European Commission

FINAL REPORT

of the High-Level Panel of the European Decarbonisation Pathways Initiative

Research and Innovation

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EUROPEAN COMMISSION

FINAL REPORT

of the High-Level Panel of the European Decarbonisation Pathways Initiative

Directorate-General for Research and Innovation
2018 Climate Action, Environment, Resource Efficiency and Raw Materials EN

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FOREWORD

Climate change is the defining challenge of our generation. And it already is a reality. We are confronted with the effects close to us. Like the devastating forest fires in my home country, and the unprecedented heatwaves of this summer.

Recently, the Special Report of the International Panel on Climate Change on the impacts of global warming of 1.5 °C above pre-industrial levels has given us yet another wake-up call. It demonstrates that a global temperature increase of 1.5 °C has large advantages over a 2 °C increase. For instance, it will mean the difference between an already disastrous 70–90 % reduction in coral reefs, or their complete disappearance. It means a difference of a 10-cm sea-level rise, which would negatively affect 10 million people. It would mean the difference between an ice-free Arctic ocean once every century, or once every decade.

The IPCC report also carries a positive message — it is still possible to limit global warming to a 1.5 °C increase. This will result in an extra investment of 12 % compared to a 2 °C increase. However, the benefits will outweigh these extra costs in the long term. It also shows that a 1.5 °C increase is still 'physically' feasible. In short, we can still shape our future. This in itself should be more than enough reason to change our thinking, to change our actions.

Nothing short of immediate action leading to net zero emissions by 2050 will suffice. This will require a massive mobilisation of public and private investments. We need a 'Marshall Plan for Climate Readiness'. Only a truly global ambitious coordinated approach will lead to success.

Research and innovation is by definition an essential element of such an approach. All kinds of R&I actions, from scientific breakthroughs to socio-economic research, will have to work hand in hand. Nothing less will be enough to face the existential threat to society as we know it.

For climate-related research and innovation, delivery will be at the heart of Horizon Europe. A 35 % target on climate mainstreaming will be linked to other EU instruments. We are pursuing a coherent framework of policies, legislation, partnerships and alignment with Member States and regions and cities.

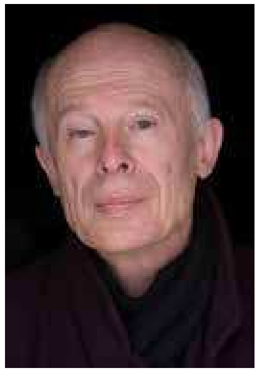
I am very grateful to the Members of the High-Level Panel on Decarbonisation for identifying the essential research and innovation elements of an ambitious and coordinated response to climate change. Their vision is crucial in designing our future research and innovation programme. And it is crucial to support the European Union in its leading role in the fight against climate change.

Commissioner Carlos Moedas

MEMBERS OF THE HIGH-LEVEL PANEL

Hans-Joachim SCHELLNHUBER (Chair)

Founding Director of the Potsdam Institute for Climate Impact Research (PIK)



Hans Joachim Schellnhuber founded the Potsdam Institute for Climate Impact Research (PIK) in 1992 and has been Director Emeritus since September 2018. He is a Professor of Theoretical Physics at Potsdam University and holds positions as Research Fellow at the Stockholm Resilience Centre and Senior Advisor at the Institute for Advanced Sustainability Studies (IASS) in Potsdam. From 2001-2005 he also served as Research Director of the Tyndall Centre in the UK and became a Visiting Professor at Oxford University thereafter.

Schellnhuber is currently member of the German Advisory Council on Global Change (WBGU), Chief Scientific Advisor of the Climate-KIC and Chair of the High-Level Panel of the European Decarbonisation Pathways Initiative of the European Commission. He is an elected member of the Pontifical Academy of Sciences, the German Academy of Sciences (Leopoldina), the Academia Europaea, the US National Academy of Sciences, the Max Planck Society and several other academies. Schellnhuber has received, *inter alia*, the Royal Society Wolfson Research Merit Award (2002), the German Environment Prize (2007) and the Volvo Environment Prize (2011). Schellnhuber was awarded a CBE (Commander of the Most Excellent Order of the British Empire) by Queen Elizabeth II (2004), the Order of Merit of the State of Brandenburg (2008) and the Order of Merit of the Federal Republic of Germany (2011). He holds honorary doctorates from the University of Copenhagen (2011) and Technische Universität Berlin (2012).

In 2017, he received the Blue Planet Prize from the Japanese Asahi Glass Foundation, which is considered the most important award for environmental sciences worldwide, and has received the Hans Carl von Carlowitz Sustainability Award.

Maria VAN DER HOEVEN (Vice-Chair)

Former Executive Director of the International Energy Agency (IEA)
Senior Fellow at het Clingendael International Energy Programme
Member of the Boards of Total, Innogy and Rocky Mountain Institute

Maria van der Hoeven is the former executive director of the International Energy Agency (IEA). As Executive Director, she steered the agency during a period of exceptional change in the global energy economy.

One of her overarching priorities was implementing a new Global Engagement Strategy to bring in institutionally the major emerging energy players of the 21st century. Another was expanding modern energy services to the 1.3 billion people worldwide who currently lack them. In recognition of the IEA's efforts to address the crisis of energy poverty, Maria van der Hoeven served on the Advisory Board to the UN Sustainable Energy for All initiative. Since 2015 she has been a Senior Fellow at the Clingendael International Energy Programme. She is a member of the Global Commission on the Economy and Climate and of the Global Commission on the Geopolitics of Energy Transformation.

Previously, Maria van der Hoeven served as Minister of Economic Affairs of the Netherlands from 2007 to 2010, during which time she demonstrated leadership on energy policy at the national, regional and global levels. Prior to becoming Minister of Economic Affairs, Maria van der Hoeven was Minister of Education, Culture and Science from 2002 to 2007.

She was an elected member of the Netherlands House of Representatives of the States-General from 1991 to 2002. Until 1987, she was head of the Adult Vocational Training Centre in Maastricht, after which she served as head of the Limburg Technology Centre until 1991.

Catia BASTIOLI

Chief Executive Officer of Novamont

Catia Bastioli is a chemist, researcher and entrepreneur.

She is CEO of the Novamont Group and Matrìca, and President of Terna (the first European independent grid operator for electricity transmission), the Kyoto Club Association and the Italian Technological Cluster of Green Chemistry, SPRING.

She has been developing and field-studying an economical, social, environmental and above all cultural development model based on territorial regeneration, conceived as an opportunity to decarbonise the economy and reconnect it with society, increase sustainability and relaunch competitiveness through continuous innovation applied to local areas and their specific features, interconnecting different territorial projects towards a common vision.

The innovative technologies developed for the bioplastics integrated value chain have led Catia Bastioli to found and grow a series of companies that today form part of the Novamont Group. Moreover, she has been a member of important EU working groups on climate change, the environment and the bioeconomy, such as the European Union Bioeconomy Panel and the ECCP-European Climate Change Programme, the Committee for Renewable Raw Materials of the Directorate General for Internal Market, Industry, Entrepreneurship and SMEs and the Environment Advisory Group of the Directorate General for Research and Innovation of the European Commission.

She is also the inventor of around 80 patent families in the sector of biopolymers and of transformation processes for renewable raw materials, and was awarded a European Inventor of the Year 2007 prize by the European Patent Office and the European Commission for her inventions related to starch-based bioplastics between 1991 and 2001.

Bastioli holds honoris causa degrees in industrial chemistry (2008, University of Genoa), in materials engineering (2016, University of Palermo) and in business economics (2018, University of Foggia).

Professor Paul EKINS

Professor of Resources and Environmental Policy at and director of the UCL Institute for Sustainable Resources, University College London

Paul Ekins has a Ph.D. in economics from the University of London and is Professor of Resources and Environmental Policy and Director of the UCL Institute for Sustainable Resources, University College London. He is also Deputy Director of the UK Energy Research Centre, in charge of its Energy Resources theme. He was a member of the Royal Commission on Environmental Pollution from 2002-2008. In 2011 he was appointed Vice-Chairman of the DG Environment Commissioner's High-Level Economists Expert Group on Resource Efficiency, and in 2012 a member of the European Commission's European Resource Efficiency Platform. In 2013 he was appointed to the UNEP International Resource Panel, for which he coordinated and was the lead author on a major report on resource efficiency at the request of the German government at the G7 Summit in 2015. In 2015, he was appointed to the Advisory Committee of the Green Growth Knowledge Platform and currently co-chairs its Research Committee on Natural Capital.

Ekins is also one of two chief co-editors of UNEP's sixth Global Environmental Outlook (GEO-6), which is the United Nations' flagship environmental report, and which will be presented to the United Nations Environment Assembly in March 2019.

In 1994, Ekins received a UNEP Global 500 Award 'for outstanding environmental achievement'. In the UK New Year's Honours List for 2015, he received an OBE (Officer of the Order of the British Empire) for services to environmental policy.

Beata JACZEWSKA

Former Executive Director at the International Visegrad Fund
Former Deputy Minister of Environment of Poland
Civil servant, diplomat

Soon after graduating from the Faculty of Law and Administration at Warsaw University (MA in legal studies), Beata Jaczewska started her professional career in Poland's public service.

She worked for the Ministry of the Economy in various positions, and was mostly involved in policymaking for the country's economic growth. In particular, as the Director of the Economy Development Department she was involved in climate change negotiations under the United Nations Framework Convention on Climate Change (UNFCCC), and identified the potential of green growth for Poland's development.

Serving as Under-Secretary of State in Poland's Ministry of Environment (December 2011–December 2013), she was a member of the board of the Green Climate Fund, organised COP19 in Warsaw and led the team of climate change negotiators, both in the UNFCCC and the EU.

Recently, she was Executive Director at the International Visegrad Fund in Bratislava (Slovakia). There, working with representatives of civil society in the region, she introduced a new impact-oriented methodology of project assessment, bringing 'community changing' ideas closer to the people.

Currently she is serving as ministerial advisor in the European Policy Department in the Poland's Ministry of Foreign Affairs.

She holds diplomas in cultural studies from Jagiellonian University in Kracow, Poland, and English and European Union law from the University of Cambridge, UK. She has also finished her PhD Studies in the Economics-Social Studies Department at Warsaw School of Economics, Poland.

Barbara KUX

Member of several Boards of Directors

Barbara Kux is a recognised Member of Boards of Directors. Her board mandates include global companies such as Henkel, Pargesa Holding (e.g. Adidas, Total, SGS) and the world's largest privately owned fragrance and flavour company, Firmenich. In her role as board member, she contributes to sustainable leadership, strategies for growth markets and digitisation. The EU Commission nominated her to the High-Level Panel of the European Decarbonisation Pathways Initiative to give strategic advice on research and innovation.

