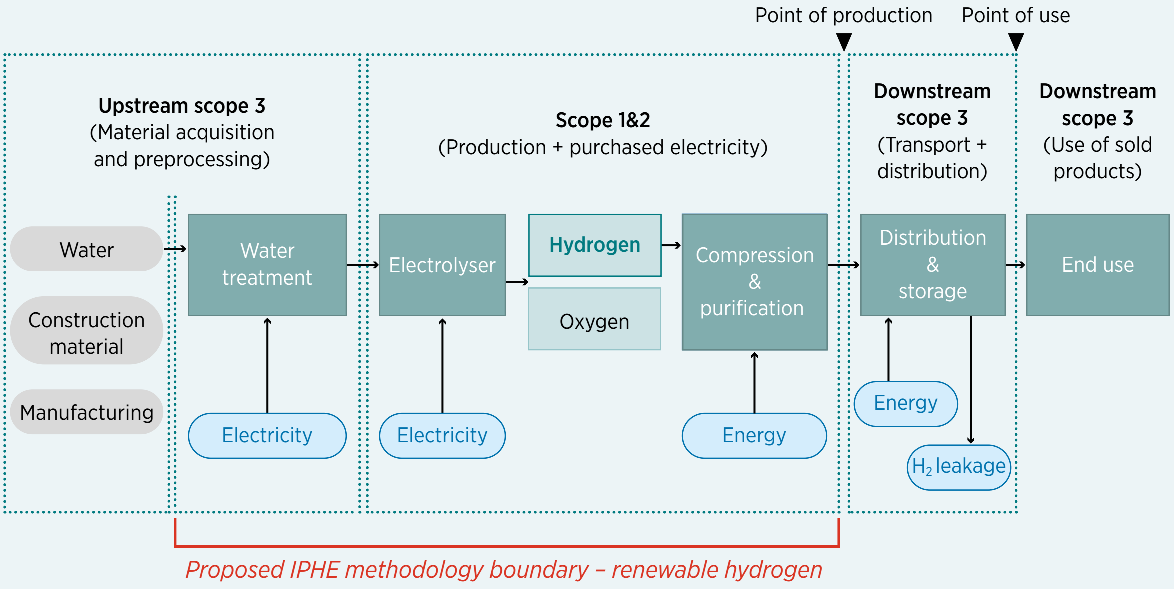
WHY Certificates are essential for the massive deployment and uptake of green hydrogen, as well as for the establishment of national, regional and international green hydrogen markets. Certificates are a way to assure consumers that the hydrogen they buy contributes to decarbonisation efforts. At the same time, certificates provide a marketable characteristic to producers of green hydrogen. Several potential hydrogen exporter and importer countries, including Australia, the European Union, Germany, France, the Netherlands and the United Kingdom, have already included certification schemes in their hydrogen strategies (Department for Business, Energy & Industrial Strategy, 2022; European Commission, 2023).

BOX 9.9 | Collaborative efforts towards market standardisation. The IPHE

The International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) is a government-to-government partnership consisting of 21 countries and the European Commission whose aim is to share information on hydrogen and fuel cell developments to inform future government policy and foster international collaboration. IPHE countries recognise that governments and industry need to work together to ensure existing and future regulations, codes and standards facilitate the production and use of, as well as investment in, hydrogen, hydrogen technology and infrastructure.

Figure 9.4 illustrates supply chains for green hydrogen, based on IPHE methodology, which is in the process of being established as an International Organization for Standardization (ISO) standard. System boundaries are typically defined to capture either well-to-gate (up to point of production) or well-to-wheel (up to point of use) pathways. These boundaries serve as the basis for differentiating hydrogen production pathways.

FIGURE 9.4 | Green hydrogen supply chains



Source: (IRENA and RMI, 2023).

Notes: H_2 = hydrogen. IPHE = International partnership for hydrogen and fuel cells in the economy.

HYDROGEN MARKET

15 Hydrogen purchase agreements

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●●●○	●●●●	●●○○

WHAT A hydrogen purchase agreement (HPA) is a legally binding contract between a supplier of hydrogen fuel and a customer, outlining the terms and conditions for the purchase and delivery of hydrogen fuel. The agreement typically includes details such as the price, delivery schedule and quality standards for the hydrogen fuel, as well as any warranties or guarantees provided by the supplier (Hernández Vidal, 2023). The operator may produce the electricity itself with a renewable energy plant or procure electricity from a third party by entering into a corporate PPA. A HPA needs to ensure that the hydrogen is certified as green hydrogen, and needs to ensure a predictable revenue stream. That means the HPA will need to provide a long-term offtake commitment (10-15 years). A HPA scheme involves the standardisation of such contracts both at the local and international level, facilitating the trade of hydrogen and increasing transparency in the process (Reinecke *et al.*, 2022).

