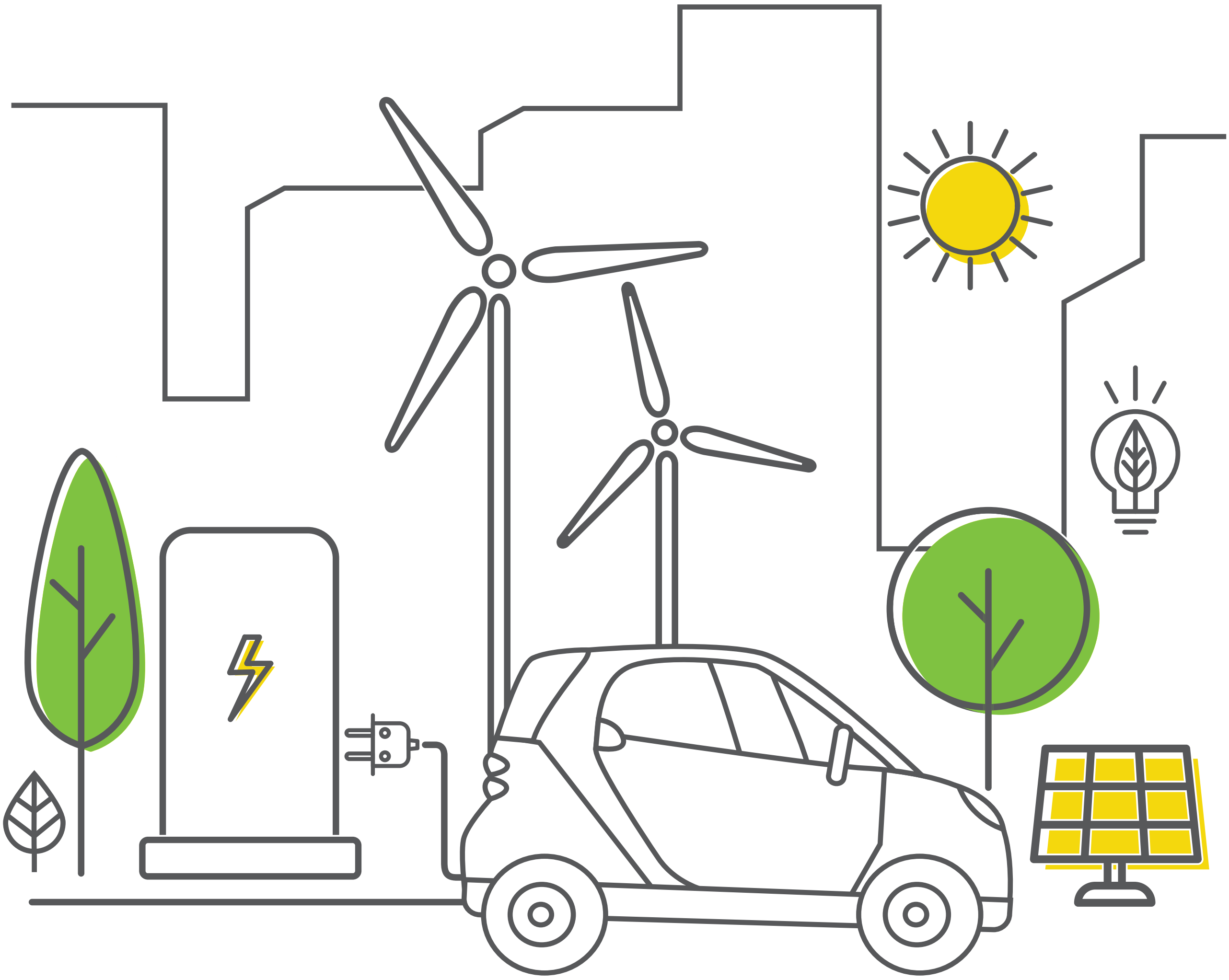
International Renewable Energy Agency

SECTOR COUPLING IN FACILITATING INTEGRATION OF VARIABLE RENEWABLE ENERGY IN CITIES



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About IRENA

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ABBREVIATIONS

°C	Degrees Celsius
CHP	Combined heat and power
CNFL	National Power and Light Company
CNY	Chinese yuan
CO_2	Carbon dioxide
CSP	Concentrated solar power
EU	European Union
EUR	Euro
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
GDP	Gross domestic product
GIS	Geographic information system
GW	Gigawatt
GWh	Gigawatt hour
HVAC	Heating, ventilation and cooling
ICT	Information and communications technology
IRENA	International Renewable Energy Agency
kWh	Kilowatt hour
m^2	Square metre
MRV	Monitoring, reporting and verification
MW	Megawatt
NDP	National Development Plan
NDRC	National Development and Reform Commission
NEA	National Energy Agency
NZC	Net zero carbon emissions
PCM	Phase change material
PV	Photovoltaic
R&D	Research and development
RMB	Chinese renminbi
TES	Thermal energy storage
TTES	Tank thermal energy storage
UK	United Kingdom
UN	United Nations
US	United States
USD	United States dollar
VRE	Variable renewable energy

EXECUTIVE SUMMARY

In the past few years, it has become increasingly clear that the world needs to reduce emissions of carbon dioxide, ideally to net zero, by mid-century if we aim to achieve the Paris Agreement target of limiting global temperature rise to below 1.5 degrees Celsius (°C) compared with pre-industrial levels.

According to the *World energy transitions outlook: 1.5°C* pathway from the International Renewable Energy Agency (IRENA), renewable energy would contribute more than 90% of the solution, both directly and indirectly through technologies across sectors, as well as through strategies aimed at making the best use of renewable electricity. As much as 60% of the reduction needed to achieve this scenario is embedded in the end-use sectors of transport, buildings and industry, while 35% is in the power and heat sectors. IRENA also estimates that renewable electricity could account for 86% of global electricity consumption by 2050 in the 1.5°C scenario, with 74% of which coming from solar photovoltaics (PV) and wind energy sources. To accommodate such high shares of variable renewables, the power system would require significant enhancement in grid flexibility.

These diverse end-use sectors, and how they would interact, have strong relevance to cities. Sector coupling technologies and strategies will play a key role in the transition. They can help decarbonise urban energy systems not only by deploying renewable-based distributed energy generation within and around urban areas, but also by facilitating the integration of variable renewable energy (VRE) sources such as solar PV and wind energy at the regional and national levels. Identifying and evaluating the various trade-offs presented by coupling different sectors to advance the urban energy transition towards net zero becomes crucial. This would facilitate the decision-making process within cities transitioning towards a net zero future, and also help other urban stakeholders understand that cities hold great potential to accelerate, and also benefit from, the race to net zero.

This report profiles sector coupling as a leveller to provide the enhanced flexibility that urban energy systems need. Cities, traditionally viewed as load centres, are transitioning towards being prosumers – both consumers and producers of energy – benefiting from the growth in renewable-based distributed energy generation within city limits. Sector coupling can help match production with consumption within the distribution network. However, it can also expand to the regional grid, when the VRE resources to be harnessed are located outside of the city, often in remote areas, and the generated electricity is carried via transmission lines to urban areas. It has become important to ensure adequate demand-side flexibility to support the grid in accommodating the large-scale generation of VRE.

In this report, the focus is on four main areas: self-consumption of VRE sources at various scales, the role of thermal energy storage in sector coupling strategies, electro-mobility (a promising scenario for decarbonising the transport sector with renewable electricity) and green hydrogen. The analysis also touches on several important areas affecting the adoption of sector coupling applications in the built environment, such as energy efficiency improvements in buildings as an enabler, and urban infrastructure that can underpin or impede the integration of different sectors into the network. These two areas are critical to set the boundary conditions within which the sector coupling opportunities can be identified to facilitate the integration of VRE sources.

In addition, the report highlights the key role that an intelligent energy management system plays in a coupled network. Instantaneously balancing variable production with demand cannot be achieved without a smart and intelligent management system. This would also avoid additional stress on the power grid if and when uncontrollable demand from end-use sectors other than the power sector is generated through the coupling approaches. In practice, deploying more advanced digital technologies in power systems can ensure greater awareness within operational systems, particularly when production and consumption are variable and uncertain on both the supply and demand sides. From a utility's perspective, making grid operations more flexible helps reduce the need for additional generation capacity to meet rising demand, thus increasing the use rates of existing energy infrastructure.

Quantifying the sector coupling opportunities at a city level requires an integrated approach to model the increasing complexity and interconnectedness of energy systems. In this report, a set of generic technical and economic indicators is proposed to preliminarily indicate the existence of sector coupling opportunities in self-consumption of variable renewables and utilising thermal energy storage as a coupling option for scaling up the use of renewables in cities. The report also introduces a modelling tool to provide quantitative evaluation of sector coupling opportunities in a given context, with a focus on the buildings sector given its importance for achieving net zero cities and communities. Cross-sectoral synergies through sector coupling technologies and trade-off options can be measured against optimisation objectives in different scenarios.

The tool was applied in a Chinese pilot study of Chongli district in Zhangjiakou city. The analysis reveals that electrifying the heating sector through heat pumps and with excessive electricity from the nearby wind farms, plays a central role to decarbonise the heating sector for the district. There would be around 360 GWh of surplus electricity consumed for the heating purpose. The use of heat pumps in combination with the district heating network provides opportunities for sector coupling for electricity and heating. It was estimated that there is a need to build a central district heating network that covers 36 000 square metres (m^2) in the short-term strategy, including seven sets of 46 MW hot water boilers, with the goal to expand the system to provide heating services for a total floor area of 4.5 million m^2. It also identifies one of the key factors to consider for the effective energy planning of Chongli district is increasing the seasonal energy storage capacity, which can be integrated into the heating system. In addition, sector coupling potentials in the public transport sector and other end-uses are also estimated in the analysis.

To better understand the pilot study results, the report provides national context on the energy transition in China. The focus is on city-level initiatives and on the key challenges associated with implementing sub-national clean energy and emission reduction initiatives – such as the lack of vertical and horizontal integration among government agencies at different levels and sectors, the lack of public awareness and engagement, and gaps between planning and implementation. Additionally, an overview of sector coupling applications in China provides historical background on pilot projects and programmes relevant to sector coupling in the end-use sectors but also in distributed energy generation with multiple sources. The focus is on renewables for heating and battery energy storage – two options that not only couple different sectors, but also enable cities to respond to VRE generation more effectively.

Within Chinese cities, the energy system has been linked increasingly with other urban functions such as municipal waste management systems. This is critical given China's growing urban populations and the limited capacity for conventional waste treatment options (such as landfills), as well as the negative environmental impacts associated with such conventional approaches. Advanced options such as waste incineration and anaerobic bio-digestion couple the waste sector with the energy sector, thus achieving gains in system efficiency and more efficient use of limited resources.

The other pilot study covered in this report is in Costa Rica. The country can benefit greatly from sector coupling from a decarbonisation perspective, given that it supplies nearly 100% of its electricity from renewable sources, mainly hydropower, and is experiencing growing energy demand in the transport sector, which is dominated by fossil fuels. The modelling tool was used to analyse sector coupling options for two districts in the Greater Metropolitan Area: Desamparados and San Rafael.

The results for Desamparados indicate that the renewable share of total final energy consumption can be increased from 36% to 60.4% by 2035 and from 39% to 100% by 2050, if sector coupling technologies are implemented. The locally generated renewable energy – mainly from rooftop solar PV – can be absorbed by electrification of the transport fleet, energy storage systems and/or used for producing hydrogen. Sector coupling potential also exists in the residential sector but depends on the household energy management system. Measures to be taken include the deployment of on-site control systems, subsidising energy-efficient electric appliances and introducing a taxation scheme for high-power-consuming equipment.

In San Rafael de Coronado, where the residential sector accounts for the lion's share of energy consumption, the district's lower population density enables ground-mounted installations for solar PV and even wind. Based on the analytical results, the renewable energy share will increase more significantly in the second half of the studied period, reaching 68% more than the reference case during 2035-2050, versus only 26% more during the first half. Among the supply-side strategies studied, the optimised solutions consider both vehicle-to-grid and hydrogen as sector coupling solutions. Here, 10% of the vehicle storage capacity can be leveraged or used by the grid at the district level, and an integrated system with multi-energy carriers can optimise the operating strategy between hydrogen production and electricity through the sector coupling approach. The result is a 100% renewable energy district at a lower levelised cost of energy (an estimated 15% reduction for the district of San Rafael) thanks to less constraint on installations of local VRE power generation systems.

In sum, cities have been stepping up their efforts to address the global climate challenge by scaling up the use of renewable energy, both locally and regionally. With the growing shares of VRE sources in electricity production, power systems have increasingly required greater flexibility. In addition to specific sources of flexibility – such as utility-scale battery systems, regulating power capacities, and regulatory instruments – there is huge potential on the demand side.

This report shows that integration of high shares of variable renewables can be achieved if demand-side sector coupling is deployed. In addition, the production of hydrogen from renewable power via electrolysis greatly expands the options for enhancing energy system flexibility. This is because hydrogen can be either used directly, or converted into different energy or industrial products, thereby tackling emissions in the hard-to-decarbonise sectors such as energy-intensive industries and long-haul shipping.

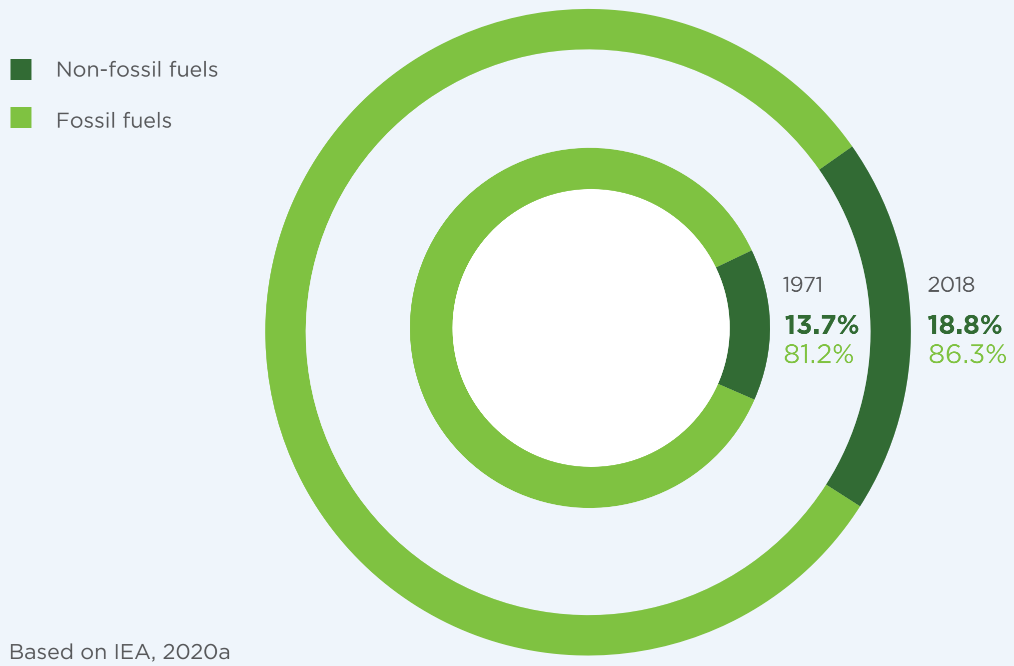

1

INTRODUCTION

1.1 The importance of cities in shaping global climate action

Cities are a key driver of global economic growth, which over the past half century has been powered primarily by fossil fuels (coal, oil and natural gas), as illustrated in Figure 1. Cities are responsible for an estimated 67-76% of global final energy use and contribute three-quarters of global energy-related carbon dioxide (CO_2) emissions (Edenhofer *et al.*, 2014; IPCC, 2018). To tackle the global climate challenge, the 2015 Paris Agreement calls for limiting the rise in the average global temperature to well below 2 degrees Celsius (°C) and ideally below 1.5°C compared with pre-industrial levels (UNFCCC, 2015; IPCC, 2018).

FIGURE 1: Share of global primary energy mix by fuel type, 1971 and 2018

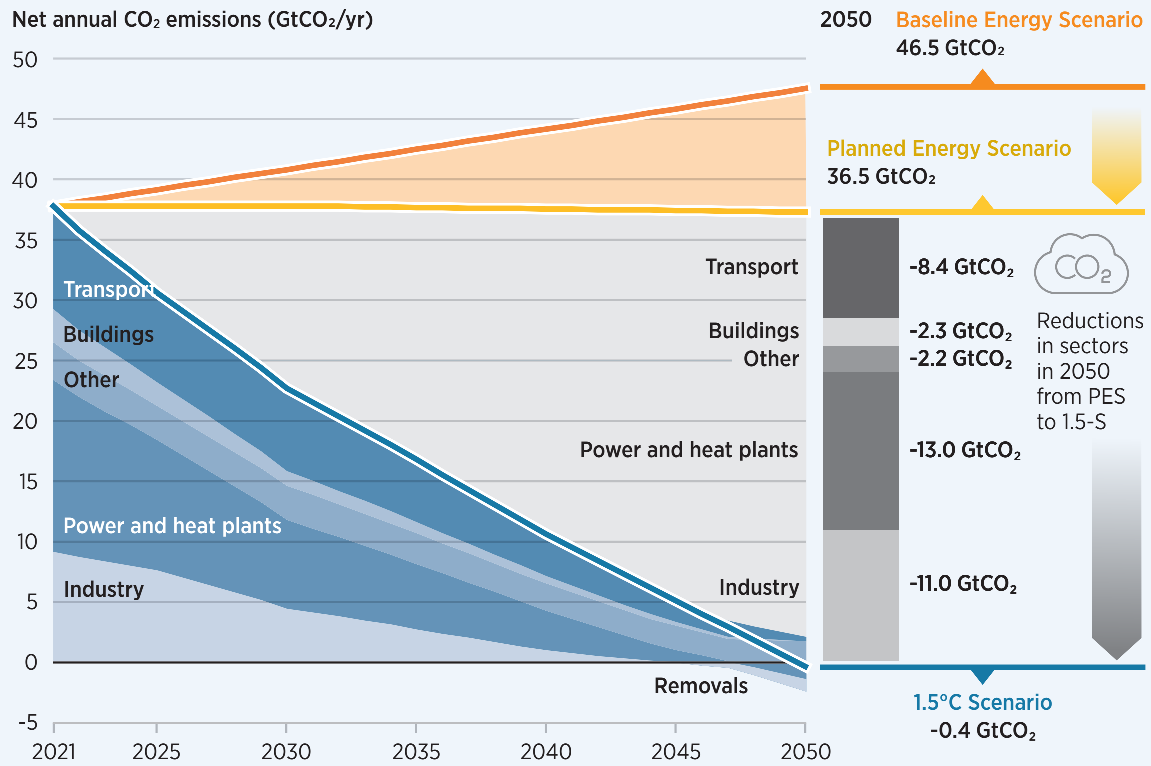


Based on IEA, 2020a

To chart out the roadmap for transitioning the energy system towards carbon neutrality by 2050, the *World energy transitions outlook: 1.5°C pathway* from the International Renewable Energy Agency (IRENA) has shown that the net zero target is technically attainable. Renewable energy would contribute more than 90% of the solution, both directly and indirectly through technologies across sectors, as well as through strategies aimed at making the best use of renewable electricity.

Importantly, the end-use sectors of transport, buildings, industry and heating hold huge potential for emission reduction through substituting fossil fuels with renewables and other low-carbon sources (Figure 2). These sectors have strong relevance to cities. Therefore, it is crucial that cities participate actively in helping to reduce global carbon emissions through effective local actions, and; the decisions that municipal authorities make regarding urban design, planning and energy infrastructure will have profound implications for future global energy and emission profiles.