From 2008 until 2013, she was a member of the Managing Board of Siemens, the first woman in the 160-year history of the company. There she increased results from green technologies and supply chain management by several billion euros, as she had done previously at Royal Philips, where she was a member of the Group Management Committee. Under her leadership, both industrial companies reached top positions in the Dow Jones Sustainability Index. In 2012 and 2013, Siemens was distinguished in this index as the most sustainable industrial company in the world. As a member of the Sustainable Development Solutions Network Leadership Council for the United Nations, she contributed to the definition of the UN Sustainable Development Goals.

In the 1990s, she led Nestlé in the emerging markets of Central and Eastern Europe, where she established the company as the leader in fast-moving consumer goods, after she had achieved the same there for ABB in power generation. She started her professional career in 1984 as a Management Consultant with McKinsey in Germany.

After studies in Switzerland and as an AFS scholar in the USA, Kux earned her MBA with distinction from INSEAD Fontainebleau. She was educated in Zurich, where she was also born.

In 2012 Barbara Kux received the environment prize for large companies from the German Minister for the Environment. The Wall Street Journal listed her among leading international business women, as did Fortune magazine consistently over a period of more than ten years. Since 1995, she has been a Global Leader of Tomorrow of the Davos World Economic Forum.

Christian THIMANN

CEO Athora Germany
Affiliated professor of finance at the Paris School of Economics
Chairman of the EU High-Level Group on Sustainable Finance
Vice-chair of the FSB Task Force on Climate-related Financial Disclosures

Christian Thimann is CEO of Athora in Germany, a solutions provider and long-term investor in the European insurance market. He was Head of Strategy, Sustainability and Public Affairs of the AXA Group and member of the AXA Group Executive Committee from 2014 to 2016. At that time, he also served as a member of the Board of Directors of Alliance Bernstein Asset Management (New York) and a member of the Board of Directors of AXA Investment Managers (Paris). Until 2013 he was a Director General at the European Central Bank (ECB) in Frankfurt.

Mr Thimann has been Chair of the High-Level Expert Group on Sustainable Finance established by the European Commission and Vice-chair of the Task Force on Climate-related Financial Disclosures established by the Financial Stability Board. He continues to advise the European Commission on financial regulation, with a specific focus on sustainable finance.

He teaches insurance and finance at the Paris School of Economics and has published on insurance, international money and finance.

Laurence TUBIANA

CEO of the European Climate Foundation
France's Special Representative for COP21
Professor, Sciences Po Paris, and Professor, Columbia University
Founder and Director, Institute for Sustainable Development and International Relations (IDDRI)
Co-Chair, Sustainable Development Solutions Network (SDSN) Leadership Council
President, French Development Agency (AFD) Board of Governors

Laurence Tubiana is CEO of the European Climate Foundation (ECF). In addition, she is the Chair of the Board of Governors at the French Development Agency (AFD), and a Professor at Sciences Po, Paris. Before joining ECF, Laurence was France's Climate Change Ambassador and Special Representative for COP21, and as such a key architect of the landmark Paris Agreement. Following COP21, she was appointed High Level Champion for climate action.

Tubiana brings decades of expertise and experience in climate change, energy, agriculture and sustainable development, working across government, think tanks, NGOs and academia. From 1997 to 2002, she served as Senior Adviser on the Environment to the French Prime Minister Lionel Jospin. From 2009 to 2010, she created and then led the newly established Directorate for Global Public Goods at the French Ministry of Foreign Affairs (MAE). In 2013, she chaired the French National Debate on the Energy Transition. She founded in 2002 and directed until 2014 the Paris-based Institute of Sustainable Development and International Relations (IDDRI). In the 80's and early 90's she founded and then led Solagral, an NGO working on food security and the global environment. She started her career as a Research Director for the French National Institute for Agricultural Research (INRA).

Throughout the years, Tubiana has held several academic positions, including as a Professor and Scientific Director for the International Development and Environmental Studies master degrees at Sciences Po, Paris; and Professor of International Affairs at Columbia University, New York. She has been a member of numerous boards and scientific committees, including the China Council for Internaional Cooperation on Environment and Development (CCICED).

Karin WANNGÅRD

Mayor of Stockholm 2014-2018

Mayor Karin Wanngård studied human resources at the University of Stockholm and worked in human resources management before becoming a full-time politician. She has a long and impressive political career. She entered the Stockholm City Council in 1994 representing the Swedish Social Democratic Party and acted as Opposition Vice Mayor 2011-2014. For the same period, she was Vice President of the City Executive Board.

After the general elections in 2014, the City Council elected Wanngård as Mayor of Stockholm for the election period of four years. She was President of the City Executive Board, Chair of the board of Stockholm Stadshus AB and group leader of the Swedish Social Democratic Party in the City of Stockholm. Karin Wanngård was also Vice President of EUROCITIES, a co-leader of the C40 Low-Carbon District Network, a Champion Mayor of the OECD Inclusive Growth in Cities Campaign and a member of the board of the Strong Cities Network.

ACKNOWLEDGMENTS

This report synthesises the work carried out by the High-Level Panel (HLP) of the European Decarbonisation Pathways Initiative. The HLP is an expert group composed of nine Members from academia, industry and public administration and was tasked by Carlos Moedas, European Commissioner for Research, Science and Innovation to provide advice to the European Commission in relation to research and innovation (R&I) strategies and priorities that will support and accompany EU decarbonisation pathways compatible with the goals of the Paris Agreement.

The work of the HLP started in autumn 2016 and ended in autumn 2018, after 10 discussion sessions. The work of the HLP was supported by many experts, who kindly agreed to take part in the discussions, as well as by the DEEDS project, a coordination action tasked to facilitate the preparation of the discussions and their syntheses, and by the European Commission secretariat provided by DG RTD.

The Members of the High-Level Panel would like to thank **Commissioner Moedas** for his guidance and for his trust in the work of the Panel, and all the persons listed below for their expertise, contributions, observations, vision and support in the years 2016-2018.

The European Commission acting as the Secretariat of the Panel

Andrea Tilche, former Head of Unit, Climate Action and Earth Observation, co-editor of the whole report; **Pierre Dechamps**, co-author of Chapter 2 and co-editor of the whole report; **Anastasios Kentarchos**, Deputy Head of Unit, co-editor of Chapter 5; **Grazyna Krzywkowska**, overall organisation and edition; **Edita Kuzmova**, layout edition; **Peter Horvath** and **Zane Treinovska.**

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The Panel Members would like to thank the coordinator **Adriaan Slob** (Netherlands Organisation for Applied Scientific Research - TNO) and the whole consortium of the Horizon 2020 project **DEEDS** (DialoguE on European Decarbonisation Strategies) for their contribution to the drafting of this report:

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<u>The Panel wishes to thank the DEEDS editors of this report:</u> **Paul Deane**, University College Cork, **Neil Strachan**, University College London, and **Bob van der Zwaan**, Netherlands Organisation for Applied Scientific Research and University of Amsterdam.

EXECUTIVE SUMMARY

What strategy to adopt in R&I in order to speed up and foster mitigation policies in the EU that respond to the goals of the Paris Agreement, while growing the competitiveness of the EU economy? This was the main question that Commissioner Carlos Moedas put to the Members of the High-Level Panel (HLP) of the European Decarbonisation Initiative when this group of nine experts was first convened in October 2016. After two years of work, the High-Level Panel has delivered its final report, but in these two years the framework conditions have changed, new science emerged and global emissions, having been flat for about three years, have started to grow again. In October 2018, the **Intergovernmental Panel on Climate Change (IPCC)** released its **Special Report on 1.5 °C** impacts and pathways, and its compelling conclusions affected the final drafting of this report. The IPCC in fact says that there is a significant difference between stabilising the average global temperature at 1.5 °C compared to 2.0 °C, with dangerous tipping points and substantially higher risks being triggered between these two temperature thresholds. A window of opportunity for remaining at 1.5 °C still exists, but the challenge is huge, and all the best means to achieve it have to be mobilised, including R&I.

The HLP has therefore considered that a very ambitious R&I programme, capable of delivering the zero-carbon solutions needed, while also promoting industrial competitiveness in the EU economy, is one of the necessary means — even if not sufficient — to achieve the goal.

For ten discussion sessions, the HLP invited experts and stakeholders in the fields of energy, transport, industry, agriculture, finance, urban planning, social innovation, policymaking and more to debate the key challenges for decarbonisation and the R&I needs, in particular those emerging from economic and societal sectors for which the transition to a zero-emission future still looks difficult.

The **recommendations** of the HLP have been based on a number of assumptions that resulted from a preliminary discussion on the fundamental features that constitute the basis of the Paris Agreement. These derive from climate change science, and in particular from the very important conclusions of the Fifth Assessment Report of the IPCC, which brought to policymaker attention the concept of the '**carbon budget**'. The burning of fossil fuels, which started massively with the Industrial Revolution around 1750, has injected in the atmosphere a huge amount of carbon as carbon dioxide (CO_2) that was previously stored in geological deposits. CO_2 builds up and shows an almost linear relationship between its atmospheric concentration and the warming of the planet. Therefore it is possible to calculate the overall CO_2 emission budget that leads to 1.5 °C or 2.0 °C of warming beyond pre-industrial levels. This budget has already been used for its greater part. The above-mentioned IPCC Special Report on 1.5 °C says that at current emissions, ranging around 42 Gt CO_2/y, the available carbon budget for reaching 1.5 °C will expire between 2030 and 2040, and for 2.0 °C will expire some time between 2040 and 2050.

The main principle that has therefore been used as the basis for the HLP recommendations is that the focus of public investments in research and innovation should be on **zero-carbon solutions**. Low-carbon technologies that only reduce but do not eliminate greenhouse gas emissions have to be used at best for the transition towards a carbon neutral future, but have to be replaced soon by zero-carbon ones. The remaining carbon budget available to stay within the Paris Agreement boundaries is too small to lock ourselves into technologies that do not lead to zero emissions. It is true that some 'negative emissions' (from technologies or practices for removing CO_2 from the atmosphere) can be generated to offset emissions that are more difficult to cut, but relying too much on negative emissions implies difficult and risky land use choices, e.g. afforestation and reforestation.

A second key assumption is that zero-carbon solutions shall be tackled at the **system level**, and for this the role of **digitalisation** is of utmost importance.