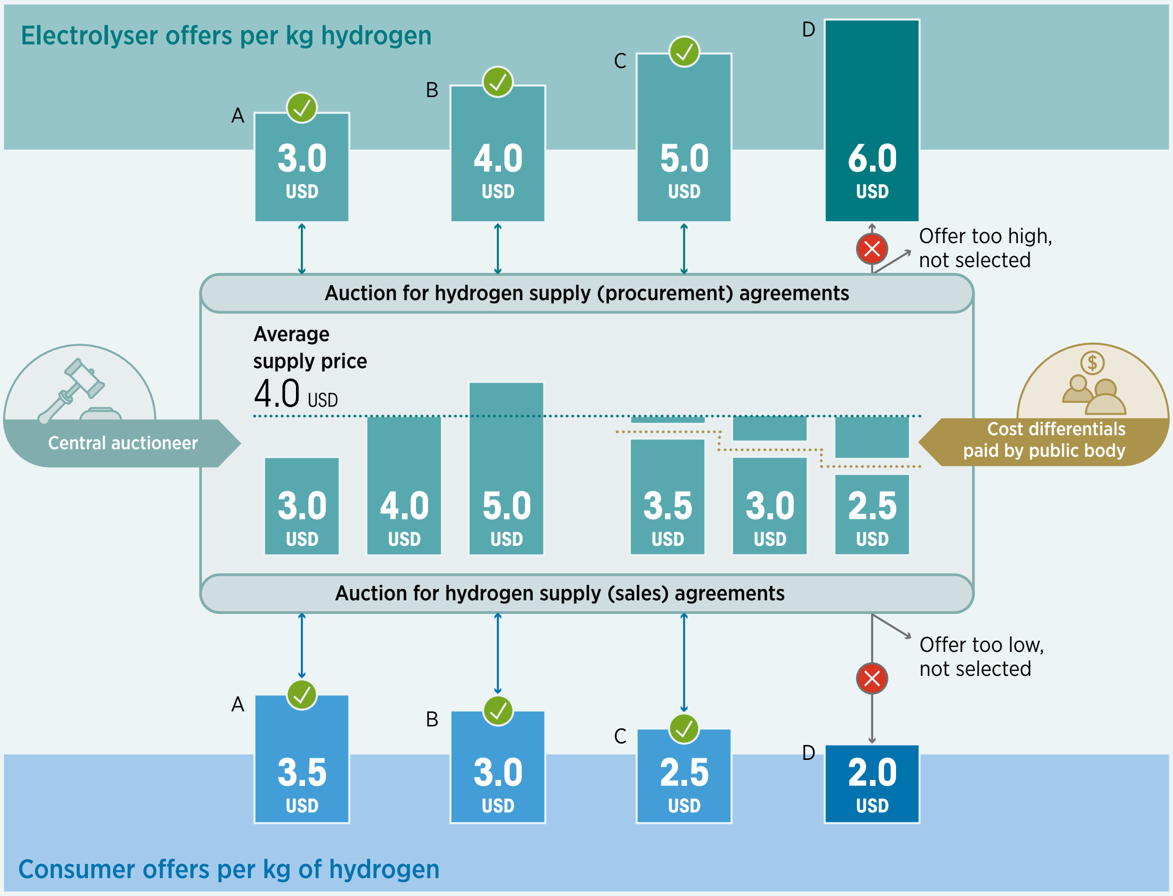
WHY Having a HPA scheme in place is important because it provides long-term certainty on the acquisition of hydrogen. It is crucial to obtain financing at an early stage and decisive for bankability in the longer run. Such a scheme can facilitate the ramp-up of green hydrogen and its derivatives.

BOX 9.10 | Bilateral auctions for procurement of hydrogen in Germany

Under the H_2Global funding programme, Germany designed a double auction scheme to procure hydrogen for German industry. The H_2Global programme established an intermediary body called the Hydrogen Intermediary Network Company (HINT.CO) to sign long-term agreements.

Through a double auction scheme, the lowest purchase agreement and the highest sale agreement resulting from the auctions would be awarded the contract, while too high purchase offers and too low sale offers would be rejected (Figure 9.5). The public body would then cover the price difference.

FIGURE 9.5 | Bilateral auction system schematic



Note: kg = kilogramme.

Depending on auction design, a captive green hydrogen producer may sign both contracts, basically receiving a premium for its green hydrogen self-production. HINT.CO is supported with EUR 900 million of funding to temporarily compensate the difference between the hydrogen purchase agreements and sales agreements.

The programme expects that future adjustments to the regulatory framework will increase industrial offtakers' willingness to pay for green hydrogen and the sale agreement price will rise over time. This will gradually reduce the need for HINT.CO to compensate for the price differential until a point is reached where the demand and supply prices are in line with each other.

Source: (IRENA, 2022g).

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HYDROGEN MARKET

16 Carbon contracts for difference

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●○○○	●●●●	●●○○

WHAT An important issue for green hydrogen development is the critical lack of offtakers, which reflects the low level of current demand. Indeed, the majority of planned hydrogen production facilities do not have agreements with any offtakers. The main obstacle is the high cost of green hydrogen compared with hydrogen produced from fossil fuels.

Resolving this issue requires policies and regulations that stimulate demand, reduce the price gap between producers and buyers, and speed up innovations in and demonstration of end-user technologies. An emerging innovation that addresses these issues is carbon contracts for difference (CCfD). CCfDs would be contracts between governments and projects that produce materials with reduced carbon intensity. A CCfD would guarantee a fixed "strike price" for tonnes of CO_2 avoided for a pre-determined number of years. If at the end of a certain period (*e.g.*, a year) the average annual Emissions Trading System (ETS) price has been below the strike price, the industrial producer will receive, for each tonne of CO_2 avoided, the difference between the two values.