FIGURE 2: Global reduction in energy-related CO_2 emissions needed by 2050 to achieve the 1.5°C climate target



Note: Gt = gigatonnes; PES = Planned Energy Scenario

Source: IRENA, 2021a

For cities, reducing today's emissions as part of the global effort to reach net zero by 2050 is only part of the challenge. Another big challenge is meeting the continued growth in urban energy demand, given that cities remain the engines of economic growth and that urbanisation is expected to continue. Between now and 2050, 2.5 billion people are expected to be added to urban settlements worldwide (UN DESA, 2018). Growth in the urban population – in addition to rising living standards and improved energy services for those who currently lack access to modern energy sources – will greatly increase energy demand in cities. The International Energy Agency projects that urban demand will drive as much as 90% of future energy growth (Carreon and Worrell, 2018).

The twin objectives of meeting rising energy demand while greatly reducing emissions will conflict if fossil fuels continue to dominate our energy systems. Reconciling these objectives in a meaningful way is a significant challenge facing cities.

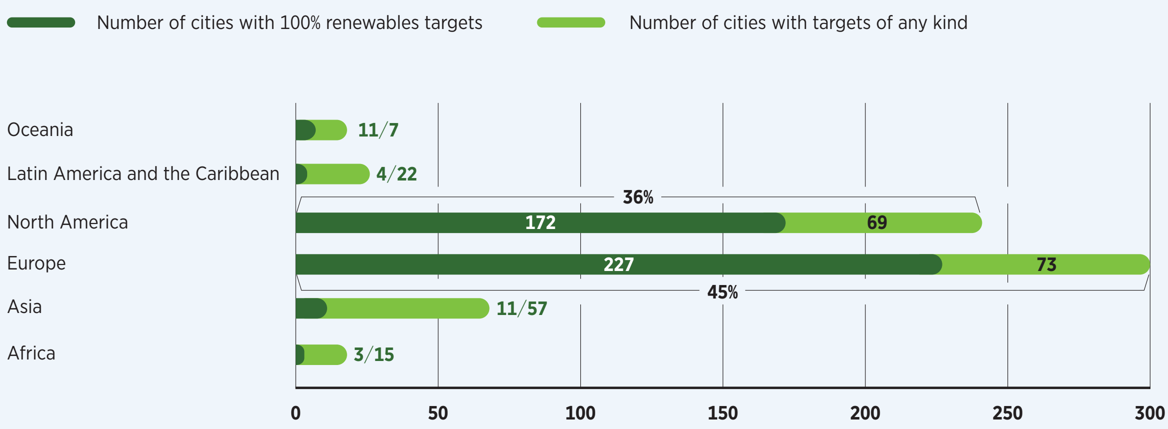
Yet, the benefits associated with achieving both objectives are rewarding, and they typically go beyond simply using more renewable energy and adopting energy efficiency measures to mitigate emissions. The co-benefits include: 1) the creation of local economic and job opportunities; 2) the development, diffusion and export of innovative technologies and business models underpinning the decarbonisation solutions; 3) greater energy independence and security of supply through the scale-up of renewable-based distributed energy systems and energy efficiency; and 4) improved environmental quality for urban inhabitants including clean air, less traffic noise and greater living comfort in buildings.

Another critical benefit of the energy transition is the enhanced climate resilience of future urban infrastructure to address the severe impacts from climate change. Already, as the average global temperature has risen 1°C above pre-industrial levels,[1] the world has experienced impacts ranging from recurrent heat waves and the recent deadly flooding in Europe, to severe drought in Africa, to large wildfires in Australia and the United States, as well as stronger wind storms and widespread flooding in Asia and the Pacific (UNISDR, 2016; Güneralp *et al*., 2015; Henley and Giuffrida, 2019; The Guardian, 2021). These extreme weather events are expected to intensify in severity and frequency and to occur in more areas and regions worldwide if we do not move quickly enough to mitigate climate change.

In this context, a growing number of cities have declared their climate ambitions and established some form of target to support renewable energy development. However, most of these cities are in Europe and North America (Figure 3). Cities in Asia and Africa need to step up their ambition and actions to tap into the opportunities emerging from the global energy transition.

1. The likely range of the increase is estimated at 0.8-1.2°C (IPCC, 2019).

FIGURE 3: Geographic distribution of renewable energy targets



Source: IRENA, 2020

Several cities have demonstrated greater ambition by pledging to be carbon neutral by 2050 at the latest. Copenhagen has taken the lead with its ambitious aim to achieve carbon neutrality as soon as 2025, which would make it the first carbon-free capital city in the world (City of Copenhagen, n.d.). Other frontrunners include Helsinki (aiming to be carbon neutral by 2035), Stockholm and Reykjavík (by 2040), and Berlin, London, New York and Oslo (all by 2050) (Carbon Neutral Cities Alliance, 2021).

In June 2020, the Climate Ambition Alliance: Net Zero 2050 launched the "Race to Zero" campaign, a partnership of various net zero-oriented initiatives and networks. More than 733 cities have joined the campaign (UNFCCC, 2021; Climate Ambition Alliance, n.d.), and C40 Cities, the Global Covenant of Mayors for Climate and Energy, and the Carbon Disclosure Project (CDP) have called for as many as 1 000 cities worldwide to sign on in advance of the United Nations (UN) Climate Change Conference to be held in Glasgow, Scotland in November 2021 (C40, 2020).

In sum, cities hold great potential to accelerate, and also benefit from, the race to net zero. They can strive to achieve this goal not only by deploying renewable-based distributed energy generation within and around urban areas, but also by facilitating the integration of variable renewable energy (VRE) sources such as solar photovoltaics (PV) and wind energy at the regional and national levels. However, for most cities, the task of achieving carbon neutrality by or before 2050 remains very challenging.

Against this backdrop, the coupling of end-use sectors in cities – from transport to buildings – with the power sector offers a promising option to unlock greater emission reduction potential and capture decarbonisation opportunities. Through such sector coupling, cities can develop urban energy systems that benefit from more intelligent energy management, higher efficiency in resource use and enhanced urban resilience against future climatic events.

1.2 About this report

This report highlights the importance of sector coupling as a key source of flexibility that cities can explore to stabilise power grid operations when integrating high shares of VRE. The expanded benefits – such as enhancing overall system efficiency, facilitating the adoption of the circular economy, and improving climate resilience through distributed generation and various energy storage systems – are beyond the scope of this report.

This report proposes a methodology through which sector coupling options in a given situation can be identified and quantitatively evaluated. A set of generic metrics might also be useful if an initial assessment is needed. Given that this report focuses primarily on quantitative evaluation, these generic metrics for initial assessment of overall sector coupling opportunities are mentioned briefly in the annex.

Two pilot studies, for China and Costa Rica, were conducted to identify the sector coupling opportunities in cities by applying this methodology. The country contexts were also provided to help shed light on the national contexts of decarbonisation dynamics. The report can be used by urban energy planners to understand the role of sector coupling technologies and strategies and to learn about the methodology that was developed by IRENA for quantitative assessment.

1.3 Sector coupling provides the enhanced flexibility that energy systems need

What is sector coupling?

While the term "sector coupling" is relatively new, the concept has been explored for decades.[2] It was first applied in Germany to underline the importance of electrifying energy end uses other than those of the power sector, such as in the transport, industry, buildings and heating sectors. Initially, the concept centred on making good use of excess electricity generated from VRE sources, particularly solar PV and wind power, which otherwise may be curtailed and wasted (Van Nuffel, 2018). Sector coupling can also provide clear benefits for a more efficient, electrified and renewable-based electricity system by enabling ancillary services in the organised wholesale electricity markets, if demand response can be enabled to participate in these markets through better design.

Over time, the scope of sector coupling has been expanded to cover the enhanced system flexibility that an energy system would require to address the emerging challenges of grid stability posed by integrating high shares of VRE. With the support of digitalised and smart systems, sector coupling technologies – such as electric vehicles (EVs) with smart charging, electric boilers and heat pumps, and electrolysers for hydrogen production – enable the demand to be more responsive to electricity prices or other signals in a physically interconnected network.

This makes it possible for a system integrated with electricity grids, the transport system and thermal energy grids to economically optimise the overall operations as one system – provided that the economic incentives for such system integration are put in place (such as supportive pricing mechanisms) (IRENA, 2019a). In return, this would facilitate the decarbonisation of

2. There is no universally agreed definition of sector coupling. From IRENA's perspective, it can be defined as the process of interconnecting the power sector with the broader energy sector (e.g. heat, gas, mobility).

end-use sectors whose energy demands traditionally have been met primarily by fossil fuels, such as petrol and diesel for transport (above 95%), and natural gas, coal or oil for heating in buildings (above 55%) (Abergel and Delmastro, 2020).

The literature around sector coupling is concentrated in three areas: 1) applications of sector coupling technologies, ranging from end users to energy generation using multi-energy sources/carriers; 2) modelling-based techno-economic analysis of sector coupling options and their associated costs and benefits, including emission reduction; and 3) the role of sector coupling in decarbonisation strategies at various scales. For instance, the European Commission views sector coupling as a strategy to build a highly flexible and integrated energy system. The aim is to achieve system-wide decarbonisation in a cost-effective manner through a combination of electrification of end-use sectors and coupling of different energy vectors on the energy supply side (European Commission, 2018).

This report is focused on the potential of sector coupling for facilitating the integration of variable renewables through enhanced energy system flexibility. However, implementing the proposed sector coupling strategies may also help improve the overall efficiency of urban energy systems and the climate resilience capabilities for cities.

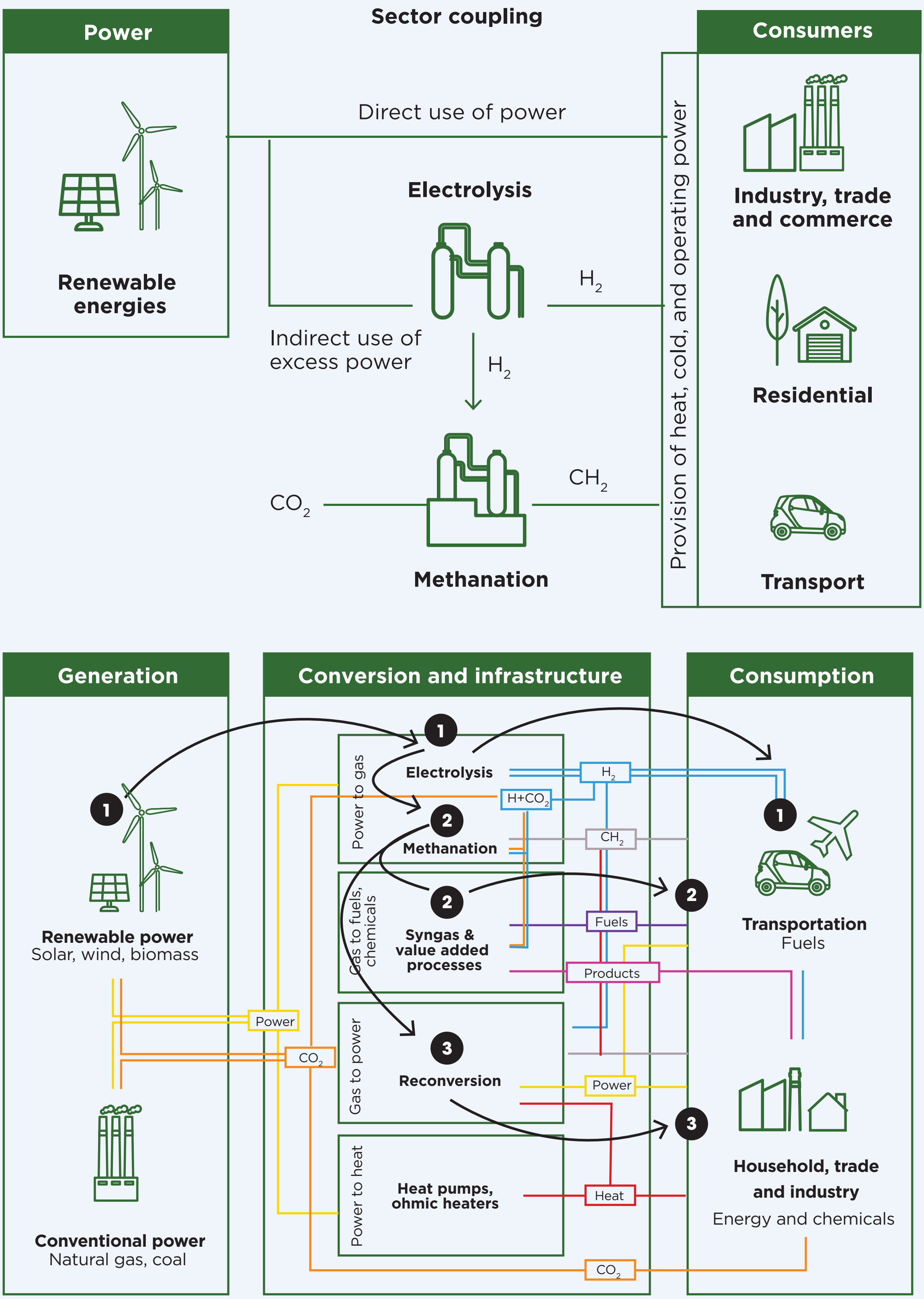
Enhancing power system flexibility through sector coupling

Renewable energy offers a promising solution for addressing today's intertwined climate and energy challenges because it can provide energy services without emitting carbon dioxide. Since 2009, the global installed capacity for renewable power generation has more than doubled, driven largely by VRE sources such as solar PV and wind power (IRENA, 2020a). IRENA estimates that renewable electricity could account for 86% of global electricity consumption by 2050 in the 1.5°C scenario, with 74% coming from solar PV and wind energy sources (IRENA, 2020b). This means that the power system would need to become much more flexible in order to accommodate such a high generation share from variable renewables.

Whether the emission reductions required to achieve the 1.5°C scenario (Figure 2) can be realised depends in part on the extent to which end uses can be intelligently coupled with the power sector. In other words, it depends on *how flexible* the future energy system can be – and sector coupling, as a key source of flexibility, has high potential to make meaningful contributions. Through approaches such as electrification and thermal energy storage, the various end-use sectors can be coupled to provide services such as heating, cooling and transport. Doing this efficiently will require support from digital technologies and smart energy management systems; advanced weather forecasting tools for solar and wind generation; and innovative business models such as energy-as-a-service, aggregation, peer-to-peer electricity trading, community ownership models, pay-as-you-go and urban energy planning (IRENA, 2019a; IRENA, 2019b).

Figure 4 illustrates the overall structure of coupling different sectors for enhanced energy system flexibility. For cities, the greatest potential of providing flexibility exists on the demand side and in end-use sectors such as buildings, transport and industry. The coupling can also take place between energy carriers on the supply side, for instance through power-to-gas, but this is beyond the scope of the study. Both approaches are instrumental to make the future energy system more integrated and flexible – a crucial enabler for scaling up the integration of variable renewable sources.

Figure 4: Illustration of sector coupling in relation to energy system flexibility



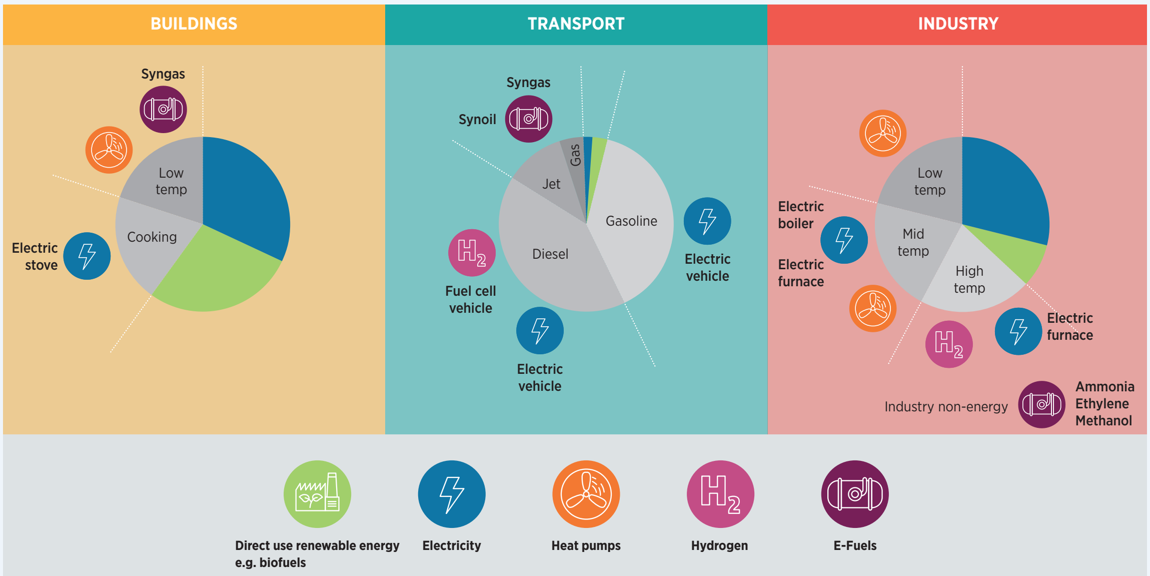
Source: Robinius *et al.*, 2017

In essence, coupling different sectors, along with the support of intelligent energy management systems, can broaden the options for dispatching electricity generated from VRE sources with greater grid flexibility to the system. In turn, this enables increased shares of renewables in the energy mix, and thus reductions in energy-related carbon emissions.

Importance of intelligent energy management systems in sector coupling

Although the technological scope for sector coupling strategies is expanding, electrification remains a key means for coupling different end-use sectors, as illustrated in Figure 5. Overall, there are two methods of electrification through which non-power sectors (on the demand side) and energy carriers (on the supply side) can be coupled with renewable power generation, particularly during periods of low demand when surplus renewable electricity is available. These are direct and indirect electrification.

Figure 5: Schematic summary of potential electrification technology applications



Source: IRENA, forthcoming-a

Direct electrification – through the use of technologies such as heat pumps with various sinks, EVs with smart charging, and electric stoves, boilers and furnaces – can be a way to replace fossil fuel consumption in end-use sectors such as buildings, transport and industry. (Indirect electrification is discussed later in this section.) With the progressive electrification of end uses, urban energy systems have the opportunity to harness intelligent energy management systems that can be applied across a greater array of coupled sectors to increase efficiency.

Coupling different sectors without upgrading the related energy management systems could lead to a situation of solving one problem by creating another. One example is the charging of EVs in an uncontrolled way, especially during peak load periods such as in the evening. One option to manage simultaneous demand during peak times is through demand-side management that uses smart charging schemes, with the aim of shifting the load of EV battery charging to off-peak periods. Electricity-driven air conditioning may pose a similar challenge. Here, cooling storage – coupling power and cooling demand – can offer a promising solution. Meanwhile, an effective demand response scheme could reduce peak electricity demand by an estimated 10-15% in most cases (Reynolds, Rezgui and Hippolyte, 2017). In this way, the overall system efficiency can be improved in a cost-efficient manner.

Such approaches require enhancements in energy management systems. The demand side can be made “smarter and more intelligent” by deploying more advanced digital technologies in power systems. Demand response would become more agile and inter-operational through sector-coupled technologies such as energy storage systems and EVs connected with smart charging facilities. This would enable increased integration of VRE in local energy networks and maximise the overall benefits by automatising the monitoring and operation of assets (Hossain *et al.*, 2016).