A set of thematic and cross cutting recommendations have been produced by the HLP, in particular for the orientation of the new EU Framework Programme for Research and Innovation 2021-2027, **Horizon Europe**. These recommendations include: 1) the need for **sustained R&I** activities **on decarbonisation** across all sectors, including a robust programme on climate change science; 2) the establishment of **large mission-oriented programmes** of a cross-cutting nature for the deployment of system-level transdisciplinary innovation; 3) the development of **partnerships with industry** to address together the most difficult aspects of decarbonisation, on which industry alone would not invest enough and with the necessary urgency; and 4) the launch of '**Transition Super-Labs**', very-large-territory initiatives of real-life management of the transition from typical fossil-fuel-based local economies to zero-carbon ones.

Putting decarbonisation at the heart of Horizon Europe and of other national R&I programmes in the EU may be the starting point of the change of pace in mitigation that is required to achieve the Paris Agreement goals. Horizon Europe in particular, with its engagement of investing 35 % of its proposed EUR 100 billion budget in climate-related activities, is a unique opportunity to transform this target into a true coherent zero-carbon programme.

CHAPTER 1

THE OVERARCHING NARRATIVE: THE PARIS AGREEMENT, EUROPE'S ROLE AND NOVEL APPROACHES TO RESEARCH AND INNOVATION

1 Some framework considerations

The challenges associated with mitigating anthropogenic climate change is the broad focus of this report, which analyses the R&I needs and proposes a strategy that shall accompany feasible EU decarbonisation pathways, compatible with the Paris Agreement goals.

However, just focusing on anthropogenic climate change is not enough to set the scene within which the EU is called to deploy **radical changes in the way in which energy, resources, goods and services are produced and used.** Modernity is in fact faced with **a multiplicity of crises**, which go well beyond the crucial environmental imperative of stopping greenhouse gas emissions.

Some ten years after the **great financial crisis**, the world is realising that the promises of **exponential growth** to increase human well-being for all have not and **may not be fulfilled**. Today, many regions of the world — including in Europe — are stricken with economic stagnation and worsening of social disparities, and are at risk of falling behind, characterised by little economic value added (VA), structural unemployment and consumption largely based on imported goods, including foodstuffs. Furthermore, accelerating digitalisation and, most notably, the development of artificial intelligence, may widen those gaps unless swift and wise governance is implemented at all political levels (Frey and Osborne, 2013).

Other core promises of modernity to the world, such as **cheap energy** for everybody, based on the massive exploitation of fossil fuels resulting from millions of years of biological and geological history, or **unlimited mobility** for people and goods, to be delivered by private vehicles, public roads and cheap oil, have clearly shown their inconsistency with the planetary boundaries of natural resources and with their huge unpaid externalities. This declination of modernity has organised entire nations in concentric rings around megalopolises, while largely degrading natural landscapes to the role of hinterlands for resource extraction, throughput of people and goods, waste disposal and industrial agriculture. This epitomises the dichotomies of conventional modernity: while the sheer supply of cheap high-calorie food has reached an unprecedented level, the social costs in terms of illness, obesity, antibiotic resistance, animal cruelty, biodiversity loss, soil degradation and GHG emissions increasingly mount.

Economic and financial **globalisation** was initially hailed as an unprecedented source of efficiency in the worldwide allocation of capital and production and as an opportunity to boost consumption possibilities globally. As it turned out, the shift of VA production to emerging economies, Asia in particular, has certainly boosted incomes in the latter parts of the world, but at the same time has been the cause of unemployment and social disruption elsewhere. It has promoted production processes in emerging economies that are often not environmentally friendly, and has resulted in an upsurge of global trade volumes which became a source of pollution, environmental degradation and CO_2 emissions. Unbridled digitalisation and robotisation may exacerbate this race to the bottom. **Keynes' forecast** of a world where the material needs of people are all satisfied and people's jobs — mostly replaced by machines — may turn into other forms of social and artistic occupation (Keynes, 1930) is unfortunately far from being achieved.

In summary, **the economy as we know it operates in a materially expansive, socially divisive and environmentally hostile way**, and receives disruptive shocks at an increasing rate, including from new business models. **This is hardly sustainable**.

The alternative to a 'more-of-the-same' strategy, which will eventually turn crisis into collapse, needs to be grounded in a fundamental re-conceptualisation of the structure and operation of the current economic system. **Such changes will deeply affect lifestyles and societies, and represent a critical challenge because they will necessarily create winners and losers**. For these reasons, the re-design of our economies should be organised around **three key notions, namely (i) purpose, (ii) capacity and (iii) viability**. For the first notion [**purpose**], one needs to ask how the current system can be redirected to serve the needs of the many (young, old and those yet to be born) and not of the few. For the second [**capacity**], one needs to take stock of the fantastic pool of mature as well as embryonic methodologies, technologies, infrastructures and institutions that classical modernity has assembled or instigated over the last two centuries. If used wisely and effectively, this pool can lead to improved living conditions, even with 10 billion people on planet Earth. As for the third [**viability**], practically everybody nowadays accepts the motherhood statement that there cannot be infinite material growth on a finite resource basis. Note that this does not exclude intangible growth — in terms of experience, science, culture, quality, design, institutional structure, digital capital, etc. — which can go on for millennia to come. It is all about the vision of a civilisation based on resource efficiency and the (semi)circular flow of resources, respecting planetary boundaries.

This vision implies that most **material fluxes** currently supporting the economy are **converted into closed loops**. For instance, in the long term one can imagine that roughly fixed quantities of certain raw materials (such as copper or rare earth elements) circulate through the entire industrial metabolism with the help of advanced recycling processes, reducing the need for further mineral extraction to practically zero. Likewise, one can envisage full recycling of organic agricultural waste, the replacement of chemical substances (such as pesticides) with biological agents, and the minimisation of the loss of hard-to-retrieve inputs (such as phosphates). Such a resource-efficient and (semi-)circular economy will still be semi-open from a narrow perspective but could result in a closed loop if we consider the system as a whole. On the one hand, it will receive energy from outside, yet the relevant sources can all be renewable. It will produce waste, yet only of the type that can be fully degraded then absorbed and recycled by natural ecosystems, which must therefore be protected and enhanced accordingly. Equally important are the many regional initiatives on sustainable agriculture that will thrive and also create meaningful employment opportunities in Europe's remote regions. Concepts such as cradle-to-cradle design can be helpful in this context, if they prove their worth in practical value creation and preservation.

In summary, **the (semi-)circular economy shall remove critical externalities, respect planetary boundaries, aim to maximise inclusiveness, be financially and economically viable, and rely on intelligence, knowledge and information**.

This (semi-)circular model in general and the decarbonisation of the economy in particular represent a brilliant perspective for a continent such as Europe, characterised by slim critical raw mineral stocks and rapidly declining fossil resources. Apart from contributing to climate stability as a common good for humanity, **rapid and efficient decarbonisation could provide numerous extra benefits for the EU**: a much increased level of energy autonomy, most notably from authoritarian countries and regimes; the saving of hundreds of billions of euros currently spent on fossil-fuel imports and subsidies; the improvement of air quality, which would save the lives of millions of people; and the avoidance of direct ecological damage such as that caused in the few remaining coal-extraction sites or by the expansion of agricultural monocultures.

Therefore it is of a paramount importance to change production processes, patterns of consumption, recycling and disposal of biological resources drastically. Integrating the bioeconomy into the (semi-)circular economy model is the key element for the development of a sustainable society, since the **circular bioeconomy** is a cornerstone linking forestry, agriculture and fisheries to the industrial production of bio-based products that are functional for both sustainable land use and societal services.

This bioeconomy model includes the notion of **'sustainable regions'** and the need to think in terms of local areas, of their socio-economic and ecological specificities and problems, thus transforming their challenges into opportunities for development. This should be achieved by reviving both regional and sustainable agricultural initiatives and local production of goods and services, using local skills and avoiding mass transport.

Europe's character and role in the world is based on a **unique set of values and convictions** that emerged from the stunning humanistic advances made during classical antiquity, the Renaissance and the Enlightenment. **Individual freedom and social empathy** are defining elements of that set. Many argue today that fundamental transformations of the industrial metabolism of a society can only be realised by non-liberal, central-planning nations. Proving that hypothesis wrong by ushering in trans-modernity in a just and democratic way would arguably be one of the greatest achievements of the EU.

It is therefore to be highlighted that despite the very clear compelling case for decarbonisation proposed for years by scientists, intellectuals, associations and several political parties, **decarbonisation is still happening at very slow**

pace compared to what would be necessary for climate stability, and what could be achieved. Decarbonisation **needs to accelerate if the race is to be won also from the standpoint of the economy and capacity for job creation.** In this respect, innovation will accelerate the pace of transformation by making the costs of zero-carbon technologies equal to or lower than those of fossil-fuel based options, as is already the case for wind and photovoltaic energy in some parts of the world. This, in turn, will give economic advantage to the front runners in these new industries and technologies and will push fossil fuels out of the market, without the need to wait for an agreement on a global carbon tax (which would be very hard to achieve today) that would internalise the global warming externality.

2 The Paris Agreement and the innovation challenge of decarbonisation

The Paris Agreement of December 2015 at COP21 (UNFCCC, 2015) opened a new phase in climate action by setting the target of keeping a global temperature rise this century to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase even further to 1.5 °C. These ambitious objectives have to be achieved through the cyclic upgrading of nationally determined contributions (NDCs) to climate action, reviewed every five years to ensure convergence towards the goals.

After the first exercise at COP21, it was clear that the **NDCs proposed by countries were highly insufficient to achieve the targets**, and are likely to lead to global warming between 2.7 and 3.0 °C, or even more. Most of modelling work around this issue shows that the world's greenhouse gas emissions should peak as soon as possible and rapidly decrease afterward if we want to have some hope of remaining within the estimated carbon budgets leading to 1.5 or 2 °C. Every further year of emissions at today's level of about 42 $GtCO_2$/y will make the Paris Agreement goals more difficult to achieve as the remaining carbon budget is low and not precisely known.

In the Paris Agreement policy framework, R&I play a major role by providing the technological and non-technological solutions for a rapid decarbonisation of the world's economy. Climate action can, and must, start and progress with today's available solutions, but these will soon be insufficient for the pace of decarbonisation required unless accompanied by climate policies of politically difficult stringency. The development of cheaper and more effective mitigation solutions is therefore essential to increase the speed and the ambition of decarbonisation.