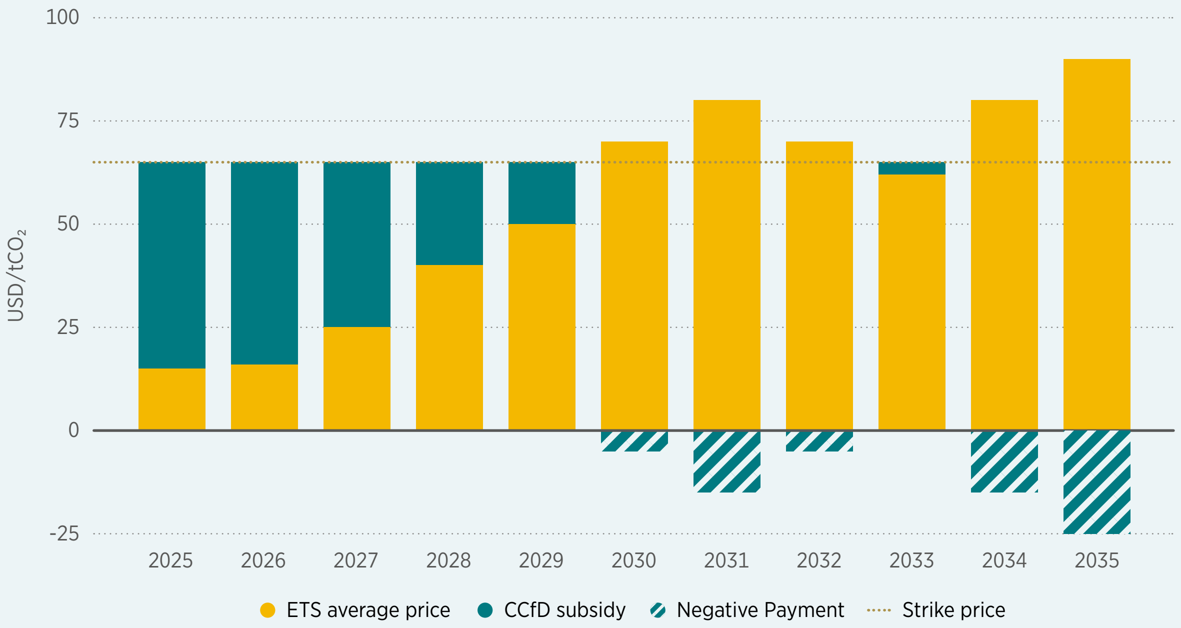
WHY CCfDs would help to ensure that a low-CO_2 industry is in place without needing to wait until a combination of economic conditions is present to justify the investment. CCfDs would cover a proportion of the cost difference between a conventional and a low-carbon product. More crucially, they would stabilise revenue streams by removing the risk of CO_2 price volatility for project investors. As a result, they could considerably increase the economic feasibility and bankability of projects. Because of the enhanced certainty of pay-offs, projects can increase the proportion of debt in overall project financing compared to equity, and therefore further support the development of green hydrogen projects in end-use sectors where this is a "no-regret" decarbonisation solution (IRENA, 2022g). Owing to the enhanced certainty of pay-offs, projects can increase the proportion of debt in overall project financing compared to equity, and therefore further support the development of green hydrogen projects in end-use sectors where this is a "no-regret" decarbonisation solution (IRENA, 2022g).

BOX 9.11 | CCfD implementation

Under the RePowerEU initiative, the European Commission's plan to make Europe independent from Russian fossil fuels before 2030, the Commission will subsidise green hydrogen for industry using a carbon contract for difference (CCfD) to cover fuel switching costs. To promote hydrogen in industrial processes, the German government will provide investment grants and launch a CCfD programme, which is mainly aimed at the steel and chemical industries.

It should be noted that CCfDs would not be expected to have a large impact on government budgets. This is because CCfDs with high strike prices would only be available to kick-start commercial projects, followed by lower strike prices as the processes mature, to be eventually phased out when the technology becomes widespread and the market for green products is established. Moreover, the government would not pay the full strike price of the CCfD. Rather, it would only pay the difference between the strike price and the actual observed Emissions Trading System allowance price. Thus, if the carbon price rises steadily over time, the net annual cost would fall and eventually become negative. Estimates indicate that CCfD prices in Europe may be in the order of a few million euros per country to decarbonise 10% of the hard-to-abate sectors (Sartor and Bataille, 2019; Agora Energiewende, 2020).

FIGURE 9.6 | **Relationship between average Emissions Trading System (ETS) price and CCfD subsidy at strike price of USD 65/tCO_2**



Source: IRENA 2022g.

Notes: CCfD = carbon contracts for difference; ETS = Emissions Trading System.

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BOX 9.12 | Clean hydrogen production tax credit

Under the US Inflation Reduction Act of 2022 (IRA), the clean hydrogen production tax credit is a new ten-year mechanism to incentivise the production of hydrogen up to USD 3/kg. The credit support is linked to the amount of CO_2 emissions up to a maximum level of 4 $kgCO_2eq/kgH_2$ (kilograms of carbon dioxide equivalent per kilogram of hydrogen).

The credit provides a four-tier incentive based on such carbon intensity (Table 9.4).

TABLE 9.5 | **Amount of hydrogen production tax credit, by degree of carbon intensity**

Carbon intensity ($kgCO_2/kgH_2$)	Maximum hydrogen production tax credit (USD/kgH_2)
4-2.5	0.60
2.5-1.5	0.75
1.5-0.45	1.00
0.45-0	3.00

In addition, projects can also elect to claim up to a 30% investment tax credit under Section 48, "Advanced Energy Project Credit (Extends IRC Code Section 48c)", that also creates funding for manufacturing projects producing fuel cell electric vehicles, hydrogen infrastructure or electrolysers.

Green hydrogen producers from renewable electricity can also benefit from the renewable electricity production tax credit (Section 45 and 45Y) with a financial support of USD 2.6 cents/kWh in 2023, and inflation adjustment of 2% per year in future years, up to 2032.

Source: (EERE, 2023).

Standards and regulations

STANDARDS AND REGULATIONS ⑰ **Regulatory framework for hydrogen network**

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●○○○	●●●●	●○○○

WHAT As in other markets, such as electricity, a regulatory framework for green hydrogen is essential for setting clear rules and preventing abuse of power, especially because hydrogen networks can be a natural monopoly. Key principles for hydrogen networks and regulatory frameworks include (ACER, 2021):

- Operation by a regulated entity, which remains neutral;
- A clear governance structure for a regulatory authority to monitor and provide oversight of the regulated entity;

- Transparency that promotes efficient network investments;
- Consumer protection rules (when households are the networks' users);
- Equal access to all parties without discrimination (third-party access);
- Decoupling ("unbundling") of the activities between networks and across the hydrogen value chain that can be competitive, preventing a single entity from controlling large parts of the supply chain or network, or having a dominant position.

However, it is important to monitor the market's evolution in order to maintain fair access and avoid abuse, and implement rules gradually (ACER, 2021; European Commission, 2021).

WHY Regulation of the infrastructure is necessary when a single entity may control large shares of a network. An effective regulatory framework for green hydrogen would prevent the abuse of market power in setting prices or restricting access to networks.

STANDARDS AND REGULATIONS

⑱ Streamline permitting for hydrogen projects

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●●○○	●●●●	●○○○

WHAT For new projects, obtaining permits and other approvals is often a lengthy and challenging process. This can cause significant delays in projects, drive up costs and discourage other applicants. Moreover, electrolyser or hydrogen infrastructure projects will typically need safety insurance, which may require additional permitting.