This also suggests that the smart energy management systems interact beyond components within the conventional power sector regime into other areas such as thermal energy networks, digitalisation, smart appliances and consumer behaviours. From the utility’s perspective, making grid operations more flexible also helps reduce the need for additional power generation capacity when demand is rising, thus increasing utilisation rates of the existing energy infrastructure (Thanos *et al*., 2013; US DOE, 2006; Dena, 2020).

With increasingly digitalised end-use sectors, the forward-looking technological breakthroughs in artificial intelligence, when integrated into smart grid management systems, offer a promising opportunity. This would help maximise the efficiency of future energy systems and the market, with high shares of VRE sources coupled with energy storage systems and other sector coupling technologies (DNV GL, 2019).

However, implementing these innovative technologies and solutions as part of improved energy management systems would require changes in existing market design and regulation. It would also necessitate smart grid protocols for interoperability between assets and systems, as some of the emerging technologies are relatively new and face non-technical challenges when adopted to make distribution grids smarter (DNV GL, 2019). Space must be created for the emergence and development of innovative business models in new market segments.

One example is the creation of local flexibility markets in which the distribution system operator can acquire aggregated flexibility from an online marketplace that brings together all resources available at the distribution level. This could include, for instance, the controllability of all the heat pumps as part of an energy management strategy to increase the grid’s flexibility to accommodate more VRE, and market signals as well if the right regulatory framework is in place (IRENA, 2019c).

The bottom line is that sector coupling technologies can add value by enhancing the level of grid flexibility, if applied properly. This is achieved by expanding the scope of responses from the various end users on the demand side. The overall efficacy can be measured by two metrics: *response time* – how fast the load can react to the alteration of generation to keep supply and demand in balance, and *scale* – in terms of both capacity (the maximal intervention it can deliver) and duration (how long the response can last, ideally weathering through the event period that needs to be managed). These can be used as generic indicators to initially screen through the possible sector coupling opportunities to identify the best fit in a particular use case or context.

However, the electrification of end uses may have its limitations – including temperature levels for certain industrial applications, energy density and constraints related to power grid infrastructure. Thus, sector coupling also has been applied through *indirect electrification* – that is, through the conversion of surplus renewable electricity into energy carriers such as hydrogen and its derivative synthetic fuels. Hydrogen is increasingly viewed as a promising decarbonisation strategy, particularly for hard-to-decarbonise sectors such as energy-intensive industries and long-haul shipping (IRENA, 2020c). Diversifying energy carriers offers an important potential way to couple the power sector with the natural gas sector – through blending of hydrogen produced through electrolysis into natural gas supply, but also utilising the gas pipeline infrastructure.

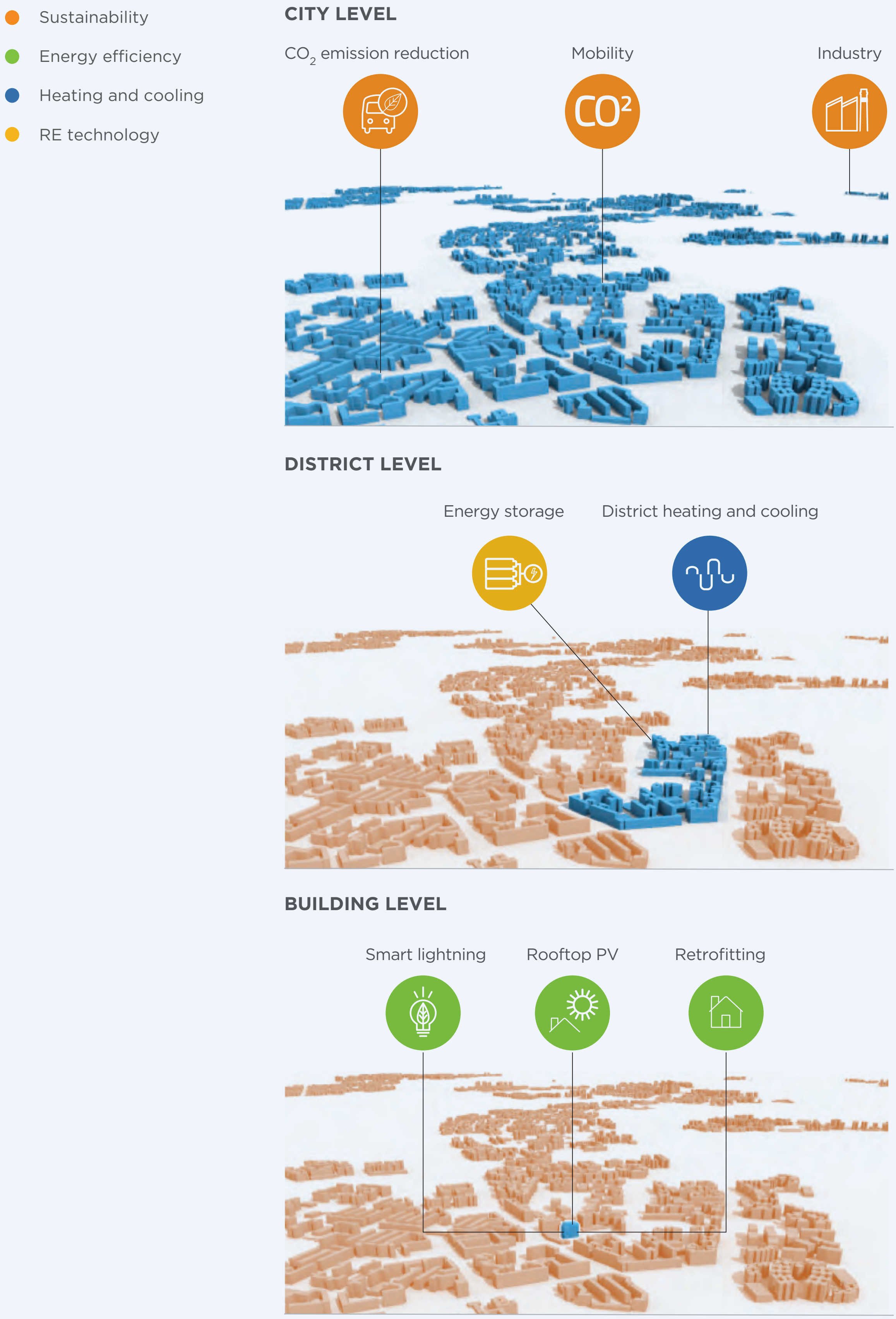
1.4 Methodology: Evaluating sector coupling potentials in cities to facilitate renewable energy integration

This report applies a combined method for assessing sector coupling opportunities in cities. First, Chapter 2 takes a descriptive approach to discuss the roles of various enablers, use cases and infrastructure, which are associated with the applications of sector coupling as a lever for cities to scale up the use of VRE. Chapters 3 and 4 then focus on quantitative analysis of two case studies – in Chinese cities and in Costa Rica – employing the modelling tool that IRENA has developed (presented later in this section). For each of these two chapters, an analysis of the country background relevant to sector coupling was conducted to provide broad context for the quantitative analysis that follows.

To quantitatively evaluate the integration of decentralised renewable energy at the urban level, an integrated modelling platform is needed that can handle the increasing complexity and interconnectedness of energy systems. Such a platform should also be able to evaluate sector coupling options in end-use sectors and on the supply side with multiple energy sources or carriers.

IRENA is developing a Planning Platform for Urban Renewable Energy that adopts an integrated approach, combining spatial analysis and energy system modelling at the building, district and city scales, as shown in Figure 6. Cross-sectoral synergies through sector coupling technologies and trade-off options can be evaluated in different scenarios that can be constructed based on the energy modelling results; however, a special focus is given to the buildings sector given the complex challenges it faces in decarbonisation. (For details, see the forthcoming user manual for the online version of the platform.) The present report focuses on application of the platform in the context of conducting quantitative evaluation of sector coupling opportunities in the studied cases.

Figure 6: Levels of analysis using the IRENA Planning Platform for Urban Renewable Energy



The following paragraphs briefly describe relevant components of IRENA's Planning Platform for Urban Renewable Energy with regard to the evaluation of sector coupling opportunities for cities.

1 **Optimising the use of variable renewables in buildings.** The energy performance of buildings, including the efficiency of the building envelope, is assessed as an indicator of the technical and economic viability of applying sector coupling technologies such as heat pumps. Retrofitting can greatly reduce energy losses and thus affects projections of future energy demand; as such, it has significant implications for the justification of sector coupling technologies and strategies. The assessment of a building's energy performance could also be used to determine the degree of retrofitting needed prior to adopting sector coupling technologies and strategies, with the interest of benefiting from surplus renewable electricity generation.

Techno-economic analysis is performed to identify optimal sets of sector coupling technologies to be used and how to operate to achieve the best performance. For example, based on the building envelope characteristics for different scenarios, when assessing space heating requirements the planning tool can provide optimised solutions among candidate technologies such as electric heaters, heat pumps for individual buildings, and district-scale solutions such as district heating networks. The end-use demand for the buildings sector can be evaluated according to granular input data on building envelope efficiency, and appliance use, or by providing a reference demand simulation model for which different building performance parameters can be evaluated. The industry and transport sectors also can be included in the analysis, provided that the demand can be measured for the industry sector and that scenarios on the vehicle fleet and use are available.

2 **Assessing energy infrastructure constraints.** Grid capacity is accounted for as a parameter for the optimal design of distributed systems. The operating strategy accounts for power flow analysis according to the optimal allocation of the building-scale energy systems deployed and the dispatch strategy. If the grid requirements are not met, another system design solution is computed, thus enabling the optimisation of import, export, local generation coupled with storage, and flexible loads enabled by the coupling technologies, according to existing grid capacity or requirements for grid upgrade. The tool can investigate trade-offs between deployment of building-level systems against network solutions, accounting for economies of scale and efficiency. This is particularly applicable for providing heating and cooling services. In this assessment, various sector coupling technologies and strategies, such as power-to-heat in district heating systems or individual buildings using different coupling technologies, can be evaluated.

3 Multi-sector analysis and sector coupling opportunities: The sectors considered in the platform span from residential to industrial, commercial/services and transport. Sector coupling options can therefore be analysed ranging from the coupling of different energy carriers to sector coupling options in the end-use sectors (for example, re-use of heat from industry processes for domestic hot water and residential space heating, or use of electricity for direct heating or within long-term heat storage technology, converted at high efficiency by heat pumps).

The key functionalities of the IRENA platform are summarised in Figure 7 and also described below.

Figure 7: Key functionalities of the IRENA Planning Platform for Urban Renewable Energy

Note: DHC = district heating and cooling

- **Renewable energy potential:** The platform includes the local renewable energy resource potential found within and near a city (based on the analysis performed). This includes solar and wind resources, biomass, waste and hydrological resources (IRENA 2020d). The temporal and spatial scales of the resource estimates vary by source. Intermittent solar and wind resources require at least hourly potential estimates throughout a typical year, whereas hydrological flows may be estimated seasonally. Biomass potential could suffice on an annual scale, whereas waste potential can be estimated on an annual scale based on macroeconomic parameters such as population and gross domestic product (GDP) if measured data are not available. The share of renewable energy that can be imported to the city is fixed by the user according to the different energy carriers and sources. These data are provided at an hourly or yearly resolution (*e.g.* the share of renewables in imported electricity or total yearly biomass resources that can be imported to the city), and include costs and carbon factors defined by the user.

- **Demand modelling:** The energy demand considered in the platform includes electricity, heat (space heat, domestic hot water, etc.), cold energy, and energy demands from other sectors such as transport or industry. Depending on data availability and the city to be analysed, the modelling of the demand can follow an engineering approach (*e.g.* demand simulation using EnergyPlus software) or statistical and calculation methods.

A combined approach can be performed for the extrapolation of the demand profiles to the city scale according to the input data. Measured data for archetypal buildings can be incorporated in the analysis to provide better estimates of the overall energy demand according to a portfolio of representative buildings.

- **Supply modelling:** This involves evaluation of the deployment potential of renewable generation within the city, considering the potential import and export from the regional grid. The energy conversion technologies (both renewable and conventional) modelled in the platform include both energy converters and carriers for the electricity, heating and cooling generation options. Renewable energy technologies include solar (PV, solar thermal, concentrated solar power), hydro (run-of-river, pumped hydro), geothermal (ground-source heat pumps, geothermal plants), biomass (biofuel, biogas and biomass converters), wind (wind turbines) and waste-to-energy. In contrast, "conventional" heat and electricity generation technologies use non-renewable resources such as fossil fuels, and include boilers and steam/gas turbines of various sizes, including conventional thermal power plants and co-generation plants (combined heat and power (CHP), micro-CHP, combined-cycle plants and tri-generation plants).

The objective is to understand and quantify at the city level how renewable technology can be deployed and integrated, and/or replace (in an optimal fashion), conventional generation. Subsequent co-optimisation at the regional or national level can then be performed with other appropriate models to reduce the risks of sub-optimal planning solutions, given the pre-defined boundary conditions at the city level.

- **Optimisation:** A multi-objective optimisation formulation minimises the overall system costs (*e.g*. investment and operation costs) and the total emissions resulting from system design and operation. A life-cycle analysis can be set up as input for the optimisation problem in order to account for the overall emissions apart from system operation.

- **Spatial and temporal visualisation (GIS):** The spatial and temporal aspects are crucial when modelling urban energy systems, especially if characterised by decentralised renewable energy penetration. Thanks to its GIS interface, the platform enables analysis at three different scales – the city, district and building levels – thus providing the option to analyse the energy system from a city level to a distributed scale (*i.e*. buildings). The inclusion of both a temporal and spatial aspect makes it possible to model the urban infrastructure networks as well, which are based on spatial information.

- **Building energy efficiency measures:** The platform allows for the quantification of the impact on heating, cooling and electricity consumption of energy efficiency measures concerning the retrofitting of the building envelope and the installation of more energy-efficient appliances in the residential sector.

- **Emission calculation:** The platform accounts for direct emissions – that is, emissions generated from the operations of conversion of fuels to meet energy demands (*e.g*. for heat, electricity, etc.) along the lifetime of the technologies. These include all renewable and non-renewable based heating, electricity and cooling technologies, as well as storage and transport options.


2

SECTOR COUPLING OPPORTUNITIES IN CITIES

This chapter highlights a range of sector coupling opportunities available for use in cities, with a special focus on the buildings sector. Specifically, it discusses the importance of energy efficiency in scaling up the use of VRE through sector coupling strategies; the opportunities for self-consumption of VRE; thermal energy storage as a sector coupling option to balance thermal energy demand and supply from variable renewable electricity. Electro-mobility and hydrogen are covered as both have emerged as promising technologies that can be applied in cities coupling different sectors. Lastly, the impact of urban infrastructure on applicability of sector coupling technologies in cities is also touched upon.

2.1. Energy efficiency in buildings as a key enabler for sector coupling

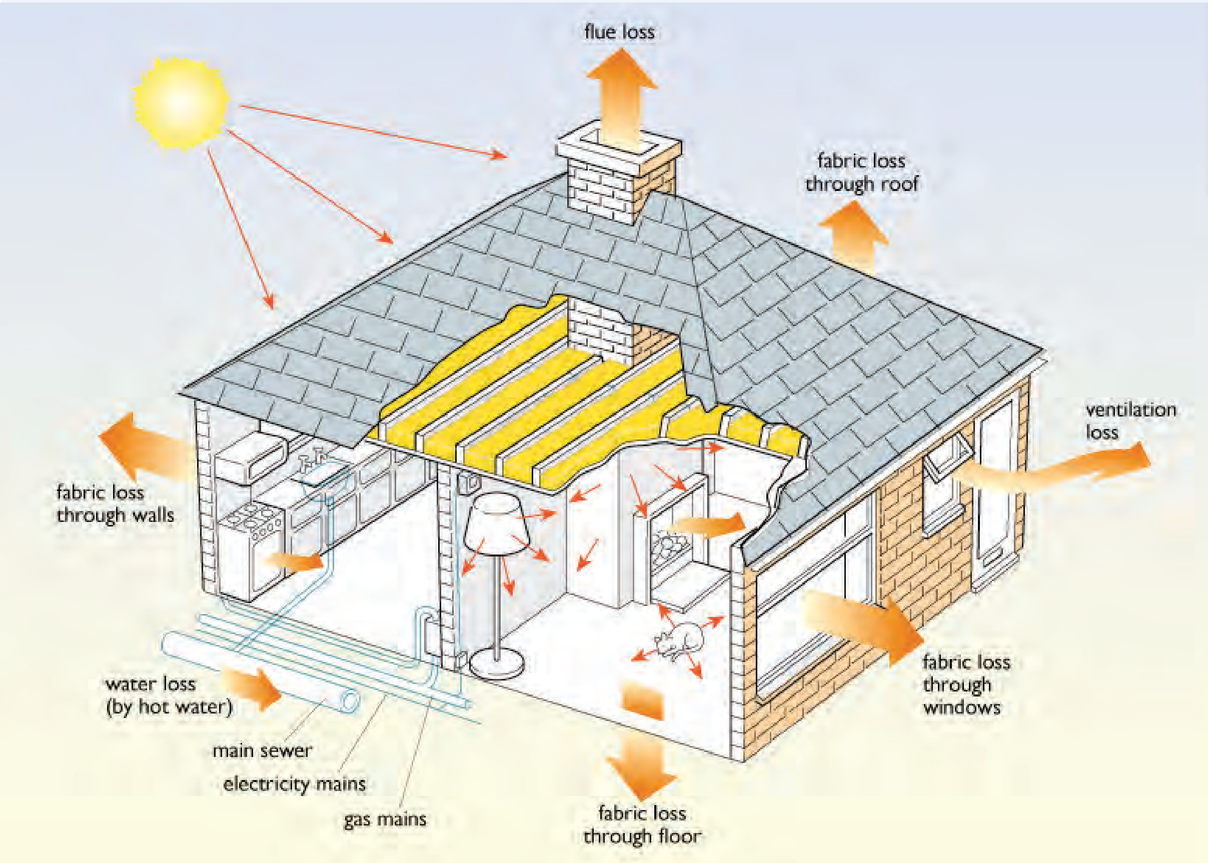
In principle, improving energy efficiency should always be the first option to take (when possible) to reduce energy use in all urban end-use sectors. This applies in particular in the buildings sector. Improving energy efficiency not only reduces the demand for primary energy, but also can increase the share of renewables in total final energy consumption; examples include the electrification of heating systems and cooking stoves (IRENA, 2015; IRENA, 2017). With the energy saved, the magnitude of the need for sector coupling would also be reduced, thus making the use of renewables through sector coupling approaches for buildings more economically justifiable.

From a sector coupling perspective, the efficiency performance of an energy end user becomes critical. This makes it possible to gauge the benefits of adopting sector coupling strategies that enable the full use of surplus electricity generated from VRE sources, while at the same time achieving greater demand flexibility. However, the prerequisite is that the electricity saved from curtailment on the supply side should not be wasted on the demand side due to low energy efficiency in urban end-use sectors such as buildings. Enhancing the efficiency of energy end uses would also improve the economic viability of applying sector coupling strategies in urban end-use sectors (WGBC, 2020).

Energy use from building operations accounts for around 30% of total global final energy consumption, with two-thirds of this attributed to heating and cooling uses and one-third to electricity consumption in buildings (UNEP, 2020; IEA, 2020b). Much of the thermal energy loss from buildings is through the building envelope (Nardi *et al*., 2018) (see Figure 8 for an illustration of heat flows through a building). Reducing such loss is crucial to minimise the need to replace fossil-based energy for space heating and cooling with renewable sources such as ground-source geothermal, solar thermal and heat pumps using various sinks.