In this context, the success of rapid and deep decarbonisation depends largely on the effective development of portfolios of low- and zero-carbon, cost-efficient and high-performance technological and non-technological solutions, and on their integration into all facets of the European economy and society. These include key productive sectors, such as industry, energy, agriculture and transport, but are also more generally related to the way of living of European citizens, which can be changed through social innovation promoting moves towards zero-carbon, sustainable cities.

Further, innovation will need to happen at all scales, including local communities and small and medium-size enterprises.

Digitalisation is key to deploying innovation at system level across all traditional sectors. Electrification is a *sine qua non* for the decarbonisation of a large part of the mobility system, of energy-intensive industries and of heating needs. Electricity needs will increase substantially, but smart grid technology and a wise management of future diffused energy storage systems — such as batteries for electric vehicles — and of diffused production may very much help to flatten peak demand. An '**Internet of Energy**' will need to be developed.

Given the magnitude of the decarbonisation challenge and the need to ensure that competitiveness and job co-benefits fully materialise through decarbonisation, R&I efforts should be intensified. The technical and socioeconomic transformation implied by decarbonisation amounts to a new Industrial Revolution, and the EU should focus its R&I funding to push the frontiers of science and knowledge in this direction. This includes funding curiosity-driven research, mission-oriented research and demonstration projects that together will accelerate the transition from the lab to the market, resulting in cost reductions, jobs and economic growth. However, it also requires innovative ways to overcome other significant barriers to technology diffusion, such as system integration, infrastructures that lock in high-carbon behaviour, transitional costs, non-technical and behavioural barriers, and difficulties in accessing and securing financing and increasing market reach.

Furthermore, there is a clear need to steer the process of innovation towards zero-carbon solutions. Historically, technological innovation has not necessarily brought about improved material, cleaner energy or input efficiency. For instance, innovation in the Industrial Revolution or many aspects of the Internet Revolution increased the use of materials and energy. The implementation of a set of policy and institutional incentives thus becomes a necessary pre-condition to foster zero-carbon innovation and the diffusion of low- and zero-carbon business models. In this respect, digitalisation — if properly steered — can become a means to support decarbonisation.

Demand-side measures and technologies should always accompany the introduction of new supply-side technologies or services. Taxation and regulatory instruments are the most common demand-side instruments. Many more examples can be cited, which are frequently facilitated or made possible by technology and in particular by ICT. One example is the potential of distributed 3D printing to reduce freight transport. Another one is teleworking, to reduce personal car use and congestion. Many other examples can be made in the realm of energy and resource use. Behavioural aspects and lifestyle changes have also to be addressed when acting on the demand-side, also because the potential emission reductions in relation to the introduction of a new technology might be partially offset by rebound effects. R&I, including on the design of social innovation mechanisms for citizens' engagement in decarbonisation plans, may bring considerable additional benefits in terms of emissions reduction.

To successfully address this innovation challenge, public and private investments need to work synergistically, and in a stable policy environment. As history demonstrates, publicly-driven mission innovation programs are crucial to giving clear and stable signals to firms and entrepreneurs, and, if properly implemented, can be extremely successful in addressing the high risk and uncertainties that characterise the early stages of the innovation process. However, private engagement and investments will also be crucial to achieving the deep technology transition necessary for decarbonisation, particularly in the demonstration and deployment phases, which should leverage the private sector's knowledge of markets, business models and customers.

3 Decarbonisation: risks and opportunities

Since the Industrial Revolution, societies have built their wealth on the availability of cheap energy derived from fossil fuels. Economic growth has grown for about two centuries in parallel with the consumption of fossil fuels. It is only in the last two decades that the two curves have started to show **signs of decoupling**, at least in OECD countries.

Fossil fuels have become so much part of our societies, economies and value chains that the process of their phasing out will be difficult and encounter barriers of all kinds, even if — as is in fact the case — **the move to zero-carbon energy sources and technologies is generating tremendous new opportunities**, alongside key challenges. The transition phase to a zero-carbon society is and will be complex and difficult, and thus needs to be managed and well supported by robust research and demonstration activities.

Any transition creates winners and losers, and it is critical to ensure that no-one will be left behind in the transition. Public support for the decarbonisation agenda is important. Region-specific transition roadmaps can be a means to maintaining public support for such a challenging endeavour. Prospective analyses should include considerations of key aspects such as EU industrial policy, competitiveness, distributional considerations, and a global view in respect of markets and trade. The importance of quick adaptation to local conditions should be highlighted, and the implications of having new competitors such as China emerge in technology innovation should be fully understood.

The HLP, in the preparatory work towards this report, analysed several sectoral (energy, transport, industry, agriculture) and inter-sectoral issues (cities, value chains, supply chains, inter-sectoral impacts, digitalisation, etc.), knowing that **solutions to the decarbonisation challenge have to be systemic**, but also taking into account that today's societies and economies tend to adopt technological solutions that create lock-in situations and rebound effects. The intervention of governments is therefore necessary to **correct market failures** and distortions, and support for R&I is a key element of this intervention.

4 A long-term strategy, including for R&I

The European Commission, at the request of the European Council, **is working on the development of a strategy for long-term greenhouse gas emissions reduction in the EU**. A strategy of R&I for the development of the necessary zero-carbon solutions must be an integral part of this. This report provides suggestions for such a strategy, together with some methodological approaches.

R&I for zero-carbon solutions, however, is somewhat different from innovation challenges in other fields. In fact, the presence of **fossil-fuel subsidies**, and the quasi-absence of taxation related to their **negative externalities**, makes for a **very uneven playing field**, on which zero-carbon solutions must be developed and compete. Zero-carbon technology diffusion will therefore require appropriate market measures to **level the playing field**, at least until a certain level of market penetration is achieved.

Diversification of technological options is essential to avoid lock-in on unsuccessful development paths. The development of an appropriate zero-carbon **technology portfolio** for phasing out greenhouse gas emissions will therefore require a very wide and varied R&I effort, one that will need to span from fundamental research — essential for developing breakthroughs — to applied research, demonstration and support for the various stages of innovation and deployment. This is essential to **foster the evolution of the existing EU industrial sector and promote the growth in Europe of a new, powerful industrial sector that will increase our overall competitiveness**.

Europe is at the beginning of a true revolution, and one that will not only be carried out in the technological domain. Social innovation will also be essential, in particular to engage citizens in the decarbonisation challenge and to promote living-lab experiments on ways to boost the zero-carbon economy through **lifestyle changes** (for instance, the sharing economy).

Digitalisation will be a key enabling factor, both to allow action at system level, to increase efficiency, to deploy a (semi-)**circular, dematerialised, service-oriented and shared economy**, and to ensure that citizens become engaged actors in this transition.

Notwithstanding the uncertainties linked to quantification of the global carbon budget necessary to remain well-below 2 °C, **the EU should continue to play a leading role in climate action, showing leadership in its decarbonisation plans**. This leading role entails risks and opportunities, and requires the engagement of the EU business sector and of citizens at large. The technological and organisational capacities that exist in Europe, its climate policy experience and the existence of channels of engagement for business and civil society, provide a good basis for acquiring a first-mover advantage if all capacities are deployed.

Five principles should inspire the EU R&I strategy for supporting its greenhouse gas emission reduction efforts:

- **engage in a race to the top** in innovation for decarbonisation, searching for new alternatives;
- **give priority to zero-carbon solutions** that have the potential to be developed and deployed within the 2050 time frame;
- **explore and develop portfolios of zero-carbon technologies**, promoting diversification, and reducing the risk of early and risky choices;
- **emphasise system-level innovation**, so that the individual elements of decarbonisation fit together in a coherent whole;
- focus R&I investments in the **high added-value segments of the value chains**.

These principles should then be applied through different approaches and combine actions at different time horizons.

In the short-term horizon (2025), considering that the main goal at a global level is to start a rapid reduction in greenhouse gas emissions, the priority for R&I programmes should be two-fold. On the one hand, they should aim to fully understand and tackle the barriers hindering the large-scale deployment of all the existing economically convenient low- or zero-carbon solutions. On the other hand, they should make financial instruments available to help boost mid-TRL[1] low-carbon technologies to the commercial level.

For the medium-term horizon (2035), it will be necessary to design mission-oriented activities that have the goal of developing key zero-carbon solutions. Taken together, these solutions shall be able to address and potentially reduce today's emissions by a level greater than 50 % per decade. These programmes have to be the backbone of the Herculean efforts of decarbonisation that have to be deployed throughout the 2030s.

R&I actions **for the longer-term** horizon (2050) then have to address those sectors and areas of decarbonisation that are currently perceived as more challenging — such as, to name a few, process-based industrial emissions (steel, cement, chemicals), air transport, shipping and animal husbandry. In many of these examples, alternative solutions are sometimes still being conceptualised. Given the size of these challenges, longer-term actions have to start now or very soon, and should be supported through multi-annual funding programmes. Within this category, technologies for generating negative emissions also have to be included. However, the investment in this category of 'end-of-pipe' solutions should never crowd out the much more necessary development of zero-carbon solutions, or finally outcompete them.

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[1] Technology readiness level (from 1 to 9).

In the conclusions of this report the recommendations are presented in relation to these different time horizons. We will not address here the post-2050 scenarios. We are convinced that the uncertainties that today still exist on the possible activation of positive emission feedbacks require us to do whatever is possible to avoid going beyond the carbon budget identified by the IPCC in its recently published Special Report on 1.5 °C warming (IPCC, 2018) for remaining within the 1.5 °C target with no or minimum overshoot. This implies — at least for industrial economies — achieving zero net emissions of all greenhouse gases by 2050.

This report has also the ambition of feeding into the strategic programming discussion that is preparing the implementation of the future **EU framework programme for research and innovation 2021-2027, Horizon Europe**, and of being of inspiration to other national programmes.

The proposal of the Commission that Horizon Europe will invest **35 % of its resources in climate-related actions** is highly welcome, and should guide the preparation of ambitious work programmes, in particular on mitigation.

In the conclusions of this report, some proposals for **mission-oriented, cross-thematic programmes** are presented. They identify medium-term thorny challenges that can be achieved through mission-oriented activities involving different stakeholders beyond the scientific and technological communities.

However, as already said, the race to full decarbonisation can be won only if multiple engagements addressing diverse timelines and appropriate financial instruments supporting the various phases of innovation can be deployed in parallel with sufficient human and capital resources.

Horizon Europe should also dedicate resources to **maintaining Europe's leadership in climate science**. The implementation of the Paris Agreement from 2020 onward requires a stronger scientific backing to help countries increase their decarbonisation ambitions cost-effectively and to ensure they comply with the Paris Agreement objective of maintaining the average warming of the planet well below 2 °C with respect to pre-industrial times and to adapt to the residual impacts.