In this context, increasing co-ordination among all permit-related departments in relevant authorities or setting up a "one-stop permitting shop" can effectively facilitate and streamline the permitting process. The one-stop shop would group all necessary services and authorities at a single location and offer a streamlined application with a limited number of documents, possibly allowing online submissions.

WHY Streamlining permitting would make it possible to build electrolysers and other hydrogen infrastructure faster and at lower costs, while reducing uncertainties, easing project management and improving communications with local authorities. This in turn can help accelerate the development of the green hydrogen economy.

BOX 9.13 | One-stop permitting shops and green channel for hydrogen projects approval

So-called one-stop permitting shops have already been used in several projects, for example, offshore wind parks in South Korea. Those examples show the following steps to be useful in setting up one-stop shops:

(1) Collect input by consulting both permitting authorities and stakeholders.

(2) Review existing procedures.

(3) Facilitate participation and discussion to increase transparency and awareness.

(4) Identify bottlenecks and priorities to reorganise the permitting infrastructure.

(5) Define an implementation plan including training for local authorities.

In China, places like Shanghai, Shanxi and Inner Mongolia have all introduced hydrogen energy policies which open a "green channel" for the approval of hydrogen energy projects. For example, the Medium and Long Term Plan for the Development of Hydrogen Energy Industry in Shanghai (2022-35) proposes efforts to clarify the planning, initiation and approval of hydrogen energy industry projects; establish a "green channel" for the approval of hydrogen energy preparation, testing services, hydrogenation infrastructure and other construction projects; and establish a "one-stop" administrative approval management system.

Source: (NDRC, 2022; Shanghai Municipal Development & Reform Commission, 2022).

STANDARDS AND REGULATIONS

19 Quality infrastructure for green hydrogen

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●○○○	●●●●	●●●○

WHAT Quality infrastructure encompasses all activities to assess and verify the quality and safety of green hydrogen–related technologies and components. These include technical standards; the use of metrology devices; and testing, certification, inspection, accreditation and quality management systems. Such activities give all stakeholders (including consumers, investors, markets, regulators and policy makers) confidence that the products, processes and services in the green hydrogen economy will work as expected.

WHY Quality infrastructure for green hydrogen will ensure sustainable and safe production of green hydrogen and its derivatives, in turn lowering risks and spurring investment and development. It will also establish a level playing field that fosters fair competition and helps encourage co-operation and co-ordination in research, industry and policy making.

BOX 9.14 | Standard and evaluation of low-carbon hydrogen, clean hydrogen and renewable hydrogen in China

A standard proposed by China Hydrogen Alliance and released in 2020 establishes a method for evaluating low-carbon, clean and renewable hydrogen across its life cycle. The goal is to promote the sustainable development of the entire green hydrogen energy industry chain from the source. The standard states that the threshold for carbon emissions per unit of hydrogen is 14.51 kgCO_2eq/kgH_2 for low-carbon hydrogen and 4.9 kgCO_2eq/kgH_2 for clean and renewable hydrogen (*i.e.* produced using renewable energy sources (Hydrogen Alliance, 2021).

STANDARDS AND REGULATIONS

20 Regulatory sandboxes

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●●●○	●●●●	●●●○

WHAT Regulatory sandboxes are temporary and spatially limited testing procedures for innovative green hydrogen-related technologies that do not fall under existing regulatory frameworks. They allow new innovations to be tested in real-life projects under a regulator's oversight, generating knowledge that can be used to develop new regulatory frameworks that will support innovative technologies and business models. Regulatory sandboxes can also be used to test legal flexibility under existing legal frameworks and market conditions, or experiment with possible new legal provisions. For example, Germany's Federal Ministry for Economic Affairs and Energy has set up the Northern Germany Regulatory SandBox with EUR 52 million funding to explore regulations that support the use of "green hydrogen to integrate industry, transport and the supply of heat in a consistent manner" (Federal Ministry for Economic Affairs and Climate Action, 2021).

WHY Regulatory sandboxes are a necessary step for translating new technical developments into innovations and practical applications, and for supporting their fast adoption. They help ensure the development of an effective regulatory framework for green hydrogen-related innovations and business, thereby accelerating the establishment of the green hydrogen economy.

BOX 9.15 | Regulatory sandbox in Denmark

The Danish government has designated GreenLab as an official regulatory energy test zone, exempting it from existing electricity regulations in order to test new solutions for integrating unprecedented amounts of renewable energy into the energy system. GreenLab's test zone permit is unique in Europe, and the insights from GreenLab will be valuable for all of Europe's green transition – including clean energy storage, green fuels, agriculture and industry (GreenLab, 2021a).

One of GreenLab's projects is GreenHyScale, which is exploring the use of pressurised alkaline electrolysis for large-scale onshore and offshore green hydrogen production (GreenLab, 2021b).

9.3 System planning and operation

Electrolysers offer a new type of flexible electricity demand that adds a wide range of benefits; for example, it paves the way for seasonal storage of energy and makes it possible to integrate large amounts of renewable energy sources into the power system. Realising these benefits, however, requires innovations in system planning and operation. Figure 9.7 shows the necessary innovations, which are then discussed in detail.

FIGURE 9.7 | Innovations in system planning and operation for power to hydrogen

SYSTEM PLANNING AND OPERATION	**STRATEGIC PLANNING**	• **21** Electricity TSOs including hydrogen facilities in their planning
		• **22** Co-locating electrolysers with renewable generators (onshore and offshore)
	SMART OPERATION	• **23** Smart hydrogen storage operation and power-to-power routes
		• **24** Long-term hydrogen storage
		• **25** Co-operation between electricity and gas operators

Note: TSO = transmission system operator.

Strategic planning

STRATEGIC PLANNING | **21** **Electricity transmission system operators including hydrogen facilities in their planning**

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●○○○	●●○○	●●●●

WHAT Transmission system operators (TSOs) can take advantage of the flexibility provided by electrolysers by including hydrogen production facilities in their planning procedures and using them to help resolve network issues. For example, electrolysers could be located in areas with grid congestion due to excessive variable renewable energy generation (*e.g.* northern Germany or southern Italy) (IRENA, 2020b). Alternatively, both electrolysers and renewable power generation facilities dedicated solely to hydrogen production could be built in areas with substantial renewable resources but very low existing electricity demand (*e.g.* parts of Northern Africa).