However, according to the International Energy Agency's *Tracking Buildings 2020*, as many as two-thirds of countries have not yet issued standards for improving building energy performance (IEA, 2020c). This suggests that energy losses from building envelopes would remain substantial even for new buildings in some countries, unless building codes with stringent requirements for energy performance of the building envelope are put in place and enforced.

Figure 8: Heat losses through a building envelope



Source: Openlearn, 2020

Improving the energy performance of the building envelope can be effective in minimising the energy demand for space heating and cooling. This can be achieved by adding adequate insulation depending on the climate zone, using low-emissivity glass, and sealing air leakage in new buildings as well as in old/existing buildings through retrofitting measures.

In addition, the benefits of improving energy efficiency are obtained for the energy conversion of different energy carriers in the process of implementing sector coupling strategies, with the aim of improving overall system efficiency. Examples include power-to-heat through heat pumps, and EVs enhancing both engine and fuel efficiency in comparison to internal combustion engine vehicles. Moreover, this would increase the utilisation rate of power grids and reduce the need for and investment in transport fuel distribution infrastructure, thereby increasing overall system efficiency.

2.2. Self-consumption of variable renewable energy sources

With the growth in distributed power generation based on variable renewables, such as solar PV, many cities, particularly utility operators, are concerned about the impact of integrating these sources on the operations of power distribution grids. However, such concerns can be addressed by performing a grid stability assessment. Analytic tools such as PowerFactory[3] and FlexTool[4] can be used to assess the grid situation, although the results are subject to the availability and quality of data.

Based on the grid assessment, broadly speaking, there are two approaches to address this issue. One is to enhance the grid infrastructure. The other is to minimise the injection of distributed power generation from VRE sources back to the grid through increased use for self-consumption with battery energy storage; this will help mitigate the negative impact of distributed generation on the grid.

Self-consumption with battery energy storage capacity – the concept of consuming or temporally storing the generated electricity locally to batteries – offers an attractive option for increasing the share of VRE. This can be done to meet growing demand, or to replace fossil-based energy generation with a minimal need, if any, to invest in enhancing the physical infrastructure. From the grid operator perspective, self-consumption of VRE with battery energy storage can in general ease the operation of the current grid even with a high share of VRE in the mix.

On the economic front, self-consumption of VRE with battery energy storage means that the overall costs can be reduced thanks to the lower requirement for reserves to cover peak demand and/or reduced demand for adding peaker plants. This is particularly applicable for conventional air conditioners and EV charging, both of which can cause a surge in power demand in a relatively short period of time. Therefore, in most cases the self-consumption of VRE without impact on the grids is welcomed and encouraged by grid operators, especially in systems that lack power generation capacity.

The factors defining the configuration of installed VRE capacity for self-consumption usually cover more than just technical aspects such as the reliability of the urban power supply, local grid capacity to accommodate variable renewables, load profiles and energy demand projection. The economic elements such as tariff structure, business models, and economic and financial incentives, if applicable, also matter. Therefore, there is a strong business case for self-consumption of renewables when the electricity tariff from the grid is simply higher than the costs of renewable electricity generation from a user's own installations, owing mostly to disparities in tariff structure (*e.g.* time-of-use schemes).

However, without coupling the power sector with non-electricity end-use sectors, the options for balancing the electricity supply and demand in real time are technically limited.

3. PowerFactory is designed for grid connection and grid impact analysis.

4. The IRENA FlexTool is aimed at analysing the flexibility needs of power systems. Its advantages include short calculation times and the ease of configuring the tool to analyse multiple alternative scenarios with various levels of integration of VRE such as solar PV.

They include merely conventional electricity appliances, or they can be economically less optimal when only battery energy storage is used to match in time the variable generation and uncontrolled demand, provided that electrification of non-electricity energy end users takes place. Hence, to maximise the use of VRE for self-consumption purposes in various use cases or scenarios, a suite of sector coupling technologies and strategies linking the power sector with non-electricity end-users through smart energy management systems and market-oriented demand response schemes should be implemented.

In addition, self-consumption of VRE can be implemented at a district, community or neighbourhood level, often in a micro-grid configuration with the capability of running on a peer-to-peer power trade or virtual grid through smart energy management systems. In this case, the concept of "self-consumption" is extended into urban micro-grids that can be operated independently of the main distribution grids. This would also allow greater capacity of VRE to be installed for self-consumption.

A new area along these lines is an urban direct current microgrid, offering the potential to enhance overall system efficiency and greater shares of VRE in the system. Another emerging trend is the development of positive energy districts, designed to enable a given district, community or neighbourhood to produce *more* energy than it consumes on an annualised basis (Aghamolaei *et al.*, 2018). Self-consumption of local renewable energy is a major component of a positive energy district.

Although self-consumption with battery energy storage can reduce the flexibility requirements resulting from the rising share of VRE integration in the power system, and enhance overall system efficiency, it might also pose a challenge to the business models for grid operation by threatening the grid business models and eroding profitability when the VRE self-consumption share grows to a certain level (Dehler, 2017).Therefore, policy adjustment should be made to ensure the fair distribution of benefits and costs associated with self-consumption models.

2.3. Role of thermal energy storage in sector coupling strategies

In the urban environment, thermal energy demands originate primarily from the need for space heating and cooling, and cooking for building occupants and for other thermal energy services in the commercial and industrial sectors. For the heating sector, fossil fuels still contribute the dominant share of supply to meet this demand (IEA, 2019). As we move into a carbon-constrained future, decarbonising fossil fuel-dominated heating systems, particularly for industrial process heat supply, is a necessary yet persistent challenge. Beyond the climate concern, the combustion of fossil fuels for heating has long been identified as a key contributor to local air pollution that affects public health, particularly in developing countries.

Tackling this challenge requires powering the future heating infrastructure in cities with clean energy sources. Switching from coal-based to electricity-based heating systems provides a promising option, along with the rapid deployment of renewables. However, matching the renewable electricity generation and the heating demand would require the installation and scale-up of thermal energy storage systems in cities. Over the past decade, thermal energy storage technologies and applications have been developed and deployed for this purpose. Box 1 provides one example.

BOX 1

Phase change material (PCM) thermal batteries with smart energy management

In the last decade the United Kingdom (UK) has seen significant progress in decarbonising its power system. However, only 16% of final household energy consumption is electricity, while 81% is heat. The fact that 90% of UK homes rely on gas heating means that, overall, domestic heating results in 25% of the country's total carbon footprint. Therefore, if the country wants to achieve its recently declared goal of net zero emissions by 2050, a significant challenge will be how to decarbonise domestic heat.

Thermal batteries that use phase change materials (PCMs) could form part of the solution. One such battery uses an inorganic salt hydrate, sodium acetate, which has a phase change temperature of 58°C. The PCM technology has been engineered so that it can run 41 000 cycles without any degradation. The thermal battery has four times the energy density of a water tank thermal energy storage (TTES) and is non-toxic and non-flammable.

Over a 15-year time period, which is less than half the potential lifetime of the battery, the battery can deliver heat at around USD 0.05 per kilowatt hour (kWh), which is considerably less expensive than the equivalent energy stored in an electrochemical battery. Given that the lifetime is expected to be much longer, and degradation impacts are negligible, the thermal battery is a far more cost-effective solution for providing energy for heat than electrochemical batteries. The latest battery is claimed to be 60-90% cheaper than the cheapest lithium-ion alternative, per unit of energy stored.

The technology can be used in conjunction with rooftop PV, grid electricity through electric resistance heaters or using a heat pump. It has been involved in several trials. The first, which involved seven households, started in 2013 and has shown how household heating running costs are 50% lower compared to a gas-powered boiler. The next generation of batteries was trialled on a larger scale across 600 households in Scotland, 404 of which had rooftop solar PV included. It has shown that the majority of the tenants saved money.

In 2019 the UK government announced that it was awarding USD 2 million to fund a trial for the developer of the battery technology to work with an energy supplier to allow domestic customers to heat their homes with low-cost renewable electricity during off-peak times, enabled through the use of the supplier's energy management platform. This pilot aims to demonstrate the feasibility of smart electric central heating on the mass market.

Such a system could be critical to the future of the UK's domestic heating plans, as the government announced in 2019 that it would ban gas heating in new houses by 2025. It shows how thermal energy storage can be used to increase demand-side flexibility, something that will be critical to supporting grid stability if the widespread electrification of heat takes off.

Source: IRENA, 2020e

Globally, cooling demand is currently much smaller than heating demand. But since 2010 it has been growing rapidly, particularly demand for space cooling, representing the fastest growth in end-use energy demand in the buildings sector. By 2050, cooling demand is projected to triple as a result of rising global demand for space cooling from a near-doubling of the urban population (90% of it in Asia and Africa, where climates are warm or hot) and also of the additional cooling demand for existing households facing warmer summers across the globe (GlobalABC, IEA and UNEP, 2019). This signals an emerging challenge in coping with surging peak demand for electricity in hot summers in the future from a grid operation perspective (NASA, n.d.), unless cold energy storage and/or thermally driven cooling systems play a bigger role in offsetting the potential peak surge (UN DESA, 2019; IEA, 2018).

Against this background, coupling the power sector with the thermal sector could help decarbonise the thermal sector, particularly heating, taking advantage of the surplus VRE electricity generation when demand is low. Thermal energy storage plays a catalyst role in this context, given its capacity to cost-effectively balance the supply and demand, thus enhancing the coupling between the two sectors. In return, it facilitates the integration of VRE sources in the power system as a whole, by providing load shifting options to the grid operation. This is particularly important to distributed systems with high VRE penetration, namely solar PV and small-scale wind power in and around cities. Depending on the application, different thermal energy storage technologies can be used in cities, including sensible, latent, thermochemical and mechanical-thermal energy storage (Box 2) (IRENA, 2020e).

BOX 2

IRENA's work on thermal energy storage

In recent years, IRENA has generated several knowledge products relevant to thermal energy storage (TES), including a Technology Brief and an Innovation Outlook. These publications highlight the core values that TES can add to accelerate the integration of growing shares of VRE in the power mix. TES technologies, applied in centralised and decentralised energy systems, enable coupling of the thermal energy supply with renewable electricity.

Through this sector coupling strategy, the stability and reliability of grid operation can be maintained even without requiring grid upgrades or curtailing the excess electricity generated from variable renewables. The heating and cooling sector can also benefit from the off-peak electricity if economic incentives are in place.

In return, thermal energy supply, currently dominated by fossil fuels, can be decarbonised more quickly, especially in built environments that have high population densities and where district energy infrastructure connected to buildings is in place or can be economically justified. Electrification of the heating sector is also discussed in the forthcoming IRENA report *Smart electrification with renewables: Driving the transformation of energy services*.

Sector coupling via TES can also be applicable for cold chains, including serving as the cooling source in refrigeration vehicles instead of consuming transport fuel or battery-stored electrical energy in the case of electric trucks. Looking forward, a variety of innovative TES technologies are still in the research and development (R&D) stages but hold different degrees of potential in adopting sector coupling strategies in various use cases in the future.

Source: IRENA, 2020e

2.4. Electro-mobility coupling the power and the transport sectors

Shifting from internal combustion engines to electric vehicles, powered potentially by renewable electricity, provides a plausible solution to decarbonise the urban transport sector. For cities, the co-benefits associated with the shift include less air and noise pollution on the road, supporting the local economy when the electricity is generated from distributed power generation systems, and reducing energy dependency on the supply of petroleum-based transport fuels, thus improving energy security.

Yet, one of the most important drivers of rising EV interest may be the vehicles' cost-competitiveness over their lifespan, due to lower "fuel" costs and reduced regular maintenance costs compared to internal combustion engine (ICE) vehicles. Looking forward, this cost advantage is likely to improve, given that the costs of batteries are expected to continue to drop along with the growth in EV users and due to sustained technological advancement. Putting a price on carbon emissions would accelerate the transition for the transport sector. In addition, a growing number of jurisdictions have set targets for phasing out sales of internal combustion engine vehicles or for increasing the share of zero-emission vehicles in new vehicle sales to 100%. By the end of 2020, at least 20 countries had made such announcements, following the strong and rapid growth of EVs during the previous decade, with the total stock now exceeding 10 million compared to a negligible level in 2010 (IEA, 2021).

According to IRENA's 1.5°C scenario, the rapid progress of adopting EVs would accelerate more in the coming decades (IRENA, 2021a). Electricity consumption in the transport sector would increase to 49% from today's 1% over the next three decades, as a result of 178-fold growth in electric light-duty vehicles in the transport fleet and 28 million heavy-duty electric trucks by 2050. To achieve this scenario, the coupling between the two sectors should be extended to full integration of these sectors through smart technologies and necessary change in the regulatory framework, such as smart charging facilities and compensation for ancillary services to grid operations (through which the power sector could also benefit from, and provide support to, the continued adoption of EVs). In this way, the negative impact on grids in cities can be mitigated, as shown in Figure 9.

Figure 9: Impact of smart charging from different studies

- Peak load with uncontrolled charging
- Peak load with smart charging
- Curtailment in no EVs scenario
- Curtailment with smart charging EVs

Study	Scenario	Uncontrolled charging	Smart charging	
IRENA	**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	9% 5%
RMI, 2016	**23%** penetration US (California, Hawaii, Minnesota, New York, Texas)	**↑11%** increase in peak load	**↑1.3%** increase in peak load (V1G)	11% 1.3%
Taljegard, 2017	**100%** penetration Denmark, Germany, Norway & Sweden	**↑20%** increase in peak load	**↓7%** decrease in peak load (V2G)	20% -7%
McKenzie, 2016	**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	23% 13%
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, 2019d

There are a few levels of sector integration. All are aimed at gaining some degree of control over the charging process using various technical and economic options. The easiest approach is simply applying the conventional demand response techniques for EV charging, such as load shedding and time-of-use pricing mechanisms. However, to fully integrate the transport sector into the power sector (as part of the electricity storage capability to deal with grid stability issues when high shares of VRE are present), more advanced charging facilities and schemes would be needed to provide close-to-real-time responses among other grid services that EVs can offer. More details can be found in IRENA's *Innovation outlook: Smart charging for electric vehicles* (IRENA, 2019d).

2.5. Green hydrogen for decarbonisation in a sector-coupled system

Green hydrogen production

Hydrogen from renewable power, often called green hydrogen, ensures a low-carbon hydrogen supply that is essential to achieve carbon-neutral goals by 2050 (IRENA, 2018). Besides having nearly zero emissions, green hydrogen has a higher degree of purity compared to fossil fuel-based hydrogen pathways (with and without application of carbon capture and storage technologies, known as "blue" and "grey" hydrogen respectively). This advantage of green hydrogen makes it suitable for immediate use in fuel cells and in many other applications for different end users in cities and beyond.

Currently, green hydrogen costs between two and three times more than "blue" hydrogen. Electrolysers, the devices necessary to produce hydrogen using electricity and water as inputs, are scaling up quickly as costs are projected to halve in the coming decade through continuous innovation, performance improvements and upscaling from megawatt (MW) to multi-gigawatt (GW) levels (IRENA, 2019e; IRENA, 2020f). At the same time, renewable electricity costs continue to fall, and renewables may soon become the cheapest pathway to produce hydrogen (IRENA, 2020g).

The role of gas infrastructure

When not produced on-site, hydrogen must be transported to end users as a liquid or compressed in tanks or gas pipelines. The existing natural gas network can be retrofitted to deliver hydrogen, making use of assets that would otherwise become stranded in the medium term. Such an approach could accelerate the deployment of hydrogen while also acting as a large and low-cost source of energy storage (Panfilov, 2016).

At low shares, the blending of hydrogen into natural gas at the transmission level should not face significant technical challenges. For up to 10-20% shares in volume, limited investment would be required, mostly for the replacement of compressors and gaskets (IRENA, 2018; Judd and Pinchbeck, 2016; Müller-Syring *et al.*, 2013; DNV GL, 2017). Other concerns relate to embrittlement for current high-pressure transmission pipelines if converted to pure hydrogen, as well as reduced energy density and line-pack buffer storage, together with a series of regulatory and safety requirements that would have to be adjusted (Dodds and Demoullin, 2013; Sadler, Anderson and Sperrink, 2018). Ultimately, optimal blending concentrations strongly depend on the characteristics of the existing network, natural gas composition and end-use applications.

The extent to which the distribution network systems need adjustment also varies. While plastic polyethylene pipelines are generally suited for hydrogen gas, old cast-iron pipelines in cities are not. Another challenge is in applications where the equipment would need to be adjusted or replaced to deal with hydrogen gas.

Applications in sector-coupled systems

Hydrogen, along with fuel cell technology, can replace fossil fuels that are used today for heating, power and transport in cities. In 2019, the government of the Republic of Korea announced plans to build three hydrogen-powered cities by 2022 where hydrogen can possibly replace natural gas boilers for heating or be converted to electricity through fuel cells to power fuel cell electric vehicles and trains or to simply feed electricity back into the grid (Edmond, 2019). The project is progressing despite being affected by the COVID-19 pandemic. Other cities may follow a similar path.

TRANSPORT

The prospects for hydrogen in transport are mainly as a complement to electrification for niche applications that are still required to meet a net zero emission goal. In other words, most passenger and freight activity is expected to be satisfied with electricity, but hydrogen is still needed for full decarbonisation[5]. Batteries will be favoured for applications that have low power requirements (*e.g.* smaller than mid-size or class D passenger vehicles), short ranges (*e.g*. buses with short routes) or with limited time for recharging (*e.g*. forklifts).

Thus, trucks in mountainous regions, trains along low-frequency routes with long distances, and large fleets with limited depot space will all favour hydrogen, but these do not represent the largest share of transport demand. The boundary for the operating conditions where each is the most attractive will depend on technology development in the coming years. Batteries continue to make strides in cost and energy density, and, if the trend continues, they might be suitable even for applications such as heavy-duty trucks (IRENA, 2020h)

Fuel cell electric vehicles (FCEVs) use a powertrain system like that of electric vehicles, with the difference that the electricity is converted from hydrogen in a fuel cell[6]. Compared to conventional vehicles, they have a similar driving range and can be refuelled just as quickly with the advantage of being more efficient on energy use, although they have half the efficiency of battery electric vehicles. However, given that range and charging time are precisely where battery electric vehicles fall short, FCEVs expand the scope of electric mobility to high-duty cycle segments, such as long-range and high-utilisation road vehicles (trucks, buses), trains, ferry boats and utilitarian vehicles such as forklifts, without adding much to the weight.

The building of hydrogen refuelling stations across cities is a fundamental step, just as developing charge centres is for battery electric vehicles. The costs of hydrogen refuelling infrastructure per vehicle are initially 3-4 times higher than for battery electric vehicles, although they are expected to decline as more refuelling stations are built and large-scale units are in place (Hydrogen Council, 2020). However, a disadvantage for FCEVs is that the net investment is

5. The bulk contribution of hydrogen in transport should be expected in long-haul modes such as international aviation and shipping, which were considered outside the scope of cities in this study.

6. A fuel cell generates electricity through a chemical reaction between the stored hydrogen and oxygen, producing water and hot air as a by-product.

much higher, and it requires a minimum number of FCEVs to simultaneously be deployed, whereas charging stations for battery electric vehicles can be deployed for a single car.

Thus, investment in hydrogen refuelling stations is risky without ensuring that there will be demand in the medium and long terms. For the technology to be viable, large-scale installations are necessary to achieve economies of scale, and securing a critical volume of hydrogen demand is a major roadblock to investments. Nonetheless, in the short to medium term, hydrogen could initially be produced on-site at smaller stations, beginning with dedicated fleets of taxis, buses and trucks that would return to their base to be refuelled, or for which travel patterns are more easily tracked. Such schemes would also ensure high utilisation rates.