Within this broader context, a wide space for international cooperation is open and should be fostered. Europe is not alone, and showing leadership implies working with others. International alliances such as Mission Innovation have high potential to build higher critical mass on key innovations. Sharing results with others does not necessarily result in lost competitiveness. On the contrary, the development of **global supply and value chains** around new zero-carbon technologies provides a **better sharing of the risks** that exist for lone forerunners, and enhances the possibility to tackle effectively what is a global problem.

International cooperation should also help less developed countries to jump over the technological divide and to ground their future growth on sustainable solutions, including through the better management of land and marine resources. This aspect will be a **critical component of future development**

policies, with multiple and reciprocal spillover effects on growth, stability and security, as all countries seek to achieve the agreed Sustainable Development Goals (SDGs) embodied in the United Nations' Agenda 2030 and essential for ensuring sufficient removals by sinks for the attainment of the Paris objectives.

5 The body of the report

The chapters that follow summarise the main analytical elements that the HLP has reviewed in its discussions and taken into account for its deliberations. The content has neither the scope nor the ambition to provide an exhaustive assessment of all the sectoral and cross-sectoral decarbonisation challenges and their R&I dimension. The chapter contents represent, however, a deliberate selection of topics that the HLP considers of primary relevance for the design of a successful R&I strategy meant to accompany and promote the European Union efforts towards carbon neutrality and a stronger leadership in the fight against anthropogenic climate change. Each chapter makes specific, more detailed recommendations regarding R&I needs in specific societal and economic sectors, which are then addressed in a more integrated and systemic manner in the conclusions.

The HLP chose to adopt a programme of discussion sessions of a sectoral character (energy, transport and mobility, agriculture and land use, industry) together with others of more cross-cutting nature (cities, finance and innovation, social innovation, digitalisation). However, the analytical approach used was similar, always focusing on the system-level dimension as well as on the cross-sectoral issues. This was clearly facilitated by the richness of the heterogeneous competences and professional roles of the HLP Members.

CHAPTER 2

DECARBONISING THE ENERGY SECTOR IN EUROPE

1 The present state of energy supply

The energy-environment/climate nexus is determined by three factors: sustainability, secure energy supply and affordability, which are the pillars of our energy and climate policy. The sustained global economic growth since 1950 is due in part to the availability of affordable sources of fossil fuels: coal, oil and gas. From a longer-term perspective, fossil fuels have been fuelling the industrialisation of all the economies of the world, starting in the middle of the 18th century in the UK, and have contributed to the increased affluence of the (growing) world population.

The mass-scale use of cheap fossil fuels has enabled global economic growth but also resulted in a great challenge for our societies: anthropogenic climate change. The growth of energy consumption in our societies also has a massive external cost, described by the Stern Review as 'the greatest and widest-ranging market failure ever seen'. Climate change is in large part a consequence of energy use. Mitigating climate change depends critically on whether energy use can be greatly reduced, energy can be decarbonised or both. Greenhouse gas emissions can be broken down by the economic activities that lead to their production. The 2017 statistics released by the European Environment Agency (EEA) show that energy in the broad sense is responsible for almost 75 % of direct greenhouse gas emissions in the EU, with the energy supply sector being the single largest contributor (28 %)[2].

Besides climate change, energy use has a substantial effect on many other societal and environmental challenges such as air pollution, resource extraction, biodiversity and land use. Taking air pollution as an example, over 80 % of sulphur dioxide (SO_2), nitrogen oxide (NO_x) and primary particulate matter ($PM_{2.5}$) emissions can be attributed to energy use (International Energy Agency (IEA), 2016). Accordingly, when aiming for a fundamental change to the energy system, it is also paramount to take into account these other externalities, and how the SDGs are affected.

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2 Numbers for 2015, which are the most recent EEA and Eurostat figures available. The circle shows the direct GHG emission shares of major economic sectors. The pull-out shows how indirect CO_2 emission shares from the energy supply sector can be attributed to sectors of final energy use. AFOLU refers to agriculture, forestry, and other land use. This graph includes international aviation, which is covered by EU targets but is not accounted for in national totals under the United Nations Framework Convention on Climate Change (UNFCCC).

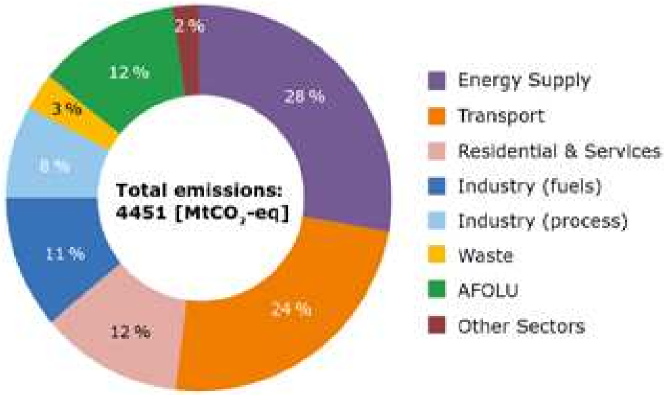

Figure 1: EU-28 greenhouse gas emissions by economic sectors.
Source: based on EEA, Eurostat and own calculations, 2015.

2 Recent developments and lessons learned

In the past couple of years, the energy landscape in Europe and the world has become more aware of the need for sustainability. The massive investments in new low-carbon energy technologies in China, the US and Europe, as well as the switch from coal to gas in the US since the shale revolution, are affecting the growth path of CO_2 emissions in the world. Since 2010, CO_2 emissions growth has been tapering off and was even flat from 2014-2016, in part because of the downturn in economic growth. However, the recent increase in 2017 shows that CO_2 emissions have not yet peaked (IEA, 2018).

The changes in today's energy landscape in Europe are the result of several interdependent mega-trends, both pushed and pulled by the EU's 2020 and 2030 climate and energy plans and the recent Clean Energy for All Europeans package. These trends are:

- greater renewable energy sources (RES) production and (potential of) increasing electrification;
- greater energy efficiency;
- new energy technologies (such as distributed energy technologies) and governance structures;
- digitalisation as a key driver and enabler of greater integration and service orientation;
- active consumers.

Up to now, these changes have taken place neither at a sufficient pace nor homogeneously throughout the EU. For instance, while overall energy-related

CO_2 emissions decreased on average by 2 % annually from 2005 to 2015, transport-related emissions reduced by only 0.6 % per year (European Commission, 2018).

In order to deeply decarbonise our economies, we need zero-carbon molecules as well as increased use of zero-carbon electrons[3]. More concretely, we need new technologies to produce, convert, store and use zero-carbon electrons and molecules. These technologies will enable new systems integration across different types of energy demand and the management of intermittent supply and demand of all types (CIEP, 2017). The European Battery Alliance, launched in October 2017, is an important first step towards the next generation of battery storage technologies. Further such initiatives, targeting both other storage technologies (including chemical and thermal) as well as other building blocks of the future energy supply system, are necessary.

A certain trade-off between the extent of decarbonisation and short-term emission reductions exists. For most processes and technologies, implementing a zero-emission solution requires higher investments than going for only partial decarbonisation. An investment into, e.g., second generation biofuels will only be economically viable at high carbon prices that are much higher than the level seen today. Furthermore, many zero-carbon solutions, such as hydrogen trucks, are not yet market ready. Thus these technologies will require substantial R&I funding and will certainly not be implemented on a large scale for at least a decade, meaning that they will not contribute to the emission reductions that are necessary over the next decade to stay within the emission budgets for 1.5 °C or 2 °C of warming. On the other hand, cheaper intermediate solutions exist that will bring down emissions in the short term, such as natural-gas-fueled trucks. While being cheaper to implement and closer to market, these technologies can potentially create lock-ins into partially-decarbonised processes that prevent the full decarbonisation required to meet the Paris Agreement targets.

This trade-off cannot be solved in general — it needs to be weighed separately for each specific case, factoring in the differential costs of additional abatement, the expected R&I timeline of a technology, the danger of lock-ins into unsustainable pathways, and the adaptability towards future zero-carbon solutions, e.g. injecting hydrogen and biogas into gas grids.

In several practical cases, given the very ambitious target of full decarbonisation by the mid-century, public R&I money should be focused on processes that achieve close-to-zero or even negative emissions, and not on processes that only reduce emissions, especially if solutions take 10-20 years to go from the laboratory stage to high market shares.

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[3] It is clear that electrons do not contain carbon, while methane or liquid fuels invariably contain carbon. The terms 'zero-carbon molecules/electrons' are used throughout this report as shorthand terms for 'fuels/electrons whose production and use result in very low or negative GHG emissions' and where carbon atoms are not of fossil origin.

Carefully designed R&I policies will ensure that reducing one externality (e.g. greenhouse gases) does not create new externalities, e.g. new material scarcities or increased land use. Although new energy technologies are coming to maturity, we cannot assume that the low-carbon character of the new energy technologies means that they are perfect on all accounts. We need to look at the energy system in a dynamic and integrated manner, rather than a static one, if we want to understand fully all the impacts of existing and proposed policy measures. This requires a fundamental update of current energy system models to include the necessary dynamic representation of links between the energy system, land and water nexus, for macroeconomics as well as the industrial metabolism.

3 Moving to sustainability with new energy technologies

Driven by diminishing costs and more extensive deployment of new low-carbon energy technologies, Europe's energy system is already becoming less carbon intense. This trend is set to continue, but needs to be accelerated and broadened from electricity generation to other types of energy demand and use. Moreover, zero-carbon electrons need to be effectively linked to zero-carbon molecules. Renewable energy sources, particularly onshore as well as offshore wind and solar PV, are now cost-competitive with fossil energy sources in many parts of Europe. In the past decade, renewables have attracted a growing share of new energy investment. Global investment in renewables has dropped in the recent past as a result of declining specific investment costs for renewables, but there has been a record installation of renewable power capacity (UNEP-FS, 2017; IRENA, 2017).