WHY Locating electrolysers appropriately in the power grid is key for the smart integration of power to hydrogen. An ideal location makes it possible to produce hydrogen entirely with renewable sources, such as solar and wind power, or help integrate renewable energy sources into the grid. Smart planning by TSOs is thus important for the smart development of the hydrogen economy (IRENA, 2020d).

BOX 9.16 | Capacity maps developed by Energinet, a transmission system operator in Denmark

The capacity maps developed by Energinet are useful tools for planning an electrolyser's location. They map the geographical locations of production and consumption in the transmission network, and also show areas of grid congestion and locations where new assets could profitably be connected. Energinet updated the capacity maps in 2021 to include areas with sufficient solar and wind capacity to power new hydrogen production facilities (Brintbranchen, 2021).

STRATEGIC PLANNING

22 Co-locating electrolysers with renewable generators (onshore and offshore)

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●●○○	●●●○	●●●○

WHAT Locating electrolysers alongside renewable generation assets is an effective strategy for producing large quantities of green hydrogen. Co-located electrolysers and renewable power plants could operate together in isolation without a grid connection, or a grid connection could be added to increase the overall system flexibility and provide services for the power system, such as acting as a "dispatchable power plant".

Studies show that levelised costs of hydrogen are lowest when electrolysers are co-located with onshore wind and solar PV, reaching EUR 4.1/kgH$_2$ by 2025 (Aurora Energy Research, 2022). Electrolysers can also be located offshore to take advantage of large-scale offshore wind plants or ocean energy technologies; the hydrogen could be shipped to the shore or transported there by pipelines. Offshore electrolysers may have higher construction, operation and maintenance costs, thus necessitating careful planning to evaluate potential trade-offs. However, technological innovation is lowering costs. For example, Siemens Gamesa and Siemens Energy are integrating an electrolyser directly into an offshore wind turbine to create a single synchronised system for producing green hydrogen (Siemens Gamesa, 2022).

WHY Co-locating electrolysers with onshore or offshore renewable power plants can substantially reduce costs and improve the business case for projects. This can reduce power losses due to long-distance electricity transmission or help avoid such losses, reduce network charges and help avoid the costs of building transmission lines. In addition, once hydrogen transport infrastructure is in place, electrolysers and renewable power plants could be co-located in remote areas with vast renewable resources, such as deserts or far offshore, making it possible to harness affordable renewable electricity and drive down the cost of renewable hydrogen even further.

BOX 9.17 | Harnessing the power of the winds in Chile: The Haru Oni project

The Haru Oni project in the Magallanes region of Chile will deploy a 1.25 MW polymer electrolyte membrane electrolyser co-located with a 3.4 MW wind turbine to take advantage of the region's abundant wind energy resources (Siemens Energy, 2023). Chile is one of a number of countries that could use their extensive renewable resources to become major producers and exporters of green hydrogen or its derivatives for a global market (Iakovenko, 2022).

9
23

Smart operation

SMART OPERATION | **23 Smart hydrogen storage operation and power-to-power routes**

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●○○○	●○○○	●●●●

WHAT Hydrogen storage offers another source of flexibility for the operation of the energy system in addition to existing sources such as batteries or pumped hydro. Seasonal storage is made possible considering hydrogen can be stored for a short or long term, from hours to months.

Stored hydrogen can be used directly, for example, in industrial processes. It could be used to produce synthetic fuels when the demand for such products is high. Alternatively, it could be converted back into electricity using fuel cells or gas turbines in a power-to-power (P2P) route, thereby reducing dependence on fossil fuels when electricity production from wind and solar falls short of demand. Hydrogen energy storage and P2P routes are under R&D to increase efficiency and lower costs in the coming years.

WHY Hydrogen storage and batteries should not be viewed as competitors for providing flexibility to the power system; instead, they complement each other in important ways. The ideal mix may be using batteries to provide short-term flexibility (minutes or hours), while reserving hydrogen for long-term flexibility over weeks or months.

BOX 9.18 | Electrical storage: The Eco-Energy World Gladstone project in Australia and the Delta Green project in France

Eco-Energy World (EEW) plans to combine its existing 300 MW solar power plant in Raglan (Queensland, Australia) with a 200 MW electrolyser plant and 100 MW of battery storage by the end of 2023. The hydrogen plant is designed to produce 33 000 tonnes of green hydrogen per year. The system will use battery storage to optimise operations (Renews, 2021).

In another example, the Delta Green project in France produces and stores green hydrogen during periods of high renewable energy production, and then converts the hydrogen back into electricity during peak-load hours (Construction21 France, 2018).

BOX 9.19 | Power-to-power route in a demonstration project on Dachen Island (Taizhou, China)

A demonstration project utilises the abundant wind power on Dachen Island in the East China Sea to produce green hydrogen through proton exchange membrane electrolysis technology, and has constructed a co-generation system comprising hydrogen production, hydrogen storage and fuel cells. It is the first comprehensive green hydrogen demonstration project on an island in China. The project promotes the clean energy consumption and power flow optimisation of power grids on the island and achieves 100% consumption of clean energy and zero-carbon energy supply throughout the process. It is expected to consume 365 000 kWh of surplus wind power every year and produce 73 000 normal cubic metres (Nm3) of hydrogen, which can generate about 100 000 kWh of electricity and reduce 73 tonnes of carbon dioxide emissions. The hydrogen storage is expected to act as a large power bank, and meet electricity demand on Dachen Island during peak electricity consumption and emergency maintenance.

Source: (Zhejiang News, 2022).