At the moment, there are nearly 650 hydrogen refuelling stations around the world, led by Japan with 163 stations, Germany with just over 100 and the Republic of Korea with 73 (IPHE, 2021). Hydrogen buses are already widely deployed, with China having the largest fleet at almost 3 600 fuel cell electric buses (E4tech, 2021). Several hundred of the buses are on the road in Chinese cities such as Beijing, Shanghai, Wuhan, Zhangjiakou and Zhengzhou (Holland, 2019). In Shanghai, a logistics company put in operation 500 fuel cell buses. Meanwhile, Japan will utilise hydrogen buses for the 2020 Olympics.

A recently announced H2Bus consortium in Europe aims for 1000 commercially competitive buses fuelled with hydrogen from renewable power, the first 600 of which are due by 2023. In Germany, 22 fuel cell buses were to be integrated into the local fleet of Frankfurt in 2021, Cologne has added 10 fuel cell buses, and Wuppertal has 15 units.

In addition to road transport, hydrogen can be used in fuel cells to power trains. The first fleet of hydrogen trains, manufactured by Alstom, is being deployed for commercial service in northern Germany to replace diesel trains on non-electrified lines, which allows system providers to avoid the high capital expense of building overhead wires. Other countries are planning similar steps including Austria, Italy, the Netherlands and the UK.

HEATING AND COOLING

The use of hydrogen for heating is potentially a decarbonisation option in regions and cities where retrofitting the natural gas transmission and distribution network is part of the agenda, in an effort to accept blending shares or to become 100% hydrogen networks in the medium and long terms. In the short term, however, the limited infrastructure and the still relatively high cost of hydrogen[7] will require collaboration between private and public stakeholders.

Natural gas boilers and appliances would have to be replaced to run on hydrogen. Since 2016, the city of Leeds in the north of England has explored converting the local gas pipeline network to a 100% hydrogen network. The project is evaluating the technical-economic feasibility of transporting hydrogen though the existing network as a key option for decarbonisation of heating. The study foresees replacing natural gas boilers with hydrogen-compatible appliances in some 3.7 million homes and businesses by 2035, and 15.7 million by 2050.

The UK undertook a similar endeavour in the 1960s when a nationwide gas conversion programme converted 40 million appliances, reaching a peak of 2.3 million per year. More

7. Transitioning from fossil fuel-based heating (mostly natural gas) to hydrogen may cost as much as three times that of natural gas.

than 80% of the UK population now uses this gas network for heating and cooking (Northern Gas Networks, 2017). Japan has already deployed more than 300 000 micro CHP units through the EneFarm programme, and the market is almost self-sustainable (subsidies for one technology have been phased out since 2019) (E4tech, 2021).

The higher efficiency and the lower corresponding fuel costs favour the use of heat pumps for low-temperature applications. While it is expected that renewable electricity will be able to satisfy the bulk of low-temperature heating (IRENA, 2021a), hydrogen could be used for applications that have space constraints, for historical buildings, or in the form of hybrid heat pumps to satisfy the peak load, representing only a small share of the overall demand. Moreover, the technical feasibility of heat pumps relies on proper insulation, which may be challenging in old buildings. In addition, a massive adoption of heat pumps may require upgrading the electrical grid due to the additional load.

STORAGE AND POWER GENERATION

Hydrogen can be stored in large quantities and represents the most feasible solution to deal with seasonal variation of solar and wind at a large scale as the global energy system moves towards net zero emissions. While the set of power flexibility options such as batteries, demand management and cross-border power exchange should be sufficient for energy systems that are up to 80% renewable, hydrogen is important to cope with the last 10-20% towards 100% renewable energy systems (and cities).

Storage can be done in pressure vessels, as liquid in insulated tanks, or embedded in organic liquids, although the most promising option may be in salt caverns. Regions with abundant salt deposits have been identified in the US, Canada and Europe (Lemieux, Shkarupin and Sharp, 2020; Caglayan *et al*., 2020). Salt cavern facilities in operation in the UK and the US have proven technically feasible with storage capacities in a range of 210 000 cubic metres to 580 000 cubic metres. According to Caglayan *et al.* (2020), the overall technical storage potential in salt caverns across Europe is 7.3 petawatt-hours of hydrogen, considering onshore and offshore caverns within a range of 50 kilometres from the shore.

Other regions with good potential based on estimates for compressed air energy storage (CAES) and CO_2, which also use salt caverns, are Africa, the Russian Federation, Latin America and the Middle East (Kearns *et al*., 2017), more specifically Siberia and the Russian Far East, Brazil, Central Africa and Libya (Aghahosseini and Breyer, 2018). The method of storage also influences the way hydrogen may be transported at a next step on the chain.

The hydrogen produced and stored in moments of energy excess can be converted back into electricity using a fuel cell. However, the entire process – power to hydrogen and back to power – has a poor round-trip energy efficiency of only 20-35%. This process should be fundamental to produce power at short notice whenever renewables and other flexibility options are not available, whether during the peak or as a result of weather patterns during the year. In other words, hydrogen is the last-mile technology needed to ensure that massive electrification and the final goal of decarbonisation are possible.

Stationary fuel cells for power generation or for decentralised use in mini-grids can play an important role in replacing back-up diesel generators in locations that require high reliability, such as hospitals, fire departments and data centres. Such systems are more efficient than conventional generators, potentially have lower maintenance rates since there are few moving parts and can meet a wide range of needs, from loads of a few kilowatts to multi-megawatts. Fuel cells can also be implemented as part of a CHP system, where the waste heat can be further used in a secondary process. Stationary fuel cells produce negligible local pollution emissions and have relatively low noise, making them well suited for urban areas.

2.6. Urban infrastructure interacting with sector coupling applications

As mentioned previously, urban infrastructure has an impact on the applicability of sector coupling technologies and strategies, whether positive or negative. The nature and extent of the impact depends substantially on: 1) how well different infrastructures – for instance, the power and transport systems – are connected technically as well as regulatorily, and 2) how smartly the networked infrastructure is managed as a whole. For the latter, the adoption of digital devices that facilitate communication among different systems is usually recognised as an enabler, as shown in Box 3 with respect to how it can address the grid congestion caused by a rapid surge in power demand associated with EV charging (Gielen *et al.*, 2019).

BOX 3

Hamburg's electrified transport sector and charging infrastructure

With rapid growth of EVs in Hamburg, electro-mobility has demonstrated exemplary benefits from the coupling of the power and transport sectors, such as decarbonising the transport sector and reducing local air pollution while increasing electricity sales by the local distribution system operator, Stromnetz Hamburg. However, such benefits were not capitalised until the resulting negative impact of this coupling on the grid operation was successfully addressed, especially in weaker sections of the distribution grid.

As with the use of heating, ventilation and cooling (HVAC), the challenge lies in the constrained peak capacity of low-voltage grids, rather than in the consumption of the electricity for charging the EVs. This is largely attributed to uncontrolled charging at households, which occurs mostly in the evening. Stromnetz Hamburg estimated that the grid congestion issues would emerge already with only 3% of the EV fleet, and that the congestion issues would paralyse 15% of Hamburg's feeders when 9% of the EVs were connected to the grid for charging at the same time period.

To address this issue, two plausible solutions exist, broadly speaking: 1) enhancing the grid capacity along with the increased peak loads – an established conventional approach that utilities often take, or 2) managing the peak loads in a smart way with the support of digital devices. Stromnetz Hamburg assessed both and found that the conventional solution would cost the utility a minimum of EUR 20 million (USD 22.4 million) for the grid enhancement to address the 9% of EVs' simultaneous charging. This also implies that additional costs would be needed if the number or share of EVs grows over time.

The second option is to modernise the grid by installing digital devices that sense and monitor the grid situation instantaneously and then automatically and autonomously make the adjustments necessary to ensure the stable, reliable and safe operation of the distribution network. This approach will address not only the issue of charging EVs, but the potential challenge from other loads such as HVAC, heat pumps and VRE-based distributed energy generation systems without battery storage installed.

Hamburg's case has proven the effectiveness of digital technologies in terms of load shedding and balancing the variability between demand and supply, thus enabling the adoption of sector coupling technologies such as EVs in urban decarbonisation strategies.

Source: Gielen et al., 2019

In addition to digitalising the power infrastructures, changes would also need to take place in the regulatory regime (such as the implementation of time-of-use schemes) and in business models (such as the aggregation of small independent power producers to formulate a virtual power plant, or end-use demand such as smart heat pumps providing grid auxiliary services) (IRENA, 2019f). Only with such systemic change will the networked infrastructure be able to support the adoption of sector coupling technologies in cities, with the aim of facilitating the integration of VRE.

Traditionally, thermal networks in cities have operated independent of the power grid. This paradigm has changed in recent years, along with using surplus electricity generated from VRE for heating, mostly through centralised or district thermal networks to maximise the overall energy as well as economic performance. Thermal energy storage systems are usually installed to balance the surplus electricity and the heating demand in time and scale. Such coupling of the power and thermal sectors requires not only the integration of physical infrastructure but also co-ordination at the regulatory level, given the disparity of the tariff structure for electricity versus thermal energy services (as also discussed in Box 4 in Chapter 3).

As the demand for cooling is expected to grow rapidly, renewable-based cooling solutions will have a bigger role to play. Centralised cooling systems that leverage the free cooling sinks or stored cold energy would provide a platform for coupling the cooling sector with the power sector.

Innovation in the thermal networked infrastructure could provide even more opportunities for sector coupling. An innovative concept, known as the ectogrid™, has been gradually applied in the real world. The core advantage is maximising the use of waste thermal energy in a closed pipeline system among different end users, such as a data centre producing a huge amount of exhaust heat, or an office building generating cold energy in winter when heat pumps are used for heating (IRENA, 2020d).


3º
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SECTOR COUPLING OPPORTUNITIES IN CHINESE CITIES

By the end of 2019, more than 60% of the Chinese population was living in cities and towns. These areas (including their surroundings) consume 85% of the country's total energy supply. The industry sector accounts for most of this consumption (71%), followed by the buildings sector (19%) and the transport sector (10%), altogether contributing to around 70% of China's energy-related CO_2 emissions (SGCERI, 2019).

At the 75th UN General Assembly in September 2020, Chinese President XI Jinping announced China's aim to achieve carbon neutrality by 2060. Although this is a national target, local authorities are contemplating how they could contribute to achieve it, and how they can sustain continued urbanisation against this backdrop.

Over the past decade, China has dramatically scaled up its renewable electricity generation capacity, particularly from variable sources such as wind and solar. Installations are set to continue to grow, according to the country's draft 14th Five-Year Energy Plan and long-term carbon neutrality goal. This has placed demand on electric power grids to be much more flexible than they currently are, and poses a challenge for grid operators. However, it also presents an opportunity for cities to scale up local VRE applications and to make demand more flexible through sector coupling technologies and strategies – not just to support grid stabilisation, but also to take advantage of cheap electricity generated from VRE when demand is low, an economic gain.

3.1. City-level initiatives on energy and emissions in China

For the past three decades, China has implemented city-level initiatives that aim to promote the use of renewables, curb emissions and improve ecological systems. Table 1 summarises the key elements of important initiatives, which have showed mixed results. However, through the process of implementing these programmes, municipal governments have learned a great deal on the technical, policy-making and institutional fronts. This experience also has been widely shared among city peers and with energy authorities at the national level.

More importantly, two key challenges in implementing such initiatives at the local level have been identified, as described below (Hunter *et al*., 2019). The first is lack of vertical and horizontal integration among government agencies at different levels and sectors. Critical missing elements include comprehensive protocols or strategies to collaboratively manage these programmes at the national, provincial and city levels, as well as a comprehensive, locally specific monitoring, evaluation and reporting (MER) system. Key reasons for these absences are the silos and disaggregation of roles and responsibilities among various departments, as well as the imbalance of interest among key stakeholders at local levels. Good practices from the near-zero zone pilot are: a) establishing multi-level, cross-sectoral task forces, b) translating an overarching emission reduction target into sectoral or even project-level targets, based on quantitative demand-driven analysis and modelling, and c) setting up clear monitoring, reporting and verification (MRV) measures.

The other is concerning gaps between planning and implementation. In recent years, sub-national planning, including the energy sector, has gained greater attention. The importance of promoting city-level initiatives, including urban energy planning, was highlighted during 2021's Two Sessions. However, most energy planning at the city-level in China follows the traditional supply-oriented approach dominated by big energy utilities. An array of modelling tools that can empower the local energy authorities to develop their own energy plans are much needed. The capacity limitations go beyond the tools, as lack the ability to tailor plans to fit their own conditions and identified feasible actions would require the local authorities to strengthen their institutional and human capacity in energy planning at the city level. When a plan is put in place, the implementation is often lacking behind, partially because of the inadequate capacity to translate the plan into specific and concrete actions and/or pipelined projects, but deviation from the original plan has often a role to play in the gap between the planning and the implementation.

Nevertheless, if cities are given a bigger role to play in achieving China's 2030 target for peak carbon emissions and its 2060 climate neutrality goal, these two fundamental issues need to be effectively addressed.

TABLE 1: Key initiatives related to urban energy development in China

TIMELINE	TARGET	DETAILS	PROGRESS OR HIGHLIGHTS	EXPERIENCE AND LESSONS LEARNED
Eco City, led by the Ministry of Environment and the Ministry of Housing and Urban-Rural Development (MOHURD)				
1997, updated in 2007	**Further urbanisation, while cleaning up and restoring the environment**	Requires setting up an eco-city construction plan and an independent agency to implement the energy conservation and emission reduction tasks. 100% green buildings, with energy efficiency above 70%, green industry, green transport supporting compact cities, water systems.	11 pilot cities by 2012, and 284 by 2016. Yichun was the first eco-city and deemed a success case. Singapore-Sino Tianjin Eco-City, a leading pilot city, started construction in 2008 in co-operation with Singapore, and launched an upgraded plan adding a smart city and circular city component.	Lack of inter-city co-operation and motivation and shared interest to build city clusters. A gap between planning and implementation, insufficient capacity on planning. Lack of MER framework. Insufficient public participation.
Low Carbon City, led by the National Development and Reform Commission (NDRC)				
2008 Shanghai and Baoding with WWF 2010: 1st batch; 2012: 2nd batch; 2014: 3rd batch	**Ensure a green and sustainable province, cities and districts**	Requires setting up a low-carbon development plan, a greenhouse gas emission target, and data tracking and management. Allows applying low-carbon interventions in local planning. Emphasises structural rebalancing, upgrade and technology innovations through developing low-carbon industries. Promotes a low-carbon lifestyle.	The scientific approaches for emission reduction provide inputs to the national urbanisation plans and impact general urban planning. 87 pilot cities and provinces; as of October 2019, most had established targets for peak greenhouse gas emissions before 2030: 59 by 2025 and 16 by 2020, with roadmaps and action plans. Set up a governance framework from the central to local levels, and engaged multiple ministries as well as local think tanks. Developed standard procedures for science-based planning, and adjusted emission inventory tools to local conditions. Low-carbon initiatives cover multiple sectors through policy and regulation support and pilot projects. Renewable energy manufacturing industries emerged in many low-carbon cities.	A gap between planning and implementation and horizontal-vertical co-operation. Less focus on the social dimension of sustainability. Dominant top-down approach and insufficient public engagement, in particular vulnerable groups, and thus fewer behaviour change efforts. Lack of scientific MER framework.
Innovative Smart City, led by MOHURD, the Ministry of Industry and Information Technology, the Ministry of Science and Technology and the State Bureau of Surveying and Mapping				
2008-2014, bottom-up 2014-2015, national level 2015-2017, mainstream 2018-present, acceleration and scale-up	**Promote urbanisation, support the digital economy and improve governance**	Multiple ministries have launched smart city pilots, including smart urban planning, construction and management based on various information and communications technologies (ICT) such as big data, cloud computing, the Internet of Things and 5G to build more liveable cities that are also energy efficient. Focus on smart transport, smart healthcare, e-governance and smart agriculture.	By the end of 2018, more than 500 smart cities were under construction, out of a total 661 cities. Detailed technical guidelines and standards have been issued. China's smart city investment was projected to reach USD 26.6 billion in 2020, the second highest in the world. Telecom operators and big ICT firms are active as well. Shenzhen is the leading pilot, saving 47.6 billion kWh of electricity annually through energy-efficient buildings. Nearly 20 major cities issued the 13th Five-Year Plan (2016-2020).	Lack of clear definition and comprehensive overarching plan. Silos remain across regions and sectors, and insufficient vertical-horizontal integration and co-ordination of data. Data ownership and privacy is a key issue .Lack of engagement of private sector and public participation.

TIMELINE	TARGET	DETAILS	PROGRESS OR HIGHLIGHTS	EXPERIENCE AND LESSONS LEARNED
New Energy Demonstration Cities, led by the National Energy Administration (NEA)				
2012: planned **2014: launched**	**To construct 100 new energy demonstration cities (industry parks) using microgrids as the basis to adapt high shares of variable renewables**	The key renewables promoted are solar thermal, distributed solar PV and wind, biomass, waste-to-energy, heat pumps and new energy vehicles. In 2014, the first batch of demonstration areas, including 81 cities and 8 industry parks, was launched. This programme has been incorporated into the National New Type Urbanization Plan (2014-2020). Following the National Notice, selected model cities issued more than 104 related supporting policies from 2014 to 2017.	Only 24 cities met the target set by the NEA in 2015, *i.e.* achieving 10.75% renewables in final energy consumption. According to the 13th Five-Year Plan, these cities are supposed to continue piloting high shares of renewables. As of 2018, most of the regional polices remained high-level guidance rather than detailed action plans or measures. Turpan New Energy Demonstration District of Turpan City, located in Xinjiang, is the first pilot of this initiative, also the first commercial operation of the microgrid demonstration project. With abundant solar resources, the District aims to develop a microgrid-based solution integrating urban planning, rooftop solar PV, solar thermal, green building and EV charging. The development period is 10 years, and the programme is ongoing. Cities such as Baicheng, Dunhuang, Yancheng and Yangzhong are actively piloting related projects ranging from rooftop solar to green hydrogen production, CSP and energy storage. However, there has been no national-level assessment or review since 2018.	The central government has yet to release incentives.
Pilot project of near-zero carbon emission zones				
2016: planned **2017: starting from Guangdong Province**	**To construct 50 near-zero zones by 2020**	Accelerates carbon emission reductions through integrated applications and management of technical solutions in the industry, energy, transport, waste management and ecology sectors. Advanced level of low-carbon pilots to achieve high-quality growth. Aims to optimise the economic structure, decarbonise the energy sector and modernise infrastructure.	Piloting in more than 11 provinces and municipalities, in both economically advanced coastal areas and in the provinces of Hainan, Shaanxi and Yunnan. Several pilot zones in coastal provinces have made good progress. Promotes advanced approaches such as quantitative analysis planning, innovative regional energy modelling and integrated energy systems, and tailored application scenarios Flexible about the scale and piloting levels including district/county level, industry parks, communities, campus, and commercial zones, promoting the interconnected near-zero campus + industry parks + communities.	Lack of unified recognition of the concept and assessment standards. Insufficient comprehensive policy support packages to foster cross-sectoral co-operation and incentives (only Guangdong Province provides fiscal incentives) to motivate other areas such as finance and taxation, land use, R&D, planning.

Source: Guo, Ren and Zhang, 2018; Hunter *et al*., 2019; CECEP Consulting, 2016; RMI, 2020.

3.2. Overview of sector coupling applications

China generated nearly 30% of its electricity from renewables by the end of 2020 (NEA, 2021). The increasing shares of variable renewable electricity pose a growing challenge to grid operations, unless the flexibility and transmission capacities of electric power networks can be enhanced.