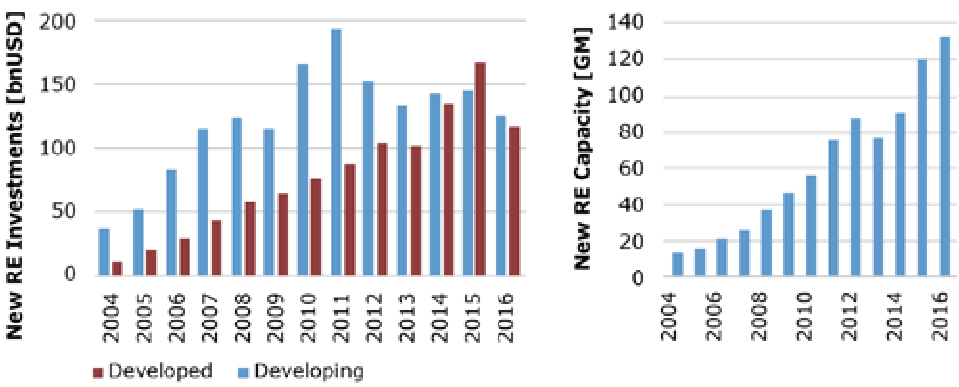

Figure 2:
Left: Global new investment in renewable energy excl. hydro (data in billion USD). Source: UNEP-FS, 2017.[4]
Right: Global capacity additions of RE excl. hydro. Source: IRENA, 2017.

[4] New investment volume adjusted for re-investment equity. Total values include estimates for undisclosed deals. Developed country volumes are based on OECD countries, excluding Mexico, Chile, and Turkey.

The rapid expansion of renewables brings manifold challenges and opportunities: knowledge growth, massive grid requirements, storage and capacity mechanisms, to name a few. Further sustained deployment of these technologies will result in more efficiency gains, greater economies of scale and additional cost reductions through processes such as automation and learning-by-doing. However, the variable (but forecastable) generation profile of solar and wind energy is starting to pose integration challenges in some Member States. To address these challenges, many potential options exist, e.g. building extensive high voltage connections to demand centres, developing energy storage through batteries or conversion to molecules (for instance hydrogen), or making demand flexible.[5] Also, variability implies that (extended) periods of low wind and solar generation occur and may in fact coincide. As a result, alternative capacity is required, either renewable or conventional in the short run, which is only needed for limited amounts of time. While electricity systems presently rely on (legacy) conventional power plants, it remains to be seen whether operators and investors are willing to put their resources into capacity given this kind of risk/reward profile. Finally, while the costs of wind and solar can now be competitive with newly-constructed fossil fuel power plants, the current oversupply of fossil capacity in combination with long-lived capital stocks means that the decarbonisation of the EU power supply will happen much too slowly without additional policy action.

Although decarbonisation is driving a general shift towards increased electrification of parts of the economy and society, a zero-carbon power sector will not be sufficient to meet the EU's climate targets. In 2015, the EU had a 'final energy consumption' of 1086 Mtoe, of which about 20 % was electricity (2752 TWh) while the remaining 80 % is mainly represented by fuels for transport, heating and industry. If we assume that electricity production is to double its current share — through renewables — by 2050, a large amount of the other energy vectors will still need to be decarbonised, underlining the importance of zero-carbon molecules. Apart from generation, the additional cost of storage and transportation will be important determining factors in the balance between zero-carbon electrons and molecules. Particularly in countries with large seasonal demand for low temperature heat, either zero-carbon molecules or heat networks with seasonal heat storage might be crucial in meeting decarbonisation goals.

Zero-carbon molecules have an important role to play, but due to efficiency considerations they should be limited to cases that lack other decarbonisation options. There are a number of different routes to producing

[5] Absorption challenges can both be technical and economic. The technical challenges are well understood and managed by transmission system operators (TSOs) and distribution system operators (DSOs). This is less so for the economic challenge. In today's liberalised European electricity markets, wholesale electricity prices reflect supply and demand balances. The variable nature of solar and wind generation means that at times, large amounts of supply are available, depressing prices. This poses a challenge to generators, which depend on revenues from sales on these wholesale markets. Over time, it can mean that (previously subsidised) capacity leaves the system unless new (public) financial guarantees are provided to (RES) generators.

liquid and gaseous fuels with minimal or even negative GHG emissions over their full life cycle:

- Hydrogen could be produced via low-carbon pathways such as electrolysis from renewable electricity or through alternative production processes (e.g. biomass gasification and carbon dioxide capture and storage (CCS) or thermochemical water splitting) to ensure a minimal or even negative emission impact. If further R&I achieves fast ramping and low capital costs of electrolysis technologies, hydrogen electrolysis could be an important source of flexible electricity demand, thus assisting the integration of large shares of variable renewable electricity sources[6].

- Methane and liquid fuels consist partially of carbon. However, if they are produced from zero-carbon hydrogen and CO_2 captured directly from the air or from biogenic CO_2 emissions such as off-gases from industrial fermentations, the net GHG emissions of production and use of these fuels would be close to zero.

- Finally, the conversion of biomass into gas or liquid fuels via the Fischer-Tropsch process or fermentation can be combined with CCS to capture and sequester part of the carbon contained in the feedstock biomass, thus yielding net negative CO_2 emissions when accounting for CO_2 uptake during biomass growth (IEA, 2011). These negative emissions could be an important contribution to compensating residual GHG emissions that are very difficult to mitigate, e.g. from agriculture or certain industry processes.

It should be noted that there is a trade-off to be considered: while electrification sometimes requires higher capital investments, e.g. into batteries or heat pumps, high conversion losses along the different conversion steps of synthetic fuels leads to a much lower energy service yield per input compared to direct electrification[7].

Zero-carbon heat can be provided in many different ways. Via electrification it can be a large source of flexible electricity demand that may facilitate the integration of variable renewable energies. The provision of heat, both for residential use as well as in industrial processes, is currently dominated by carbon-rich solid, liquid and gaseous fuels. For deep decarbonisation, different routes exist:

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[6] At high capital costs, high full-load hours would be required to recover the investments. These loadings are difficult to realise when using only surplus electricity that would otherwise be curtailed.

[7] Rough estimation of conversion efficiencies for provision of heat or motion along different routes:
Heating: Electricity -> E-fuels -> Heat: conversion efficiency ~ 0.6 * 0.9 = 0.54 vs.
Electricity -> Heat pump -> Heat: conversion efficiency ~ 3;
Mobility: Electricity -> E-fuels -> motion: conversion efficiency ~ 0.6 * 0.25 = 0.15;
Electricity -> electric engine -> motion: conversion efficiency ~ 0.9 * 0.6 = 0.54.

- Direct solar-thermal is a well-known technology, but its use is hampered due to a lack of standardisation and the mismatch between supply and demand.

- Electrification of heat provision can be either direct (resistive) or via (geothermal, water- or air-based) heat pumps, which have much higher conversion efficiencies but also higher capital costs.

- Industry boilers and heaters can easily be upgraded to hybrid systems that include direct electric heating at minimal additional costs. This creates a sizeable flexible electricity demand that can be used to accommodate surplus electricity from variable renewable energies and thereby decrease the use of carbon-rich fuels.

- In areas with high heat demand, e.g. densely populated cities or clusters of industry, heat networks can provide substantial benefits by pooling demand and supply. This allows the use of capital-intensive heat pumps and taps substantial economies of scale to provide cheap seasonal underground heat storage, thereby facilitating the use of waste heat from industry as well as solar-thermal heat that is mostly supplied during summer. An example is the city of Hamburg's plan to source the heat required for heating ~300 000 apartments from a number of different low-carbon sources and store it seasonally underground.

- For use cases that are not amenable to electrification, other options to decarbonise heating include direct use of solar thermal energy, connection to a heat network or the use of zero-carbon molecules in regular boilers.

Despite and because of zero-carbon molecules, the electricity system will grow.

While there are many paths to decarbonising the different energy services, electricity is a key input to most of them, either directly or indirectly as an input to the conversion of fuels and gases. Accordingly, deep decarbonisation will — through increased direct and indirect electrification — lead to growth in electricity demand and to an increasingly fundamental role of the electricity system in decarbonisation.

R&I has a pivotal role in this transformative transition. An essential R&I question is: 'What is required next, from a technical, market and policy perspective, to achieve a step change towards a quickly decarbonised electricity system?' To develop a fully decarbonised energy system, the complementary R&I question is: 'How can renewable energy technologies contribute to the transformation outside the power sector, and what advances may be needed to exploit renewables differently from today?' To drive decarbonisation achievements beyond the power supply sector, another crucial R&I question is relevant, namely: 'How can electrification be increased, and what will be the main bottlenecks to full energy-system-wide decarbonisation?'

4 From centralisation to decentralisation

Next to existing centralised systems, new decentralised systems are emerging, based on social innovation and citizen involvement, differentiated by Member States according to their respective characteristics. Today's energy system is moving from a structure with a few very large operators and centralised power generation and distribution to one where facilities are more widely distributed and control is potentially shared on platforms where 'prosumers' can also participate. Some important challenges remain, particularly how to guarantee the stability of the electricity grid in the face of greater fluctuations in supply from small renewable sources. But on the whole, the trend to more decentralisation and more market actors seems unstoppable, and is backed by the Market Design regulation proposal from the European Commission. The emergence of energy prosumers, who produce some of the energy they use themselves, and the growing availability of smart products and services, such as new platforms, allow consumers to participate in the energy market. Cities, towns and communities at large are among the chief beneficiaries of this trend, which allows for more autonomous energy choices. Nevertheless, the pace of decentralisation may differ among Member States as cultural, socio-economic and geographical differences between regions and Member States are expressed in differing market rules, regulation and technology support mechanisms. Consequently, some places are seeing the emergence of renewables primarily in the form of large installations, with the associated economies of scale, whilst other regions are going for very small scale installations, for instance rooftop PV.

In light of the decentralisation and high shares of renewables, large-scale innovation on transmission and distribution networks is necessary to prepare the power system for the digital age, while safeguarding security of supply and flexibility. The large investments that are necessary for the zero-carbon transformation will require efficient, multi-actor financing schemes since interconnection infrastructure is largely characterised by up-front costs. Financing of decarbonisation projects is pivotal for keeping the cost of this transition low, and is closely related to the presence of a stable policy environment. Innovation is also required in the way in which the control of distributed sources is managed and connected to demand. From developments in the field of information and communication technology, we can learn that platforms facilitate suppliers and consumers of products and services on the one hand, and at the same time may lead to a transfer of power or control to platform owners on the other. Network effects can intensify and solidify these dynamics.