SMART OPERATION

24 Long-term hydrogen storage

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●○○○	●○○○	●●●●

WHAT Hydrogen can also bring flexibility and resilience to an energy system expected to become deeply electrified over the coming decades. Hydrogen's true competitive strength lies in its unique ability to store energy for long periods of time and in large quantities. As clean hydrogen displaces fossil fuels in some end uses, hydrogen storage could become increasingly critical to energy security, just like natural gas storage is today in many regions. Yet, there are differences between natural gas and hydrogen storage. Natural gas is stored mostly to meet (seasonal) variation in demand. Hydrogen demand, in contrast, is likely to be more constant, at least in the early years of the hydrogen market scale-up, when the bulk of demand is likely to come from industrial customers (primarily steel, ammonia and high-value chemicals).

Long-term hydrogen storage is important in countries with significant seasonal differences between power demand and renewable power generation. For example, Germany has 30% higher energy demand in winter than in summer, but its current renewable energy sources generate about 50% less power in winter than in summer. Hydrogen could thus be produced in summer to help meet the winter demand.

WHY Hydrogen storage will be needed primarily to meet variation in supply, not demand, as green hydrogen is made with variable renewable energy sources. Long-term hydrogen storage can play an important role to increase energy security and the resilience of a system.

SMART OPERATION

25 Co-operation between electricity and gas operators

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●○○○	●●○○	●●●○

WHAT Planning and building the most efficient and cost-effective energy system requires a coherent approach across sectors. In particular, gas and electricity TSOs need to co-ordinate and synchronise their planning and timing as the hydrogen ecosystem develops. This will ensure the information in different plans is consistent and complementary. For example, hydrogen and electricity transport companies are potential competitors; careful planning must be done to achieve the most effective balance in transport investment decisions.

WHY By leveraging new synergies between energy carriers and sectors, it is possible to provide reliable electricity and gas supply to consumers, especially during periods of peak demand. Much like the transmission infrastructure, electricity and gas storage are complementary. For example, existing gas networks and storage facilities can absorb large quantities of green hydrogen for long-term storage. Coupling electricity and gas grids can, therefore, help utilise existing gas storage facilities in renewable energy.

BOX 9.20 | Examples of electricity and gas transmission system operator co-operation

A study published by transmission system operators (TSOs) TenneT (electricity) and Gasunie (gas) shows how the Netherlands and Germany can achieve the Paris climate targets using a more integrated energy system. The study emphasises the need for close collaboration between the gas and electricity infrastructure to guarantee the reliability of the energy system and integrate increasing shares of variable solar and wind energy. The study highlighted two requirements for a successful energy transition: (1) political willingness to build new electricity grid connections and create a clear, supportive regulatory framework; and (2) creation of a regulatory framework specifically for the integration of power-to-gas (hydrogen) installations into the system in order to add flexibility and avoid unnecessary grid expansion costs for grid expansions (Gasunie, 2019).

Similarly, ENTSO-E and ENTSOG jointly published their Scenario Report Ten-Year Network Development Plans 2022. For the first time, the plans use new sector-coupling methodologies and dedicated modelling tools to optimise overall system efficiency and flexibility of use, as well as better capture the interactions among end-use sectors at different geographical scales and with other carriers. It is also the first time that the scenarios have modelled hydrogen and electrolysis at a pan-European scale (ENTSO-E, 2021).

In another example, the TSO in Denmark, Energinet, has combined the operations of its electricity and gas systems into a joint system operator subsidiary. The expectation is that joint operations will make it easier for Denmark to reach its very ambitious climate targets (ENERGINET, 2021).

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9.4 Business models

Electrolysers have the advantage of being able to connect different markets (electricity, heat, hydrogen and hydrogen derivatives) and applications that have different supply and demand curves, and prices. This enables electrolysers to stack revenue streams, which can then be realised with emerging innovative business models. Those business models (Figure 9.8) include hydrogen industrial hubs and the sale of electrolysis by-products, and are discussed in the following section.

FIGURE 9.8 | Innovations in business models for power to hydrogen

BUSINESS MODELS	**PRIMARY REVENUE STREAMS**	**26** Local hydrogen demand
		27 Hydrogen trade
		28 Hydrogen industrial hub
	STACKING OTHER REVENUE STREAMS	**29** Revenues from flexibility provided to the power system
		30 Sale of electrolysis by-products (oxygen and heat)

Primary revenue streams

PRIMARY REVENUE STREAMS | **26 Local hydrogen demand**

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●●○○	●●●○	●●○○

WHAT Electrolysers earn their revenues primarily from supplying hydrogen to meet various types of demand. One strategy is to co-locate electrolysers with the hydrogen users, to minimise the cost of transport (Figure 9.9). One type of demand is the so-called critical load, which requires a large, continuous, reliable supply of hydrogen. This demand comes, for example, from ammonia production plants and refineries, and from iron and steel industries. Supplying critical load leaves electrolysers with little operational flexibility. Another type of demand are the non-critical loads, which do not require continuous supplies of hydrogen. They are thus much more flexible than critical loads. For example, refuelling stations and some small industries typically have large storage capacities compared with their daily consumption. Supplying non-critical loads allows more flexible operation of electrolysers.