In this context, the electrification of end-use sectors through sector-coupled technologies, technologies such as power-to-heat and electric vehicles, has a critical role to play in terms of enhancing the demand side flexibility in support of the power grid operation. This would also facilitate the decarbonisation of such end-use sectors as the transport and heating sectors where fossil fuels remain the dominant energy sources.

This process has been underpinned by the ongoing digitalisation across the buildings, mobility and energy sectors. Since 2015, the central government has made efforts to promote integrated energy systems, multi-carrier energy system pilot projects and ambitious hydrogen programmes, as summarised in Table 2. These technologies as well as energy storage systems have been increasingly applied for meeting the new energy demand from the around 6000 industry parks and industrial development zones near city centres in China. This has offered considerable untapped potential for demand response, which can provide greater demand flexibility for national as well as local grids.

TABLE 2: Pilot programmes relevant to distributed energy generation and sector coupling in cities

YEAR	NAME	DETAILS
2015	**Piloting the power trading of distributed energy trading**	China has introduced policies to support the marketisation of distributed energy systems with fewer direct subsidies. The 13th Five-Year Plan (2016-2020) promoted distributed renewable energy systems and set a target for 60 GW of distributed solar systems by 2020. Distributed solar systems have seen explosive growth since 2016, and distributed wind systems attracted attention in 2017. In 2017, the NDRC and NEA issued a new policy allowing distributed wind and PV power generators to participate in power trading, and in 2019 they announced the first batch of pilot projects across 26 cities for subsidy-free distributed power trading. Jiangsu Province is in the lead and issued detailed trading rules. However, none of these pilots had started trading as of August 2020 due to policy ambiguity.
2016	**Integrated multiple-energy pilot projects**	The first batch of 23 projects includes 6 projects on the supply side, integrating VRE with storage, and 17 projects on the demand side including combined cooling, heating and power (CCHP), smart distribution networks (smart meters) and demand response and EV charging facilities.
2017	**Internet+**	The first batch includes 55 projects that share a similar concept, with multiple-energy pilots: 22 at the city level, 12 at industry parks, 5 for cross-regional systems, 6 for vehicle-to-grid, 2 for enhancing grid flexibility, 3 for energy trading, 4 for internet of energy, sector integration, 8 for big data and 3 for smart infrastructure.
	Smart energy pilot projects	Including energy conservation, environmental protection, and integrated energy systems, and engaging local government, research institutions and industry players.
2017-2021	**Buildings, Clean Heating Plan in North China**	To convert 70% of the northern region to clean heating by 2021. The first batch of 28 pilot cites should reach a 100% clean heating rate, by replacing coal heating. Technologies such as district heating, gas boilers, biomass boilers, heat pumps and geothermal are encouraged.

YEAR	NAME	DETAILS
2019	**Green finance enhances support for green building**	The People's Bank of China, NDRC and five ministries jointly issued the *Green Industry Guiding Catalogue*, which clarifies green financing. It expands the scope of green building projects by adding applications of renewables in buildings, green building retrofits, etc.
2020	**Scaling up multi-carrier energy system programme**	The NEA has said it will include integrated energy systems in the 14th Five-Year Plan (2021-2025) and promote it further, in particular supporting the construction of EV charging facilities and energy storage. The central government will also work on the policy for horizontal integration of the energy supply, transmission and distribution, and storage and facilitate equal market access to energy supply, demand and independent storage service providers. In industry parks and energy bases, integrated energy projects will be promoted, such as supply + transmission and distribution + storage + energy-intensive industry, and supply + transmission and distribution + storage + data centre, waste heat and waste steam harvesting projects.
Transport, EVs		By September 2020, the number of EV charge points reached 1.4 million with more than 4 million battery electric and plug-in hybrid vehicles. The subsidies for EVs have been scaled down and will instead support charging infrastructure, with USD 1.4 billion earmarked in the new stimulus package. The newly issued New Energy Vehicle (NEV) Industry Plan (2021-2025) forecasts that the share of NEVs in new car sales will increase from 5% to 20% in five years. The Plan encourages the development of distributed solar, storage, charge and discharge hybrid stations, and battery swapping networks.
Energy storage		The focus is on pumped hydropower storage construction and electrochemical storage for peak shaving, grid stabilisation and renewables deployment. A new pilot of eight projects was launched in October 2020, including energy storage for the demand side, renewable electricity generation, and grid and thermal power plant auxiliary services.
Hydrogen		Since 2019, China has seen a boost of hydrogen development at the regional level. More than 30 local governments have issued hydrogen development plans, although the central government has yet to issue a hydrogen strategy. By September 2020, 7 000 fuel cell EVs had been deployed; the target is 1 million, with 1 000 refuelling stations by 2030. In 2020, the central government released the subsidies for fuel cell EV industrialisation and deployment for the following four years.

Source: Zhu, 2020; China Energy News, 2020a; Argus Media, 2020; china5e, 2020; Rui, 2020; China Energy News, 2020b

With this wide range of programmes covering the electricity, heating and transport sectors, the market for integrated energy services enabled by multi-carrier energy sources and sector coupling technologies is estimated to grow rapidly over the coming years, reaching RMB 0.8 trillion to RMB 1.2 trillion (USD 122 billion to USD 183 billion) by 2025 (Epaper, 2020).

3.3. Renewables for heating

Urban heating demand increased at an average rate of 9.4% from 2014 to 2018, and the trend is expected to continue in the coming years (China Heating, 2020). Currently, more than 70% of the primary energy source for heating is still met by coal, although this situation is improving rapidly as coal is replaced with cleaner energy sources. In most cities, the sector relies heavily on coal-fired CHP and coal-based heat-only boilers, which have caused severe air pollution and high carbon emissions. To address this challenge, renewables for heat, through both conventional and sector coupling technologies, are being prioritised in northern China.

With growing shares of VRE, surplus renewable electricity has become a viable source of energy to provide heat through heat pumps and electric resistance heaters or boilers. Thermal energy storage is often installed, particularly in district heating configurations. Box 4 provides an example.

BOX 4

Power-to-heat in Zhangjiakou

Zhangjiakou, a city in northern China, has a long and cold winter period (5-6 months) that demands heating service. Coal provides around 95% of the space heating supply, while around 65% of the total area is connected with district heating systems of various scales through 3453 kilometres of thermal pipelines and 270 heat sub-stations.

To decarbonise the heating sector, Zhangjiakou has adopted an innovative scheme to take advantage of its surplus electricity generated from local solar and wind energy resources. The so-called Four-Party Mechanism is a joint endeavor of the local government, solar and wind farm owners, grid operators and customers. The scheme was designed to minimise the curtailment of renewable electricity caused by lack of local demand and constraints in grid transmission capacity. It aims to increase the share of renewables in replacing coal to provide heating services, initially just for residential customers but later extended to the commercial and industrial end-use sectors, including through production of green hydrogen.

The business model works as follows: First, the municipality has teamed up with the grid operator to establish a platform for trading excess electricity from VRE. This was a crucial step, as the grid operator had to offer a discounted rate for the wheeling charge of the electricity traded for heating purposes. The local government announces on a monthly basis the amount of electricity to be purchased at the guaranteed prices. This invites renewable electricity producers to take part based on their projection of production, which might exceed the amount of electricity that is allowed to be sold under the current feed-in tariff scheme. This way, the generators are guaranteed to sell their excessive output of electricity from VRE at an agreed reduced price rather than being curtailed – a total loss of revenue from the surplus.

For the end users, the heating cost is as low as 2.2 US cents/kWh, which can match that from conventional heat suppliers. For the local government, the scheme expands the spectrum of using local renewable energy resources to meet local demand, and in turn creates a space for further growth in renewable electricity installations. For the grid company, which is state-owned, it facilitates the process of energy transition towards a green, low-carbon and sustainable energy future, thus fulfilling a key mandate given by the central government.

Since 2018, the Four-Party Mechanism has been increasingly adopted as a successful practice by neighbouring areas in the region.

Source: IRENA, 2019g

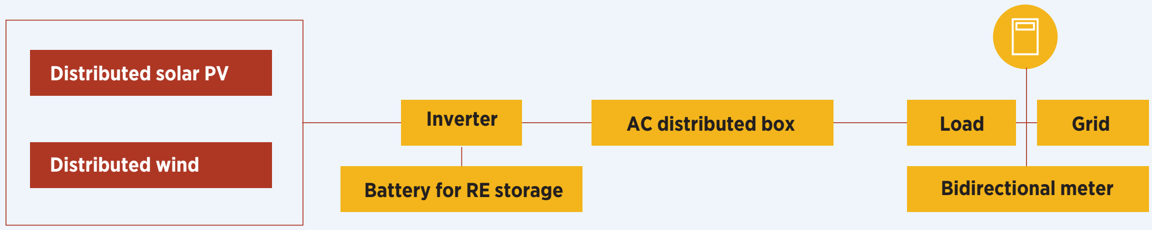
Heat pumps have also been strongly promoted as a clean and efficient distributed heating solution, particularly when they are combined with renewable electricity to reduce carbon emissions from the heating sector. The industry association estimates that the air-to-air heat pump market in China will grow 10% annually in the next few years, reaching RMB 38 billion (USD 5.8 billion) in 2024 (Smarthome 2019).

In addition, the direct use of geothermal energy for district heating has been increasingly adopted in in northern China. This is usually coupled with large-scale heat pumps to increase the overall system efficiency.

3.4. Battery energy storage in support of distributed energy generation

Apart from the benefit to grid stability, battery energy storage coupled with variable renewable electricity generation capacity, typically generated from solar PV, presents an appealing business case in cities. The typical storage-integrated renewable energy system is shown in Figure 10.

Figure 10: Renewable energy storage sector coupling system



Such a combination, especially for self-consumption, could be economical in China given the high electricity tariff for commercial and industrial consumers in urban and surrounding areas, which averages around CNY 0.8 (USD 0.12) per kWh. For example, industrial parks, located in suburban areas, often have large roof areas for solar PV. A typically sized industrial park has the available space for 10-20 MW of generation capacity from rooftop solar PV. The return on investment of industrial park solar PV is around 15%, with a payback period of usually less than seven years, making it an attractive investment even without subsidies (pwc and TUV Rheinland, 2019).

In addition, the difference in tariff between the peak and the valley of power demand, as much as 40%, provides another opportunity for loads that can be interruptible and benefit from the energy storage systems (Sohu, 2018). Considering the increasingly stringent carbon emission policy for China's industry sector, it is a general trend for industrial parks to adopt sector coupling solutions combined with renewable energy generation.

Lastly, the grid service that battery storage can provide is another incentive that has yet to be monetised, if and when the market for grid auxiliary services is set up in favour of integrating higher shares of variable renewables in the power grid.

With rapidly growing EV sales, particularly since 2018, lithium batteries can potentially provide a cost-effective way to enhance grid flexibility, if smart charging is applied (Box 5). EV sales in China now total more than 1 million units annually and are expected to increase 40% in the next five years, according to the deputy secretary-general of China Association of Automotive Manufactures (CAAM). The cascading use of EV power batteries also looks promising. The annual total capacity of retired EV batteries was expected to exceed 24.6 gigawatt hours (GWh) in 2020, and to near 45 GWh in 2022 (Guotai, 2020). Overall, coupling battery storage, either stationary or EV batteries, offers a good way to maximise the use of local renewable resources.

BOX 5

Smart charging for EVs

With the growing shares of VRE in power grids, electrification of the transport sector offers a promising solution for decarbonisation while also reducing local air pollution caused by conventional internal combustion engine vehicles. However, EVs can be a double-edged sword in terms of impact on grid stability, depending on how they are charged. If the charging is handled smartly, EVs can be an asset for grid operators (and vice versa).

IRENA's *Innovation outlook: Smart charging for electric vehicles* highlights the importance of smart charging – that is, harmonising the charging practice with power grid operation, thereby facilitating the integration of VRE through enhanced demand flexibility without jeopardising mobility needs. This is critical, as the number of EVs is expected to exceed 1 billion by 2050. Without smart charging, this would pose great stress to grid operations in managing power peak demand.

In contrast, smart charging can provide grid flexibility services through various pricing and technical schemes while reducing the impact on peak demand by a factor of 6, as presented in a UK study (AER, 2018). This usually requires close examination of the conditions of a given use case – including the power mix, demand profiles, distribution network and driving patterns – to figure out the best way to configure an intelligent interface (smart charging infrastructure) for coupling the transport sector with the power sector.

Among other dimensions, IRENA's *Innovation outlook* report assesses the short-term and long-term impacts of various charging strategies, with a special focus on the advantages that smart charging can bring from a system perspective, such as peak load shedding, supporting the grid integration of VRE particularly for distributed energy generation systems, and lowering costs for consumers. The *Innovation outlook* also depicts scenarios of EV development for 2030 and 2050 and provides policy recommendations while pointing out potential disruptive technologies such as mobility-as-a-service and autonomous vehicles, which could reshape the outlook for EV and smart charging development in the future.

Source: IRENA, 2019d

3.5. Coupling waste management systems with energy production

Waste-to-energy is an important sector coupling solution in urban China, and also plays a critical role in city management nationwide. The primary technologies applied under this category include incineration and anaerobic digestion, whose detailed technical description can be found in IRENA's recent report, *The rise of renewables in cities* (IRENA, 2020d).

China generates around 300 million tonnes of municipal solid waste annually, and around 50% of this is incinerated, making waste a green energy source for the regional power grid and for local thermal networks. Waste incineration is encouraged as a sector coupling solution, as it not only produces heat and power (via CHP) but it also couples the waste disposal and management sector with the energy sector.

The national feed-in tariff for waste-to-energy is RMB 0.65 (USD 0.1) per kWh, while electricity production per tonne of municipal solid waste is calculated at the rate of not greater than 280 kWh, and the excessive electricity is paid at the same price of local coal-fired power generation, which is around half of the feed-in tariff (NDRC, 2012). The policy remains in effect and applies to all projects operating after 2006. Normally, incineration CHP is a build-operate-transfer or build-own-operate project with a return on equity of 10%-15%. However, due to the NIMBY ("not in my backyard") effect, it usually takes more than two years to obtain approval from the local government.

Since the costs of wind and solar power in many regions of China are close to grid parity, there is a possibility that the central government will reduce the subsidy for waste incineration. However, the reduction in the feed-in tariff may not affect the economics of such projects, as the waste treatment fee is increasing. The urbanisation process in China is shifting from megacities to small and medium-sized cities. In cities with growing populations, mainly in southern China, there is still a big potential for waste incineration. Landfill gas is also a good source for distributed power generation in urban areas. The tariffs vary regionally but are usually in the range of CNY 0.5 to CNY 0.65 (USD 0.08 to USD 0.1) per kWh. Due to the shortage of land resources, the construction of landfills in China has slowed since the 2010s.

Since 2018, the central government has started garbage segregation and recycling promotion in Chinese cities, and this provides a good opportunity for the newly built facilities to utilise anaerobic treatment for organic municipal waste, especially kitchen waste. Through anaerobic digestion and biogas power generation, electricity is generated and sold directly to the local grid, as such treatment facilities are usually located close to city centres to reduce transport distances. A premium subsidy of around CNY 0.25 (USD 0.04) per kWh is also provided to biogas power generation, decided by the local government. Megacities such as Beijing and Shanghai are planning new anaerobic digestion capacities of 2 000 tonnes per day, whereas cities with populations of 1-10 million are planning capacities of 400-800 tonnes per day.

Wastewater treatment facilities are an important infrastructure component in urban areas. The coupling of solar PV and sewage treatment plants has seen rapid growth in China since 2019, driven by the significant decline in the price of PV module installation (to around CNY 3 500, or USD 534, per kW) (Longgi, 2020). Compared to traditional solar PV facilities, the integration of PV into sewage plants can save 50% of the construction investment and 20% of the grid connection cost. These plants can help reduce 15% of the total wastewater treatment cost. With the scale-up of cities, residential communities are built close to water treatment facilities, and this promotes the coupling of water-source heat pumps for heating and cooling.

3.6. Sector coupling potential in a Chinese case study

The evaluation results in this section were generated by applying IRENA's Planning Platform for Urban Renewable Energy (see section 1.4), with a specific focus on Chongli district (Figure 11). The section presents the key sector coupling options that the district could take for decarbonisation over time, along with important factors that the district should consider in the process of energy transition. (For more on these discussions, see the IRENA reports *Zhangjiakou energy transformation 2050* (IRENA, 2019g) and *Renewable energy policies for cities* (IRENA, 2021b), where Chongli is presented as a key case study).

Chongli is a district of Zhangjiakou City in Hebei Province. With its hilly topology and heavy winter snow, it is one of the locations supporting Beijing's hosting of the 2022 Winter Olympic Games, which aims to be a low-carbon event. The district has a population of 130 000, but its energy demand is highly affected by winter tourism (Zhang, 2019). Winter tourism activities currently require a large amount of conventional fuels to power the equipment used to maintain the ski resorts during the winter, accounting for almost a third of the resorts' energy consumption. In the ramp-up to the 2022 Winter Olympics, Chongli aims to decarbonise its energy system using abundant renewable energy resources.

Figure 11: An Illustrative overview of Chongli analysis

Note: Enablers of the deployment of renewable energy include building retrofitting measures, distributed energy systems and district heating networks. The illustration provides an overview of the different aspects analysed in the study: a) overview of the district, node distribution, data points collected and wind potential; b) overview of demand assessment at the building level for one of the scenarios and zones of the district; c, e and f) combined imagery and methodology enhancing data processing for more accuracy on building characteristics; and d) solar potential on building rooftop (annual and time series) and approximation of network characteristics (used for network dimensioning and network losses calculation).

Figure 12 provides a conceptual overview of the opportunities for sector coupling applications. IRENA's Planning Platform for Urban Renewable Energy performed the overall analysis based on data collected on-site and provided by local experts, combined with data available from satellite imagery and GIS-based analysis, as well as meteorological data, to evaluate the potential of the sector coupling opportunities. More details are presented below.