5 Digitalisation

This brings us to the next major trend, the Internet of Energy: the digitalisation of the energy system which gives an additional boost to these changes, helping to further sector and consumer integration and overall system optimisation. Digitalisation of energy use and energy supply promotes the growing interdependence of the different types of energy use that until now were quite separated, e.g. for transport, heating or appliances. Digitalisation is starting to penetrate activities, products and services related to smart homes and other smart energy-efficient solutions. Digitalisation could help to enhance the management of energy demand, improve grid reliability and reduce energy costs, but it could potentially also have a number of negative effects. Digitalisation itself requires additional energy (data centres for big data), and digitalisation-enabled services could lead to substantial additional energy demand — as, for example, seen with the blockchain-based crypto-currency bitcoin. Digitalisation, once combined with the vast possibilities of social innovation, can also create a new situation of information asymmetry for prosumers. With the increase in data availability and use, as in other sectors of the European economy, concerns over data collection, data control, data integrity and data ownership, etc. arise. To get the full benefits of these developments in digital technologies in the energy sector, concerns over privacy and data security remain. All in all, digitalisation is likely to have a strong impact on energy use and GHG emissions, but the direction of change is still unclear. Accordingly, R&I is required in all aspects of energy digitalisation.

6 Service orientation and active consumers

Digitalisation is making possible a range of new, more integrated energy-related services, and allows, if new networks are developed, much greater integration between industrial sectors and processes. This favours the emergence of novel, potentially disruptive business models alongside new job profiles and skill requirements. The respective industries no longer just sell goods or deliver energy as a commodity. Instead, they offer integrated solutions extending into areas such as home comfort, entertainment, or personal security. European energy policies and regulation are largely based on a distinction between parts of the energy supply chain that can benefit from competition, on the one hand, and natural monopolies that stem from network effects, on the other. The question is how to support new value chains, new product and service propositions, prosumers, the emergence of platform economics and potential related network effects, and innovative small and medium-sized enterprises (SMEs) through the evolution of the existing regulatory environment for the energy sector. This has the potential to see the emergence of new products and services, for which R&I is required.

7 Implementation challenges: combining policies and markets

The success of the zero-carbon transformation relies on the development of credible policies and their integration with well-functioning markets, as has been the case over the last decades for the fundamental changes in the EU energy supply sector, which can be traced back to market and policy development. In this regard, the European Commission has recently presented the Clean Energy for All Europeans policy package, which aims to provide a stable legislative framework to facilitate the clean energy transition. Private companies can only develop new business models and technologies if there is credible long-term commitment to market designs and policy environments that set the right incentives. The decarbonisation of the energy supply will only happen if there is credible commitment to a sufficiently high CO_2 price or other strong policy signals and supportive regulations. The success of new storage technologies, demand flexibility and sector-coupling, as well as that of innovative SMEs in general (as important carriers of new technology and solutions to the market), hinges on regulation not impeding these new developments.

The importance of robust policy design was clearly demonstrated in the past decade, when the large-scale uptake of new renewable energy in different EU Member States was initiated through strongly supportive policies. The exact design of these policies determined their effectiveness as well as their cost-efficiency. As an example, the feed-in-tariffs in Germany and Spain proved very effective in stimulating PV deployment but the policies were not designed robustly. For instance, they did not contain quantity safeguards — faster-than-expected production cost reductions led to unsustainably fast growth and substantial excess costs. The resulting retro-active policy changes in Spain have had a long-lasting effect by contributing to increased business risk and reduced investor confidence in policy stability.

Similarly, the interactions between different policies at EU level, national level and regional level need to be better understood in order to guide the transformation and prevent unwanted interferences. The EU emissions trading scheme (ETS) is a main pillar of energy supply decarbonisation but over the past decade, the price signal has not yet been sufficient to lead to substantial decarbonisation action, partially due to the price-weakening effects of additional climate policies (e.g. RES, energy efficiency) in addition to a lax emissions cap. While the recent reform has strengthened the ETS, it is as yet unclear whether the current design is robust enough for future national climate policies such as coal phase-out plans to allow a strong price and thus a cost-efficient EU-wide transformation.

R&I on both policy instruments and market design as well as the interaction between the two is crucial to better inform robust policies and market regulations that reduce the amount of costly trial-and-error iterations.

8 The next major issues to solve

8.1 Early opportunities

There are a number of changes which could be quickly implemented to put us collectively on a credible path to deep decarbonisation along with significant societal co-benefits. These early opportunities or low-hanging fruit do not require technology innovation, and sometimes cut emissions and costs, representing win-win opportunities. Improved energy efficiency in buildings, industry and transport is a major pillar of EU decarbonisation, bringing multiple societal benefits in a cost-efficient manner. Integrated energy system transition could avoid costly solutions when more market opportunities for new energy supplies are created and zero-carbon electrons and molecules can be balanced. In addition, the McKinsey CO_2 abatement cost curve, initially introduced in 2009 and revised several times (McKinsey 2010), has identified changes and technologies by their greenhouse gas savings and their abatement costs, from the negative costs (cost savings) to more expensive options. Energy efficiency measures are amongst the negative cost options and are a prerequisite for the decarbonisation of certain demand sectors. Many options, such as LED lighting or insulation retrofitting, bring cost savings within a reasonable assumed payback time and depreciation rate. Energy efficiency is a key component of the zero-carbon transformation. It is discussed in detail in subsequent chapters of this report that focus on the demand side (cities, industry, mobility) and on the role of finance.

However, several factors prevent these early opportunities from happening spontaneously, among which are the initial investment, as well as regulation, split incentives, demographics and income development in individual Member States. Measures and R&I should focus on overcoming these barriers to immediate implementation while acknowledging that each region or country can have a different merit order of 'low hanging fruit'.

8.2 Taking stock of quantified decarbonisation roadmaps

There is a very broad range of studies commissioned or conducted by a number of institutions, including international institutions, European research projects, NGOs and the private sector. More concretely, scenarios were recently published by the IEA, the European Commission, several research projects funded by the European Commission (among which are ADVANCE, AMPERE, LIMITS and SECURE), the International Institute for Applied Systems Analysis (IIASA), NGOs, including Greenpeace and the European Climate Foundation (ECF), as well as Eurelectric. Further, more detailed scenarios are currently being developed in the EU H2020 projects SET-NAV, REEEM, REFLEX, MEDEAS, EU-CALC, REINVENT and INNOPATHS.

The European Commission's 2011 low-carbon roadmap presents five decarbonisation scenarios, assessing five different combinations of the four pure decarbonisation options (energy efficiency, renewables, nuclear and CO_2 capture and storage). All of them detail potential developments of the EU energy mix to 2050 to allow a decrease in domestic EU GHG emissions of at least 80 % compared to 1990. This roadmap and its scenarios need to be revised regularly to be made even more ambitious and up-to-date with advances in technology and research to be brought into line with the Paris Agreement objectives. A more short-to-medium-term update was presented in the Clean Energy for All Europeans package and the EUCO scenarios, while further updates towards 2050 and beyond are pending.

The main topics emerging from the European Commission 2011 low-carbon roadmap, which are described below, have formulated a concrete framework for climate and energy-related policy-making, leading to concrete measures and commitments.

Coal phase-out and CCS are key. The requirement for a near-term coal phase-out has been made more obvious and necessary by the commitments made at the Paris COP21 meeting at the end of 2015. Several EU Member States have already stated their intention to phase out coal and lignite completely by a date between 2025 and 2035. Such an objective is of course more ambitious and difficult for countries which rely heavily on coal.

The 2011 EU roadmap scenarios seem to imply that disregarding CCS and nuclear simultaneously would pose challenges for a sustainable pathway to decarbonisation for the entire EU. On the other hand, there has been almost no progress in deploying CCS or nuclear within the EU over the last seven years. Besides fundamental technical and economic challenges, substantial public opposition in several Member States contributed to the non-delivery. This is not necessarily a problem as different regions or states can still opt for different energy technology mixes. From a technology point of view, the outlook on CCS has substantially shifted. The recent cost reductions in renewable energies and storage have removed expectations that coal-based CCS will be a key pillar of decarbonised power systems. However, CCS could be highly relevant and cost-competitive for i) decarbonising in the short/medium-term a number of industry processes with inherent CO_2 emissions such as cement production, and ii) the production of net-negative-emissions liquid and gaseous fuels from biomass combustion.

'Energy efficiency first' remains a key pillar of deep decarbonisation. Energy efficiency is a key pillar in facilitating the decarbonisation of the full economy, promising substantial emission reductions at comparatively low (or even negative) financial costs. Like all technologies, low-carbon technologies are bound to have some negative externalities or limitations, such as land requirements for biomass or specific materials for wind and solar power. To keep these negative externalities to a minimum, it is necessary to reduce the total final energy demand by increasing the efficiency of all demand sectors. The research needs for policies and technologies to implement and realise these efficiency increases will be discussed in the individual focus chapters.

Innovation and market integration of renewable energy has to be supported. Support is necessary to make sure that new energy technologies undergo the innovation cycles required to bring their costs down. Some renewable energy technologies have already experienced high cost-reduction rates which now put some of these technologies on a par with fossil-fuel-based power generation. In photovoltaics, for instance, the cost reductions for solar panels has been such that the high added value is not in the panels themselves but in the system integration, converters, meters, system installation and maintenance. This whole set — which partially at least cannot be delocalised — represents more than 50 % of the added value, and should be further developed with EU know-how and expertise.

The electricity system has to become more flexible and has to be better integrated into the wider energy system since the reliance on variable renewables such as wind and solar is increasing. There are several resources for flexibility in the electricity system. These resources can be categorised into:

- flexible, easy-to-dispatch, generation sources, either conventional or carbon free;
- expansion of transmission and distribution for solving local/regional integration issues;

- demand-side response and management, including electrification of flexible energy uses that previously were served by other energy carriers, such as provision of heat to industry processes and buildings;

- storage and integration into the wider energy system.

Flexible (dispatchable) generation is an enabler of solar and wind integration, while it must fit within an increasingly restrictive carbon space. As such, a transition from carbon-intensive to low-carbon to carbon-free fuels could be pursued. While fossil fuels with CCS constitute a theoretical potential, it remains to be seen whether the economics are favourable given the relatively low number of running hours each year in a highly renewable electricity system.

Improvements in electricity transmission and distribution provide additional flexibility at a relatively low monetary cost but are slow to deploy and often face public opposition. They must therefore be started early and always be balanced with other options. Demand-side responses and management are expected to be an important source provider of intra-day and inter-day flexibility. However, for prolonged periods of low wind and solar generation, other options may constitute an essential part of the new system. With respect to storage, it is crucial to measure chemical electricity storage (batteries) against alternatives in the electricity system (e.g. pumped hydro) or storage options in the form of clean gases, liquids, heat and other products. Higher interconnection of the different parts of the energy system will also provide further flexibility.