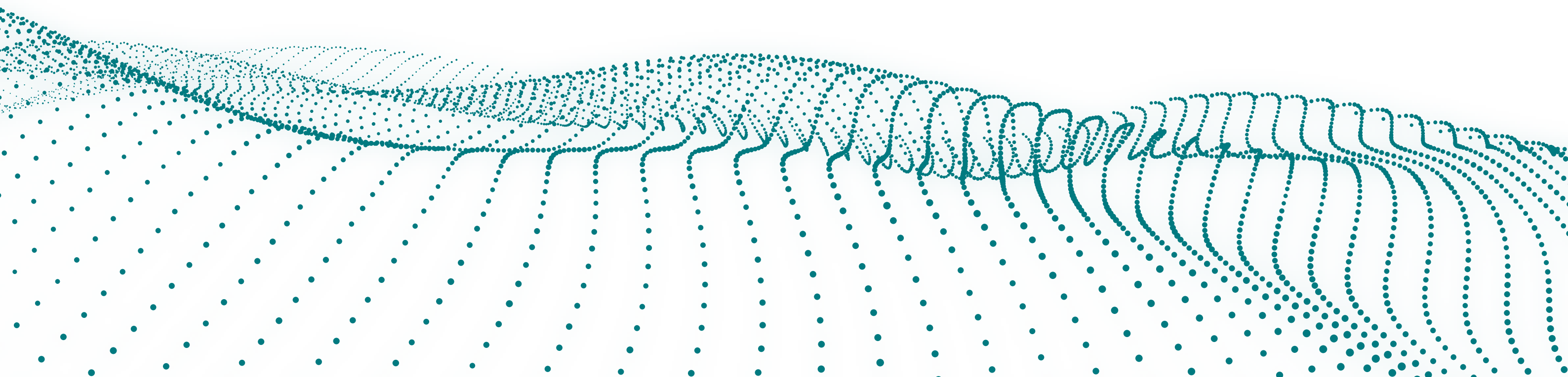
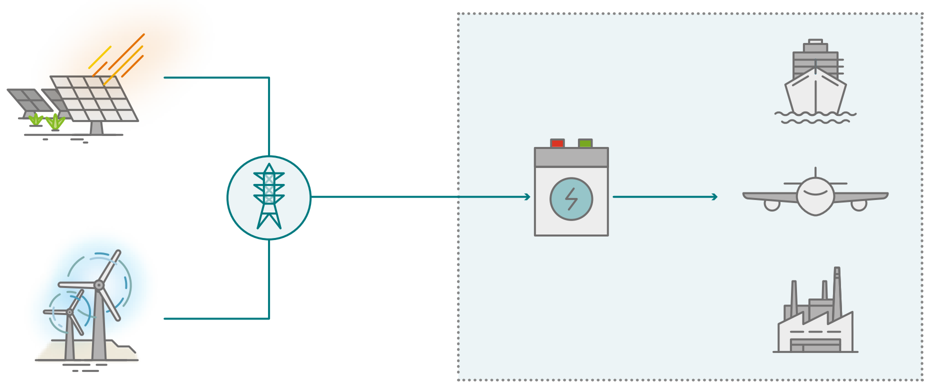


FIGURE 9.9 | Co-locating electrolysers with end uses



CO-LOCATING ELECTROLYSERS WITH END USES

H_2 produced with electricity form the grid

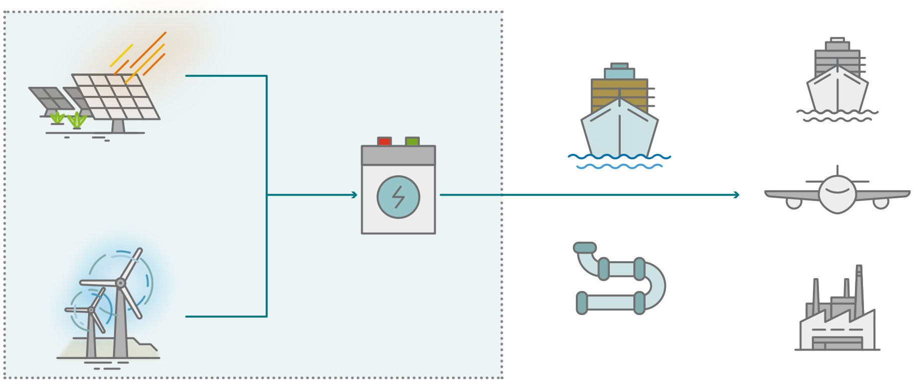
WHY Co-locating the electrolyser with the end use offers predictable revenue streams for electrolyser facilities, thus reducing investment risks.

PRIMARY REVENUE STREAMS | ㉗ **Hydrogen trade**

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●○○○	●●●●	●○○○

WHAT Electrolysers earn their revenues primarily from supplying hydrogen to meet various types of demand. When the electrolyser is not co-located with the end use, hydrogen transportation and trade is needed. National and international hydrogen trade involves transporting hydrogen and its derivatives via pipelines or in ships. Long-distance trade, usually via ships, can unlock the abundant renewable energy potential in many remote locations by allowing hydrogen to reach markets far from production sites (Figure 9.10). To encourage and facilitate such trade, countries have begun to establish bilateral relations and deals concerning hydrogen molecules and related production technologies. It will also be necessary to use certification schemes, such as certificates, to build trust in green hydrogen, ammonia, methanol and other e-fuels.

FIGURE 9.10 | Transporting hydrogen to end-use locations



CO-LOCATING RENEWABLES AND ELECTROLYSERS

H_2 transport to end-use

WHY The development of an international hydrogen trade market would greatly accelerate the uptake of green hydrogen. Hydrogen trade will help secure the demand for green hydrogen in areas with limited renewable resources. By 2050, one-quarter of all the hydrogen produced could be globally traded, with about equal shares transported by pipelines and ammonia ships (IRENA, 2022e).

BOX 9.21 | Chile as a hydrogen exporter; Japan as a hydrogen importer

Chile has the potential to become one of the world's largest green hydrogen producers and exporters. The Magallanes region in southern Chile (a region with substantial wind resources) already has a combined electrolyser and wind turbine facility (see Box 9.17). In the north, the Atacama Desert receives some of the highest global solar irradiation, which could be harnessed by solar facilities and electrolysers. Chile also has the necessary infrastructure and port experience to become a large green hydrogen exporter and is already in discussions with Singapore and the Port of Rotterdam.

Japan has already taken steps towards large-scale hydrogen imports. Four Japanese companies (Iwatani Corporation, Kawasaki Heavy Industries Ltd., Kansai Electric Power Co. Inc. and Marubeni Corp.) have signed a memorandum with two Australian energy infrastructure firms (Stanwell Corp and APT Management Services Pty Ltd.) for the Central Queensland Hydrogen Project. The project will produce hydrogen using power from the 600 MW Aldoga solar project in Queensland, liquefy the hydrogen at the Port of Gladstone and ship the liquefied hydrogen to Japan.

Source: (IRENA, 2022e).