Figure 12: Reaching 100% renewable energy in Chongli through the adoption of cross-sectorial measures

TECHNICAL SCOPE

1 Efficiency measures

2 Mobility strategy

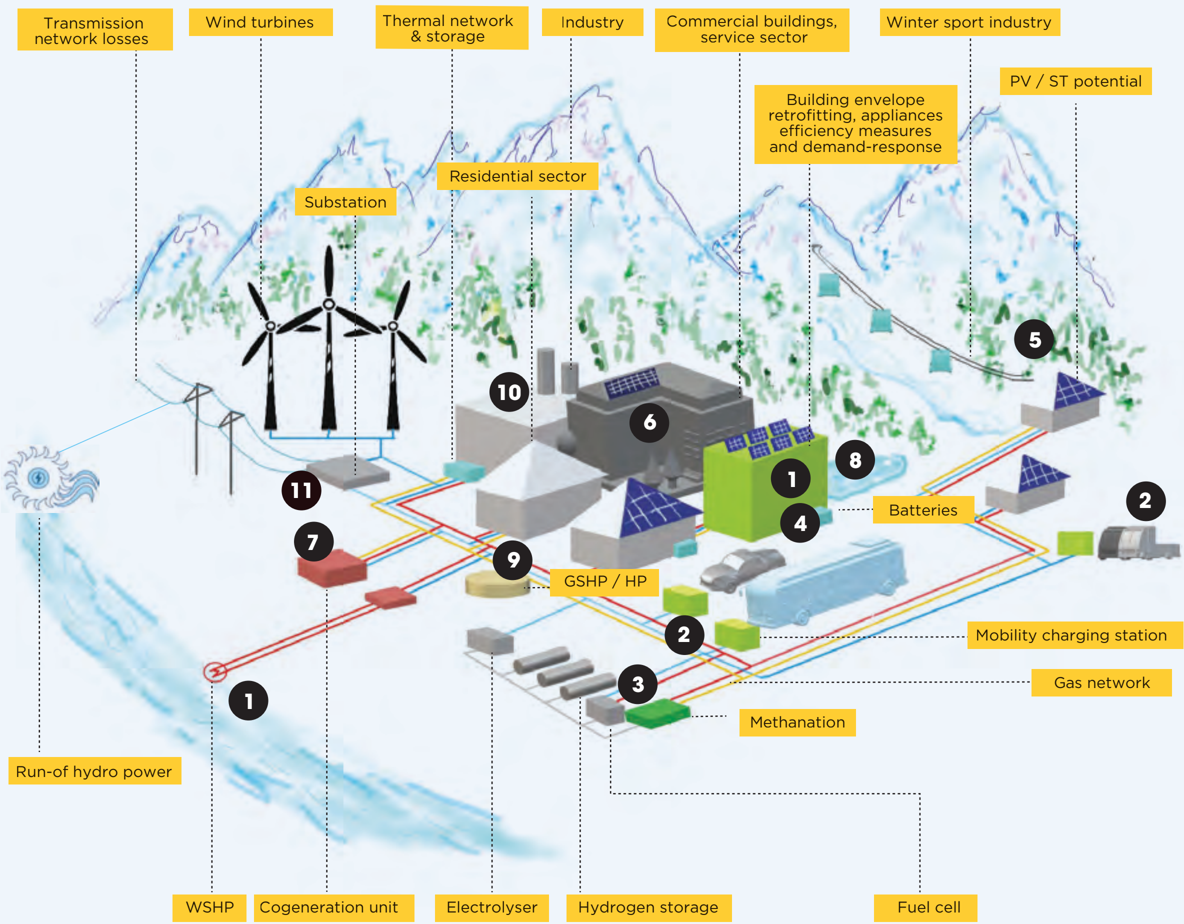
3 Hydrogen strategy

4 Smart grid – demand response

5 6 7 8 10 Sector-coupling: Power-to-X

9 Role of energy network & storage

11 Resilience & energy import/export



Note: This illustration presents Chongli's integrated energy system based on analysis of cross-sectorial potentials for evaluation of local renewable energy integration options and benefits. These include: 1) building envelope retrofitting and efficiency measures, 2) e-mobility and hydrogen refuelling stations for public transport, EVs and snow groomer / ski resort maintenance equipment, 3) a water-based electrolysis, hydrogen storage and methanation facility, 4) demand-side measures, demand response and smart grids, including vehicle-to-grid, 5) sector coupling in power-to-heat and monitoring, 6) coupling at the city level of requirements for cooling and heating services for different applications (*e.g.* ice skating and indoor swimming pools or gyms), 7) a municipal solid waste co-generation centre, producing affordable and clean electricity and heating services, 8) harvesting water potential as a heat or cooling sink for water-source heat pump application, extracting heat from rivers or ponds established to provide flexible snowmaking, 9) district heating, gas, and electricity grid network infrastructure, constituting energy converters and storage to provide grid stability and security of supply across seasons, 10) an innovation hub to attract start-ups and increase the scientific R&D parks, and 11) a grid sub-station and imported renewable energy from nearby existing potential (*e.g.* wind).

1 **Potential for energy demand reduction through efficiency measures.** This includes, firstly, the building envelope retrofitting potentials (building materials and insulation layers) and retrofitting rate (targeting different building uses and construction ages); and, secondly, an evaluation of the energy and emission savings potential through efficiency measures for appliances and lighting. The study estimated energy savings up to 37.1% by 2050 according to the retrofitting strategy (renovation rate per building type and construction period) and retrofitting targets (new building codes, improved energy performance of building envelope and efficiency measures for electrical appliances).

The cumulative energy consumption savings over the studied period can reach up to 67 million tonnes of coal equivalent in 2050 when combining building envelope retrofitting (3% annual rate for buildings built before 2010 and 2% for buildings built before 2020), performance building insulation for new buildings (thick insulation, triple glazing) and appliance efficiency measures (up to 25% more efficient electrical appliances). When the energy efficiency measures on the demand side are optimally combined with supply-side solutions locally (*e.g.* the combination of heat pumps with rooftop solar PV, electric battery storage and thermal energy storage), carbon emissions emitted for energy services are expected to decrease by around two-thirds.

2 **Decarbonising the heating systems through sector coupling.** Electrifying the heating sector through heat pumps and with excessive electricity from the nearby wind farms, plays a central role. There would be around 360 GWh of surplus electricity consumed for the heating purpose. The use of heat pumps in combination with the district heating network provides opportunities for sector coupling for electricity and heating. It was estimated that there is a need to build a central district heating network that covers 36 000 square metres (m^2) in the short-term strategy, including seven sets of 46 MW hot water boilers, with the goal to expand the system to provide heating services for a total floor area of 4.5 million m^2. If and when the shortage of electricity production from the local wind turbines occurs, importing from the power grid outside the district boundary, which currently relies on 60% renewable energy is necessary.

The analysis also revealed that a key factor to consider for the effective energy planning of Chongli district is increasing the seasonal energy storage capacity. The seasonality of energy demand – accounting for the region's extreme temperatures – can be addressed through cross-sectorial integration of long-term energy storage systems, the deployment of local distributed renewable energy systems, demand management and energy efficiency measures.

3 **Sector coupling potential in the public transport sector.** Two options are considered for the public fleet. The first one considers a fully electrified fleet, and the second one represents a mix of hydrogen (green hydrogen) fuel cell and electric vehicles, with three-quarters of them hydrogen-based buses. The relative difference in the levelised costs of energy for the district ranges from 25% to 13% for different optimised solutions with the aim to achieving minimisation of the energy costs and carbon emissions. Although the second scenario costs slightly higher, the combination of hydrogen fuel cell and electric vehicles can deliver a further 10% carbon emission reduction compared with the fully electrified transport sector scenario. Public transport would need to adapt, with e-charging and hydrogen refuelling stations.

Optimised solutions, in addition to base the energy supply on renewable energy resources, also require deployment of storage (battery and hydrogen storage) capacity.

The analysis suggests that the 20 MWh for hydrogen storage capacity and 60 MWh for electricity storage capacity (easing the stress on the grid from the surge for power demand in the fast charging model) would support coupling of the power and transport sectors. Another important element is the upgrading of the energy management systems to unlock the sector coupling potential.

4 **Power-to-hydrogen solutions.** These represent an attractive alternative for the district, since the severe cold weather limits the efficiency of certain technologies (e.g. air-source-heat pump and batteries). Including the implementation of an electrolyser within the city, near the charging station, will provide grid regulation benefits and enable harvesting of the full potential of VRE, limiting curtailment. The high-temperature process of the electrolyser creates waste heat that can be re-used through coupling with the district heating for space heating requirements. The hydrogen can be used for heavy transport, such as buses, freight or ski resort maintenance equipment such as snow groomers.

Excess hydrogen and storage capacity provide an opportunity to balance the demand and the supply over a long-term horizon. It can particularly be used for: a) relieving the grid during the peak tourist season, providing heating and electricity for micro-grid configuration with a capacity for co-generation of heat and electricity (micro-CHP); b) exports such as hydrogen or methanation to decarbonise heavy transport modes (train/airplane) or industry outside Chongli (Collins, 2020). In the scenarios analysed – prioritising a coupling strategy through energy storage – multiple optimal solutions point towards micro-CHP solutions, for a total capacity of between 100 MW and 150 MW to produce local heat and electricity, combined with capacity for the electrolyser to produce local hydrogen, based on local or nearby renewable energy sources.

The Chongli study presents various sector coupling options identified by applying the Planning Platform for Urban Renewable Energy to achieve different levels of adoption of renewables in final energy consumption based on different pathways for the long-term energy planning of Chongli. Increasing the share of renewables in the district with the integration of distributed renewable energy systems, along with demand management measures, will allow increasing the overall flexibility of the district's energy system. With the implementation of storage systems, the surplus locally produced electricity can be used in the transport sector to power EVs. The combined use of a thermal energy system and hydrogen storage further increases the system's flexibility and provides security of supply through diversification over longer period of time.


4

SECTOR COUPLING OPPORTUNITIES IN COSTA RICA

This chapter highlights the sector coupling opportunities identified by applying IRENA's Planning Platform for Urban Renewable Energy (see section 1.4), with a specific focus on Costa Rica. The forthcoming IRENA study on local energy planning for districts of the Greater Metropolitan Area of Costa Rica (IRENA, forthcoming-b) also provides more detailed background for this discussion.

Already today, electricity generation in Costa Rica is close to 100% from renewable energy sources – mainly from hydropower, followed by geothermal, wind, and smaller shares of biomass and solar. The country has set a new target to achieve total decarbonisation by 2050. However, huge challenges remain, as oil accounts for 65.8% of the national energy mix, consumed mostly by the transport and industry sectors (83.2% and 12.4%, respectively) (MINAE, 2018).

In 2018, energy-related CO_2 emissions in Costa Rica reached 7.63 million tonnes (a near doubling from the levels of the 1990s), of which three-quarters come from the transport sector (IEA, 2020d). If measures are not taken, the country's emissions are estimated to increase 60% between 2015 and 2030, and 132% by 2050 (Rivera, Obando and Sancho, 2015). Electrification of the transport sector can offer a realistic option for decarbonisation. In the forthcoming IRENA study on Costa Rica (IRENA, forthcoming-b), different pathways are analysed to achieve total electrification of the transport sector and increase the use of renewables in the industrial sector. However, one of the key findings demonstrates that without taking the necessary demand- and supply-side measures, and taking advantage of sectoral coupling opportunities, this goal will not be possible.

4.1. Electrification and sector coupling

Costa Rica has identified the electrification of its transport sector as a priority. The country is also stepping up efforts to deploy non-hydropower renewables as a means to scale up its power generation capacity while also enhancing the security of power supply during the low season for hydrological resources. If such diversification is expected through the addition of variable renewable capacity such as solar PV and wind power – including distributed energy systems in and near cities and load centres – then this would require greater flexibility in the energy system. The main challenge lies in the existing grid infrastructure, as it needs to be prepared to cope with the new electricity demand, while at the same time adapting itself to a diversified portfolio with an increased share of VRE.

Sector coupling is one of the most important solutions to address this challenge. This would enable Costa Rica to achieve decarbonisation through an electrification pathway, from the district to the national scale. In cities in particular, it would enable the complete electrification of the residential, commercial and transport sectors. Intelligent demand-side management systems, with the support of energy storage, have an important role to play in regulating the load in response to variable electricity inputs. Energy storage systems include both electric and thermal storage capacities, which are often hosted in buildings in both the residential and commercial sectors. This storage is usually coupled with the use of heat pumps, ensuring higher overall energy efficiencies.

The results of the study show that for the residential sector, heat pumps – acting as power-to-heat – increase the efficiency for cooling and hot water, replacing the use of traditional air conditioners and electric water heaters and preventing curtailment during peak hours by using buildings as storage capacities.

The implementation of storage technologies enables storing locally produced energy that can be used to deliver electricity to private EVs and adding more flexibility to the overall system. The use of EVs is projected to grow not only for private users, but also in the public transport sector. Already, the implementation of electric public buses is being explored in Costa Rica (Figure 13), and the entire fleet of municipal public buses is expected to be electric by 2050, based on targets in the National Decarbonization Plan (NDP).

Figure 13: Electric bus pilot project in Costa Rica

Photo: Julieth Méndez / Presidency office.

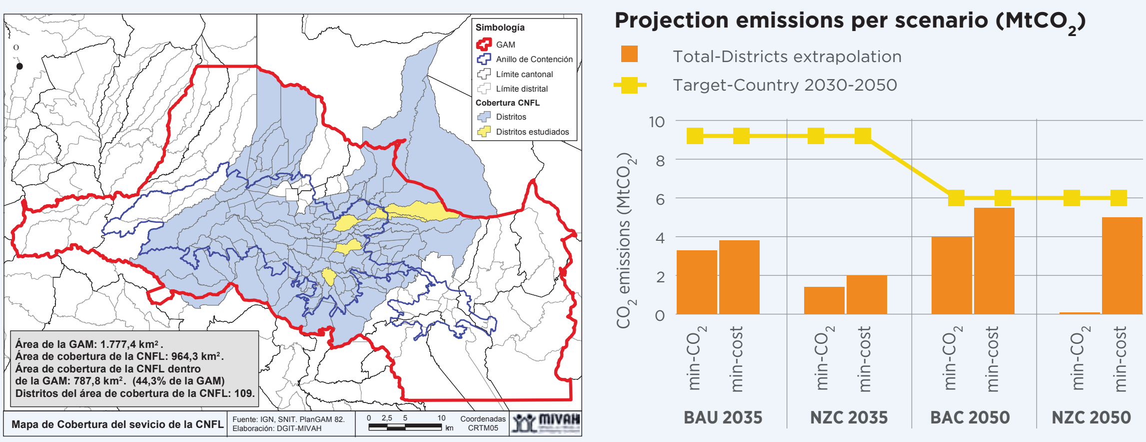
The industry sector also demonstrates a high potential for sector coupling in Costa Rica, mainly through the deployment of co-generation systems based on hydrogen sources, producing heat and electricity mainly for the food, glass and cement industries. Hydrogen produced from excess renewable electricity can be applied in the agricultural sector by converting the gas to ammonia for producing fertilisers. The transport sector can also benefit from using hydrogen to power heavy-duty trucks for shipping, among other purposes.

4.2. Key findings on sector coupling from the case studies

In an overall planning study for districts of the Greater Metropolitan Area of Costa Rica, IRENA analysed how municipalities could play a key role in achieving the country's decarbonisation goals. The study explored how districts could support national renewable energy planning through the deployment of distributed generation to cope with the electrification of end-use sectors, which provide opportunities for sector coupling. Different long-term scenarios were evaluated, including a net zero carbon emission (NZC) scenario that accounts for the most ambitious targets for the years 2035 and 2050.

The detailed study of the districts under the different scenarios shows that reaching near net zero emissions is technically possible, with a 90% reduction of emissions in cities by 2050 through the deployment of solar PV, energy storage and heat pump technologies, combined with electro-mobility. Increasing this ambition is also possible with larger penetration of solar PV and energy storage at the city level, combined with grid upgrades and green hydrogen strategies.

Figure 14: Geographical presentation of the study areas and projection emissions of scenarios



Note: The map shows the Greater Metropolitan Area (red contour) and the CNFL area (light blue) corresponding to the study area, with corresponding results in terms of decarbonisation potential evaluated for the different scenarios and objectives and compared to the national carbon emission targets for 2030 and 2050.
Source: MIVAH, 2021; IRENA analysis
Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

The integration of distributed energy systems allows the renewable energy share in cities to increase by between 14% and 40% by 2035, depending on the city, compared to the current national targets. Meanwhile, for most cities, decarbonisation will result in savings of up to 18% by 2050, compared to a scenario of continuing the current policy and action levels.

One of the key findings is that scaling up the use of local renewable energy resources, together with imported renewable energy from the national grid, would require a large investment in grid infrastructure. However, this can be minimised by optimising the flexibility of the energy system through demand response measures and, most importantly, power-to-X applications that enable sector coupling and smart management.

These opportunities of optimised cross-sectoral strategies such as power-to-mobility and vehicle-to-grid, power-to-heat, power-to-gas along with energy efficiency measures the two studied districts are summarised in the following sub-sections.

DISTRICT OF DESAMPARADOS

With its Human Development Index among the lowest in Costa Rica, Desamparados is one of the country's most populated districts, at more than 35 000 inhabitants. Although its current electricity consumption is low, it is expected to double by 2050, driven by economic growth. The breakdown of energy consumption is 88% residential, 11% commercial and only 1% industrial. Dense districts can represent a particular challenge for urban planners to reach decarbonisation goals due to their rising energy consumption and to spatial constraints that limit the installation of distributed energy systems. Therefore, analysis of Desamparados offers a good example of how to overcome this challenge.

The results show that with the net zero carbon emissions (NZC) scenario, the renewable share of total final energy consumption can be increased to 60.4% by 2035 and 100% by 2050, compared to 36% and 39%, respectively, under the business-as-usual scenario. However, implementation of the NZC scenario requires sector coupling interventions, mainly in the transport sector. In this scenario, the increasing electricity consumption in the transport fleet can be covered by locally generated renewable energy – mainly through rooftop solar PV, storage systems composed of lithium batteries and hydrogen, and upgrading the existing electricity grid so it can cope with the new intermittent loads. By improving public transport planning through electrification of the fleet and digitalisation, the use of private vehicles can be minimised, avoiding the waste of productive time of the district's inhabitants that is consumed by traffic hours.

In the residential sector, energy efficiency strategies focused on demand-side management are needed. Controlling the energy demand of a dense district can be difficult but not impossible. The measures to be taken include the deployment of on-site controlling systems, subsidising energy-efficient electric appliances and introducing a taxation scheme for high-power-consuming equipment. By regulating the load when it is produced and using EVs as an alternative storage mechanism, the flexibility of the entire energy system will be increased. Even if industry represents the lowest share of consumers in this district, it can play an important role by using the municipal solid waste generated by the rapidly increasing population to produce electricity and heat to meet its energy requirements through the implementation of CHP systems.

DISTRICT OF SAN RAFAEL DE CORONADO

San Rafael has only 8 000 inhabitants, making it the least-dense district and the lowest energy consumer in Costa Rica. However, as in Desamparados, the economic growth that the country is experiencing will rapidly increase overall energy consumption by 2050. The district's electricity consumption is 87% residential, 7.6% commercial and 5.4% industrial. The land is used mainly for farming purposes, as reflected in the district's industrial activities, which are based primarily on milk and cattle production. Low-density districts allow for the penetration of technologies (such as wind turbines) that may not be suitable for highly dense districts such as Desamparados; therefore, as there are no spatial constraints, technologies that require greater space may be explored within this district, contributing to effective urban planning.

The results show that under the NZC scenario, San Rafael can achieve a 57% renewable share in its total final energy consumption by 2035, and 100% by 2050, compared to 30.9% and 31.2%, respectively, under the business-as-usual scenario. For the NZC scenario, a sectoral change through technological transformation needs to be implemented, considering a range of opportunities for sector coupling. The integration of locally produced renewable energy and the electrification of the transport sector are key factors for increasing energy system flexibility and decarbonising the district, opening the path for an effective coupling of the transport and residential sectors.

However, the peculiarity of this district in terms of space allows for not only considering rooftop solar PV technologies as a potential solution, but also wind turbines and large-scale storage systems (*i.e.* compressed air energy storage, or CAES). The latter systems can be deployed both to satisfy the district's electricity demand and also to import electricity to other, denser districts, such as Desamparados. The organic waste produced by the cattle industry offers great potential for applying CHP technologies to generate electricity and power that can be used for the industry itself, as well as for the residential and commercial sectors.

Alternative supply-side strategies were studied for the NZC scenario. The optimised solutions consider both vehicle-to-grid and hydrogen as sector coupling solutions. In this scenario, 10% of the vehicle storage capacity can be leveraged or utilised by the grid at the district level, and an integrated system with multi-energy carriers can optimise the operating strategy between hydrogen production and the electricity through the sector coupling approach. This results in achieving a 100% renewable energy district at a lower levelised cost of energy (a 15% reduction is calculated for the district of San Rafael).