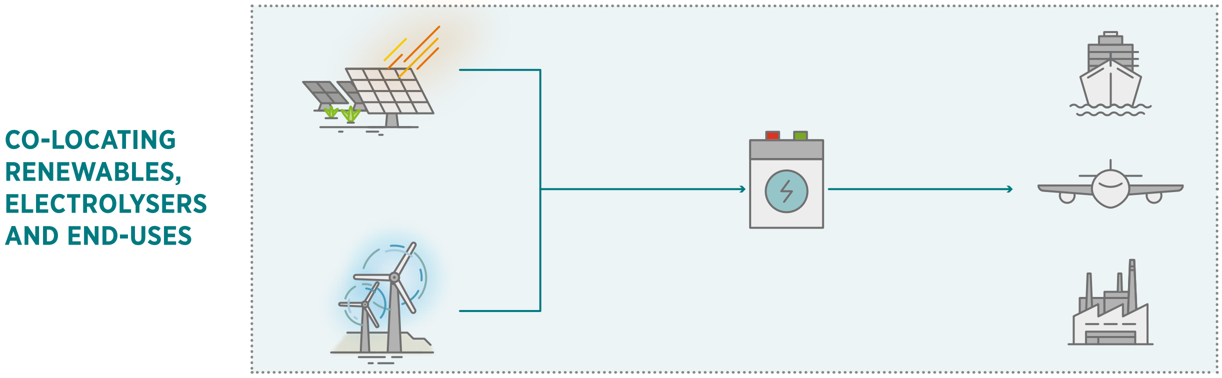
PRIMARY REVENUE STREAMS

28 Hydrogen industrial hub

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●○○○	●●●○	●●○○

WHAT Hydrogen industrial hubs group together renewable electricity generators, electrolysers for green hydrogen production and hydrogen storage facilities with industrial consumers (Figure 9.11). The idea is to locate all these facilities in close proximity to minimise the hydrogen delivery infrastructure, reduce logistics costs and enable the use of massive clean hydrogen production plants. These hubs thus provide economies of scale in producing, delivering and using hydrogen.

FIGURE 9.11 | Co-locating renewables and electrolysers with end uses



WHY Hydrogen hubs reduce the costs of transporting hydrogen and electricity from producers to consumers, while also ensuring reliable hydrogen supply for users and providing important economies of scale. All these benefits strengthen the business case for clean hydrogen investments.

BOX 9.22 | Decarbonisation of a major industrial cluster in Valencia, Spain

The industrial district of Castellón is one of the largest ceramic industrial clusters in Europe, and accounts for 95% of the ceramic industry in Spain. Because the ceramic industry is so energy intensive, this single industrial cluster emits 33% of the total CO_2 emissions in the Valencia region. The ORANGE.BAT project is designed to reduce those CO_2 emissions by replacing natural gas with green hydrogen. It will use a 100 MW pressurised alkaline electrolyser system. The project will also make use of the electrolyser's by-products. The oxygen will be used to improve the kiln process and the heat will be used for industrial and residential heating.

Source: (Evwind, 2021).

Stacking other revenue streams

STACKING OTHER REVENUE STREAMS | ㉙ **Revenues from flexibility provided to the power system**

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
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WHAT In addition to selling hydrogen, electrolysers can gain revenues by providing various grid services (*e.g.* offering reserves, peak shaving, capacity firming or alleviating grid congestion). Although these services are unlikely to provide the main revenue stream, when added to the revenues from providing hydrogen, their revenues can significantly improve the economics of electrolyser operation.

WHY Electrolysers can provide valuable grid services and help keep the power grid stable by ramping production up and down depending on its needs. The additional revenue from these services would then drive down the final price of green hydrogen, helping to accelerate the development of the green hydrogen economy.

BOX 9.23 | Pressurised alkaline electrolyser to provide grid-balancing services in Austria

The Demo4Grid project in Austria will use an "above" state-of-the-art 3.2 MW pressurised alkaline electrolyser to demonstrate the commercial potential of providing grid-balancing services in real-market conditions to the regional electricity supplier TIWAG. Meanwhile, the green hydrogen produced will be used to heat the Therese Mölk Bakery owned by regional food producer and trader MPreis.

Source: (Sunfire, 2021).

STACKING OTHER REVENUE STREAMS

㉚ Sale of electrolysis by-products (oxygen and heat)

Innovation readiness level	Impact on Hydrogen market development	Impact on Smart electrification and renewable integration
●●○○	●●○○	●○○○

WHAT In addition to producing hydrogen, the electrolysis process also produces pure oxygen and low-temperature heat. Electrolysers could sell both these by-products to gain additional revenue streams. The oxygen market is already well established, with many uses in industry, such as blast furnaces and glass melting. However, electrolysers selling oxygen would face strong competition from air separation units that produce oxygen at a very low price. Meanwhile, the low-temperature excess heat could be used for applications such as district heating or direct process heat in industry.

WHY Selling by-products has the potential to improve the energy and economic efficiency of power-to-hydrogen applications, strengthening the business case for electrolysers. This business model should be especially considered when developing large-scale clean hydrogen projects.

BOX 9.24 | HySynergy: Excess heat for district heating in Denmark

The HySynergy project, which is located next to Shell's Fredericia refinery in Denmark, will produce and store hydrogen in large quantities to supply the refinery and create a competitive supply of green hydrogen for use in heavy-duty transport. The project will begin with a 20 MW electrolyser, and then a 300 MW electrolyser and a 1 GW unit will be added. These electrolysers will also send surplus heat to TVIS (a utility located in the centre of Denmark), which uses a regional heating network to provide heat to 180 000 citizens in four major cities. The project will also explore the use of its oxygen by-product for carbon capture processes.

Source: (FuelCellsWorks, 2022).

BOX 9.25 | Power-to-gas-to-heat facility in Lahti, Finland

Nordic Ren-Gas developed a power-to-gas plant in Lahti for the production of synthetic methane, green hydrogen and district heating from the excess heat of the process. The location of the plant enables integration with a nearby district heating system.

Ren-Gas's objective is to build a production network that will deliver 20% of the fuel needed by the heavy road transport sector and 8% of the district heating needs by 2030 in Finland. This translates into the replacement of 2.5 TWh of district heating produced from fossil fuels. The overall project expects to avoid 1.5 million of CO_2 per year.

Source: (Ren-Gas, 2022).

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