Figure 15 shows the final carbon emission avoidance for the year 2050 under the NZC scenario compared to the business-as-usual scenario in Costa Rica, including in the Desamparados and San Rafael districts. From the analysis of both districts, it can be concluded that reaching the country's most ambitious decarbonisation goal for 2050 is possible – but only if the correct measures are applied and adapted based on each district's characteristics. This requires personalised feedback from municipalities and communities. The involvement of citizens in these actions is essential, as demand-side strategies (*i.e.* subsidies, taxation schemes and on-site control technologies) will support the flexibility and capacity of the district's energy system.

Local renewable energy production, electrification of the industry and transport sectors, and the concept of the circular economy represent clear opportunities for sector coupling in Costa Rica. This can be adequately supported through upgrade of the electricity grid and the deployment of storage technologies, while also integrating hydrogen fuel into the energy matrix.

Figure 15: Carbon emissions avoidance in 2050 with optimal carbon reduction

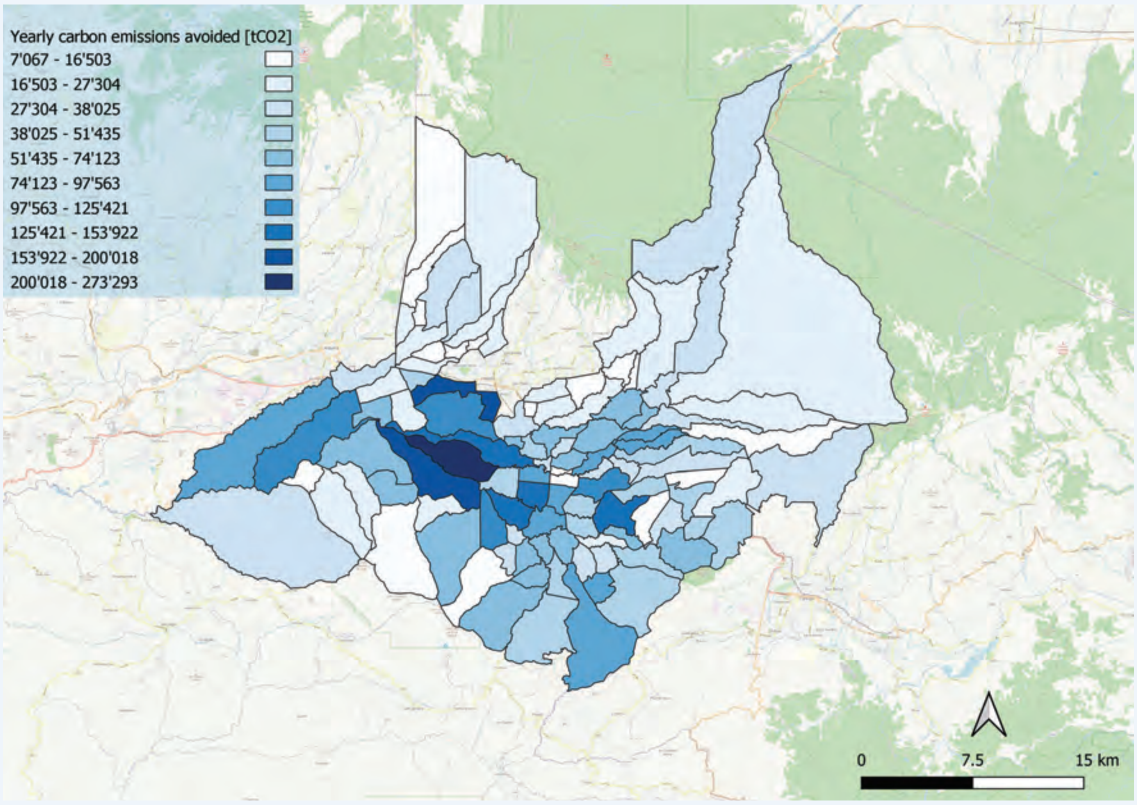


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Table 3 presents a summary – with a description and potential solutions for the deployment of renewables – for the two most relevant districts in the study, as well as for the entire concession area considered to be representative of the Greater Metropolitan Area. These districts are interesting to compare as their potential decarbonisation solutions are clearly related to their specific demographic and geographic characteristics, showing the importance of considering municipality-level conditions that can contribute more efficiently to national-level targets.

The dominant renewable energy technologies to consider for decarbonisation of the Greater Metropolitan Area are solar PV and wind, combined with large storage capacity. However, electricity imported from the regional grid, combined with grid upgrades to accommodate the increase of electricity needs (mainly related to electrification of the transport sector) is a clear solution to reach the National Decarbonization Plan (NDP) and NZC scenarios for the Greater Metropolitan Area. This is especially true for the district of Desamparados, which is highly populated and has limited space for local generation.

TABLE 3: Key analytic results for two selected districts in the Greater Metropolitan Area

AREA COVERED	DESCRIPTION	POTENTIAL SOLUTIONS FOR RENEWABLE ENERGY DEPLOYMENT
District of Desamparados	High population density. 12 000 electricity customers: 88% residential, 11% commercial and 1% industrial sector.	More than 50% of electricity is imported from the regional grid for the different scenarios. Upgrade of the grid is required for the NDP and NZC scenarios. Electricity is provided from combined solar PV and electricity storage.
District of San Rafael de Coronado	Least-dense district among the districts studied, with around 8 000 inhabitants. Around 3 000 electricity customers; 87% residential, 7.6% commercial and 5.4% industrial. The district is sparse and can allow deployment of wind technologies to compensate the low solar potential due to cloud coverage. The use of waste has great potential given the presence of cattle factories.	Electricity is produced locally from solar PV and wind power combined with larger storage capacity. Electricity imported from the regional grid represents the lowest share of the electricity mix.
Greater Metropolitan Area (area of CNFL concession)	107 districts of the concession area of CNFL representative of the Greater Metropolitan Area and the city of San José.	Decarbonising the city increases electricity imports to the districts by up to 25% compared to today's electricity demand. Potential installed renewable energy capacity of 1.7 GW to 1.9 GW of solar PV and 100 MW to 200 MW of wind power, combined with the deployment of options providing system flexibility in 2050, including 26 MW to 80 MW of electrolyser capacity (13 MW fuel cell) and up to 1 GWh of electricity-based storage capacity.

5º

CONCLUSION

The energy transition has shifted from a niche movement to the global mainstream. The need to halve worldwide emissions by 2030, and to reach net zero emissions by 2050, has been recognised not only by national leaders participating in global climate talks, but also by local authorities tasked with developing future urban infrastructure. Cities have been given a greater role in both climate mitigation and adaptation, while more and more cities across the globe are joining the race to net zero.

Renewable energy resources are expected to scale up significantly over the next three decades. The direct use of renewables can help reduce emissions from end-use sectors such as transport, buildings and industry – all of which are closely relevant to cities. Importantly, these three sectors can benefit greatly from the power sector by applying sector coupling technologies and strategies to provide energy services that otherwise would not be met with electricity. In return, higher shares of variable renewable energy sources can be integrated into the power mix as a consequence of enhanced grid flexibility.

Whether or not such sector coupling opportunities are worth exploring from a technical and economic perspective can be evaluated through key generic metrics that were proposed in this study. However, it is critical to conduct quantitative assessment of sector coupling options within a given context. This study has applied an optimisation tool – IRENA's Planning Platform for Urban Renewable Energy – to conduct multi-sector analysis and quantify sector coupling options through a multi-objective optimisation. Cross-sectoral synergies through sector coupling technologies and trade-off options can be evaluated in different scenarios based on the energy modelling results for achieving objectives such as carbon emission reduction and cost minimisation.

The Planning Platform for Urban Renewable Energy was applied here for two pilot studies – Chongli district in China and two districts in San José, Costa Rica – mapping out various sector coupling options.

The application of the tool for Chongli district has shown that electrifying the heating sector through heat pumps and with excessive electricity from nearby wind farms, which can provide around 360 GWh of electricity for heating purposes, plays a central role. Large-scale heat pumps and thermal energy storage systems are recommended to be integrated in the district heating network. The analysis also found that coupling the power and transport sectors would make the best use of renewable energy resources; however, this coupling option would require 20 MWh for hydrogen storage capacity and 60 MWh for electricity storage capacity, unless the energy management system can be further improved to minimise the storage requirements.

For the tool's application in the two districts of Costa Rica, the analysis has shown that reaching near net zero emissions is technically possible, with a 90% reduction of emissions in cities by 2050 through the deployment of solar PV, energy storage and heat pump technologies, combined with electro-mobility. A key finding is that scaling up the use of local renewable energy resources, together with imported renewables from the national grid, would require a large investment in grid infrastructure. However, this can be minimised by optimising the flexibility of the energy system through demand response measures and, most importantly, power-to-X applications that enable sector coupling and smart management.

Another notable conclusion that can be drawn is that the sector coupling options can be assessed under different boundary conditions, which can generate different results. Some options can facilitate the integration of locally available variable renewables within and around urban areas in the optimal way, whereas different coupling technologies and strategies should be considered when the optimisation aims to be achieved at, for instance, a regional level. Therefore, it is essential for municipal authorities to understand the importance of striking the right balance between utilising local resources and facilitating the decarbonisation of grid electricity. In either case, sector coupling serves a key instrument to enhance grid flexibility.

Moreover, the production of hydrogen from renewable power via electrolysis can greatly expand the options for enhancing energy system flexibility. Hydrogen can be used directly or be converted into different energy or industrial products, thereby decarbonising the hard-to-decarbonise sectors such as energy-intensive industries.

The opportunities and benefits of sector coupling in cities are clear. For local policy makers and urban planners, it has become increasingly critical to view energy-related issues from a holistic perspective. In this regard, sector coupling offers a tool to connect the dots. Through such strategies, cities will not only unlock the potential they hold for climate mitigation, but also improve their urban infrastructure – helping it to run more efficiently, to be more resilient against climate impacts, and to be more people-centric by improving the local environmental quality, public health and well-being.

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ANNEX: PROPOSED GENERIC INDICATORS

Technical indicators to identify the sector coupling opportunities for self-consumption of VRE

To identify the general opportunities for sector coupling within a defined system boundary, a combination of qualitative and quantitative technical indicators is proposed and described as follows.

QUALITATIVE INDICATORS

- ***Grid integration restriction*** can be used as a qualitative indicator. This means that the grid operator or regulator makes the decision in advance that no variable renewable electricity is allowed to inject into the grid; in other words, only self-consumption of VRE is allowed. This is either because the grid operators clearly understand that the grid or a particular feeder cannot accommodate VRE above a certain level, after the grid stability assessment is conducted, or because it is not clear how much local VRE can be accommodated in the grid or a particular feeder because no relevant study is done. By taking a precautionary approach, such restriction is made for all potential VRE generators.
- ***Security of energy supply*** can be another qualitative indicator to incentivise the use of VRE for self-consumption purposes. This usually results from concern about the reliability of grid electricity supply (*e.g.* in some of the developing countries where the power shortage persists) or about the inferior quality of electricity from the grid affecting appliances or other end-use equipment that is sensitive to the electricity quality (*e.g.* data centres).
- ***Emission reduction target*** can be viewed as a technical indicator from the emission perspective, although usually it is seen as a political commitment.

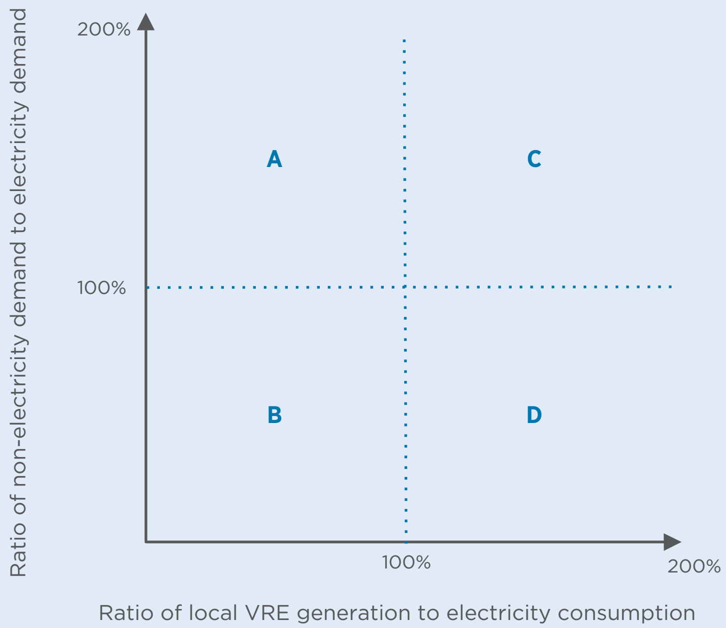
QUANTITATIVE INDICATORS

In view of the data challenges at the city level, quantitative indicators should be developed based preferably on existing energy statistics that cities would make available relatively easily. These statistics can provide a general indication of the potential opportunities for applying sector coupling technologies and strategies to increase the use of local VRE as a solution to cut carbon emissions from cities.

- ***Ratio of local VRE generation to electricity consumption (annualised)*** is proposed as an indicator. The local VRE generation might not be immediately available but can be estimated fairly straightforwardly by using renewable energy resource data and layers of filters/constraints. For instance, IRENA's Solar Simulator (IRENA, 2019h), a tool to assess the rooftop potential for solar PV installations in cities, can be used for this purpose. Annual electricity consumption is generally accessible, although hourly data are usually hard to acquire. The ratio can tell the extent to which the local VRE being generated exceeds consumption. If the ratio value is above 1, this means electricity end users cannot consume all the electricity generated, and thus sector coupling technologies might be needed for the non-electricity end users to take the surplus (if the objective is to maximise the use of local VRE while avoiding curtailment). If the ratio value is below 1, this does not necessarily mean that no such opportunities for sector coupling exist, because the value is annualised, but it suggests that scrutiny would be needed to gain greater clarity.
- ***Ratio of non-electricity demand to electricity demand*** serves as another useful indicator to figure out whether the coupling of non-electricity end users with local VRE is possible. It is worth noting that even though the ratio is high, this does not automatically indicate that sector coupling makes sense to do, as it depends on the kinds of non-electricity demand that exist, and whether the alternative energy carriers derived from renewables can be used as a replacement. For instance, for some industrial energy consumers, high-temperature process heat would require high-energy-density carriers. So, the sector coupling options might not fully satisfy the demand.

Figure 16 illustrates that Zone C presents the greatest opportunities for sector coupling, whereas Zone B presents the lowest opportunities.

Figure 16: Illustration of levels of sector coupling opportunities



The general technical indicators can be used only for initial identification of the possible opportunities for sector coupling. To assess the potentials, when such opportunities can be capitalised, a model tool is typically used to perform a detailed analysis on a more granular basis, usually on an hourly basis for both generation and consumption across all the sectors. Doing this makes it possible to determine when, where and to what extent the mismatch between supply and demand exists. Based on such information, even though imperfect, the modelling tool can be used to identify specific sector technologies or to develop sector coupling strategies to bridge the gap.

Economic indicators to identify the sector coupling opportunities for self-consumption of VRE

Technical indicators can tell only half of the story, while the other half is revealed by examining the economic implications if sector coupling is adopted. This is comparatively more complex, given various tariff structures and incentive schemes in different countries. But the principle economic indicator can be *the ratio of the levelised cost of energy of local VRE electricity generation with battery energy storage to electricity tariffs charged by the utilities* – *i.e*. the grid parity as a break-even point. Where the demand profiles match the renewable electricity generation to a greater extent, higher levels of self-consumption could be achieved (European Commission, 2015). This might be subject to different end-use sectors, namely residential, commercial and industrial, not only because of different patterns of electricity consumption but also because of the different tariffs applied in many countries.

When there is greater generation of electricity from local VRE to demand, in a cost-competitive fashion in comparison with grid electricity generation costs, there is an economic case for sector coupling technologies. It is then possible to take advantage of the excess cheap electricity by converting it into other energy carriers to meet the demand for heating and/or transport or industrial processes, such as hydrogen for direct reduction.

As with the technical indicators, the economic indicators proposed here are also general ones, as the specific economic indicators should be customised to specific end-use cases or scenarios given that the contexts and technologies to be used for the coupling can be very different. This aspect is usually assessed, together with technical indicators, in the model, as techno-economic analysis – the results of which usually contribute to the optimisation to form the best sector coupling strategies with the most suitable sector coupling technologies.

Indicators for identifying the sector coupling opportunities of thermal energy storage in cities

For applications in the urban environment, the following factors need to be checked out before assessing their technical and economic viability in cities, with the aim of facilitating the integration of local VRE into utilities.

Scale: One of the advantageous features of thermal energy storage over battery energy storage is the much larger scales of storage. However, this also means a much larger physical footprint, or the size of area that is needed for installation of the storage devices and auxiliary devices. Certainly, most of the technologies can be modularised. But as a general principle, the storage capacity is proportional to the project size. To mitigate the negative impact, some of the facilities can be installed underground, also to help avoid heat losses, particularly over seasonal storage. However, this requires engineering, which could be challenging and costly in the established urban environment. It would be much more cost-efficient to install thermal energy storage facilities in new areas of a city or in cities.

Measurement and charge of thermal energy services: This is an important aspect for investors because even though it is cheaper to store and deliver thermal services compared to electricity, if there is no metered system for measurement of thermal usage and thus no proper system for charging consumers, in some cases, no matter how much thermal energy is used, the consumers/users are charged based on the floor area only; thus, it would be difficult to make a business sense out of it. Given that this discussion falls into the area of regulation, it is beyond the scope of this study; however, it is worth mentioning as a prerequisite to check out before going into the technical and economic analysis.

Specific indicators for assessing the opportunities of using thermal energy sources as sector coupling are hybrid ones.

First and foremost, ***thermal energy demand*** (spatial and temporal dimensions) can serve as a technical indicator. As noted previously, the demand here refers to the demand to be met through thermal networks, rather than an individual household – typically through an array of stand-alone solar thermal collectors with a smaller water tank to store the heated water. The volume, temperature and nature of applications, as metrics to specify the thermal demand, would help identify the technologies and inter-operability between systems – power and thermal in this case.

To avoid a huge energy penalty, once the VRE electricity is converted into a thermal energy carrier and stored, it is meant to be converted back to electricity. The molten salt energy storage for concentrated solar power (CSP) is to store the heat collected directly from the solar field, and CSP is more applicable to an area where land-use availability does not pose a constraint for project development. For cities, when solar PV electricity or wind power is converted into thermal energy, it makes both technical and economic sense to use it to meet thermal demand. Therefore, the thermal demand, especially where and when, could be useful to assess the extent of VRE that can potentially be used for various thermal purposes, which will enable ensuing further assessment and identification of specific technologies and system requirements for configuration.

System efficiency, excluding the heat losses in transport networks (as usually the conversion and storage occur at the source, before injection into thermal grids), can be considered as another important technical indicator for thermal energy storage. This is because the round-trip efficiency of energy storage is important, but it is crucial to look at the system efficiency, and thus to identify a suitable conversion technology from power to heat that also affects the temperatures it can reach and the insulation that would be required for the storage facilities.

To make thermal energy storage economically viable compared to the cost of battery energy storage,[8] the ***ratio of the cost of storing energy using these two technologies respectively (battery storage costs / thermal storage costs (USD/kWh)*** could be viewed as an indicator to assess the potential. This is because one of the advantages that thermal energy storage has is its cost-competitiveness compared to electricity storage, especially on a large scale.

The combination of the system efficiency and the ratio of battery storage costs to thermal storage costs (USD/kWh/day) could give a preliminary indication of the thermal energy storage opportunities in cities. If the value from this simplified techno-economic analysis is higher than 1, then there might be such opportunities for thermal energy storage as a sector coupling technology. However, the detailed options need to be further investigated by applying an energy model for quantitative analysis.

8. The comparison would make sense only if the rest of the factors such as response time are assumed to be equal or are not factored in.

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