It is important to develop market designs and policies that ensure that all these flexibility options are used to the full to enable a fast scale-up of renewable power and to minimise the need for carbon-intensive fossil fuel power plants. When designing new market mechanisms and support policies, e.g. capacity payments, it is important that they do not indirectly subsidise fossil fuel use and thus slow down their phasing out.

A holistic approach that is transversal to the sectors as well as consideration of non-technical barriers to technology deployment are thus required. An integrated energy system transition increases the absorption capacity of electricity markets for renewables towards, for instance, the low-temperature heat market or industry. Take energy storage and conversion for example. A totally new system based on the batteries of electric vehicles, connected to a fully-digitalised smart grid, can be used to store electricity produced from variable renewables when it is cheap and available and, conversely, feed power back to the grid when it is scarce and expensive. For prolonged times of relatively low wind and solar availability, especially during moments of high energy demand (winter months), additional volumes of clean energy can be stored in and sourced from liquid, gaseous or heat forms. Technology is not the only component of successful de-carbonisation. Deployment of new technologies and solutions also requires attention to non-technical aspects, e.g. consumer readiness or societal acceptance. This shows that decarbonisation requires a holistic approach — the emergence of not only new technologies but also new business models, rules and regulations, in which the digital dimension is paramount.

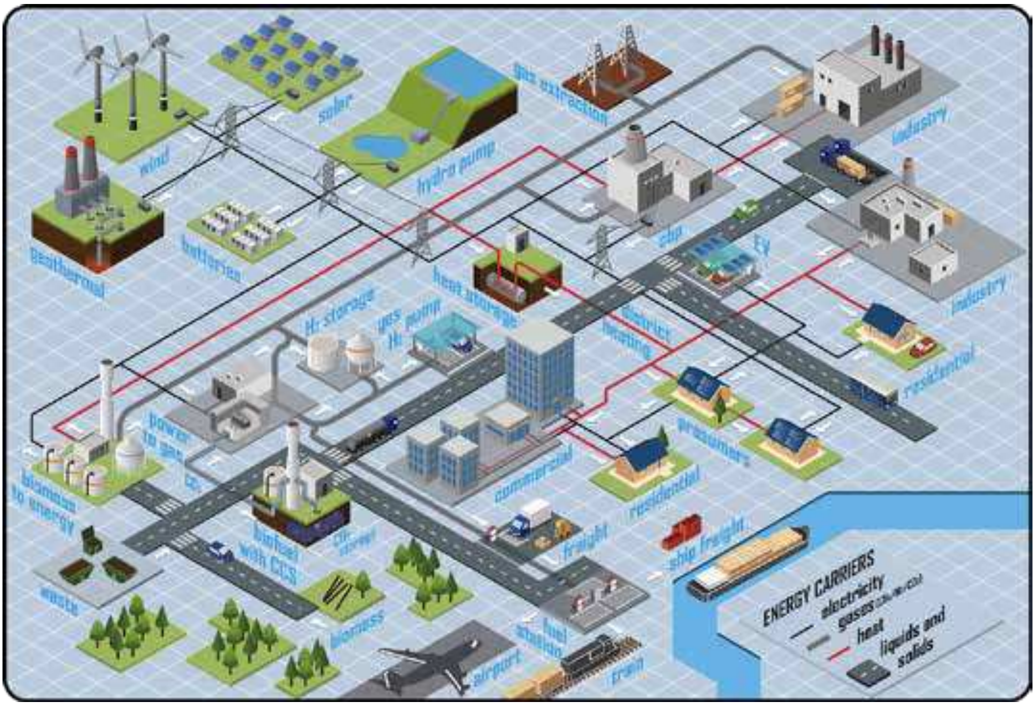

Figure 3: Sketch of a deeply integrated zero-carbon energy system.[8]

R&I is needed both on the technology side (energy storage and energy conversion, at all timescales and looking at all the different technologies) **and on the management side** (connecting the different energy markets and infrastructures, setting robust regulation and policies that do not hinder sector-coupling, addressing barriers beyond technology and market design, setting the ground for new business models), with the holistic integrated energy system approach emphasised above. More R&I is also needed on networks to include spatial issues.

Bioenergy will play an important role in the decarbonisation of certain activities such as aviation or shipping, where currently no other decarbonisation options seem economically deployable at large scale. R&I should thus focus on finding synergies with agriculture and forestry and on removing potential trade-offs. In recent years, impressive

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8 From an economic viewpoint, it can make sense to still use (relatively low-carbon) natural gas while at the same time creating negative emissions through bio-CCS, afforestation and soil carbon management to achieve net GHG neutrality. Differences in process costs and efficiencies of the various conversion steps (biogas production, CO_2 capture from biofuels, synthetic fuel production) are the main reasons for this seemingly counter-intuitive assessment.

cost declines for solar and wind electricity technologies have been observed. Yet it should be kept in mind that bioenergy plays an important role in renewable energy production in Europe today and will likely continue to do so in future, especially in certain transport modes. The versatility and storability of biofuels makes them a promising option to decarbonise activities where other options such as electrification remain economically unviable. Furthermore, the conversion of biomass into gas or liquid fuels can, in combination with CCS, lead to net negative emissions when accounting for the CO_2 uptake during the biomass growth. These negative emissions could be an important contribution to compensating residual GHG emissions that are very difficult to mitigate, e.g. from agriculture or certain industry processes.

It should be noted that the energy return per land area is a factor of 10-25[9] lower for biomass than for PV, thus land conservation is strong reason against using biomass for electricity generation and for enhancing electrification wherever possible.

It is a challenge to find synergies between biofuel production and agriculture and forestry. Resources that Europe has in the form of abandoned or set-aside land and vast forests could be developed to serve both as carbon sinks and to provide energy and job creation.

The transition can be affected by material scarcity and by new externalities. The development and roll-out of new energy technologies imply new needs with respect to natural resources as well as positive and negative external effects beyond the reduction of direct greenhouse gas emissions.

Demand for new materials (e.g. rare earths) is rising rapidly and creating new markets. The concept of the circular economy should be recognised in this respect, in addition to its positive impacts on energy savings, as it can help to address the new set of challenges emerging from the use of new technology. These challenges are: security of supply of resources (global supply chains, strategic sectors, material scarcity), the affordability of resources (European industrial competitiveness) and the environmental costs (new externalities related to resource extracting and processing industries such as cobalt, lithium, polysilicon refining).

R&I is required to find the optimal use, mix and re-use of resources and technology, considering EU and global markets, to develop the European circular economy. Challenges related to new technologies and potential trade-offs should be understood well in order to assess the various alternatives (for instance, hydrogen-based storage options versus lithium or cobalt battery solutions).

Addressing the challenge of climate change calls for a transformative transition of the energy system, incorporating all available technologies

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9 Biomass: 12-28 TJ/km^2/yr (IPCC, 2011) vs PV: 60-110 MW/km^2 * 1 000-1 700 MWh/MWp/yr * 0.0036 TJ/MWh = 180-720 TJ/km^2/yr (Pietzcker et al, 2014)

for negative emissions, electrification, power-to-X and hydrogen. Negative emissions need to be introduced in the longer term to compensate for current emission levels. To this end, CCS could be applied to biomass-based energy (BECCS) to provide net negative emissions. Innovation is also being directed towards alternative CO_2 removal techniques from other sources than renewable fuels or industry process emissions, for instance directly from the air. Further research is required for CO_2 utilisation techniques to produce synthetic liquids and gases for decentralised utilisation. E-fuels or Power-to-X could potentially be a major enabling technology for decarbonising the energy system, although the high conversion losses along the repeated conversions lead to a much lower final energy service yield compared to direct electrification (see the discussion of zero-carbon molecules). Higher deployment of hydrogen can further decarbonise end uses such as transport and heating or cooling in buildings. This should be broadened to R&I that looks at all the carbon-containing molecules, which can be useful for chemical or other sectors.

8.3 An inclusive and just transition

Like any change, the transition towards a decarbonised society will entail winners and losers. While society as a whole will benefit from the transition to decarbonisation, there will inevitably be countries or regions, industrial sectors and people to protect during the transition to ensure that the transition does not endanger social cohesion and justice.

It is quite obvious that decarbonisation will not be a one-size-fits-all exercise for the various Member States and regions of the EU, which are in very different situations. For instance, there are differences in their indigenous fossil fuel reserves and renewable energy potentials, technological capacities, energy demand patterns, infrastructure, and labour and capital markets.

Policies should pave the road for an inclusive transition that also comes with many opportunities for industrial development, with new sectors and yet-to-be-created skills with employment opportunities, often more numerous in the new renewable energy sectors than in traditional sectors. Quite obviously, these new jobs do not necessarily have the same characteristics as the ones they will replace. For example the labour requirements of coal mines might be substituted by personnel for the design and implementation of RES. Hence training and education are required, with more emphasis in these countries and regions which will be more impacted by the phasing-out of traditional fossil-fuel-based activities. Overall, the low-carbon transition can lead to job creation, especially when the entire value chains of new and old technologies are taken into consideration, revealing the more labour-intensive production patterns of decentralised low-carbon energy systems. Beyond an adapted decarbonisation trajectory and objectives, it is in these countries and regions that most of the new job opportunities should be pushed to materialise.

Citizen involvement is an important part of the decentralised energy system. Each European citizen could play an equal part in the solutions as an increasing number of citizens act as prosumers and participate in energy cooperatives. Social innovation must be enabled through a new legislative framework. R&I is needed on how to turn consumers into prosumers and finally advocates of decarbonisation, and in a second step to develop solutions that increase transparency, efficiency and engagement as well as ensure that citizens are protected (cyber security, privacy, data protection, use of the market power of new emerging businesses in a digital economy that may be characterised by classic network effects). It is also important to note that digitalisation increases the need for electricity. Energy efficiency in digitalisation is an important point for consideration here.

It is necessary to address energy poverty. The EU Survey on Income and Living Conditions (EU SILC) estimates that 54 million European citizens (10.8 % of the EU population) were unable to keep their home adequately warm in 2012, with similar numbers for the late payment of utility bills (Pye et al., 2015).

The decarbonisation scenarios and pathways could impact the level of energy poverty in the Member States, and thus the affordability of decarbonisation pathways must be a key parameter in the decision-making process. It is essential that this problem is recognised and addressed, as ensuring basic energy services is critical to ensure that communities do not suffer negative health impacts, do not become further entrenched in poverty, can maintain a good quality of life, and above all remain globally supportive of the transition. To enable good policy making and allow progress to be tracked, data collection on energy poverty needs to be enhanced and affordability must be assessed through quantitative tools and careful evaluation of taxation policies.

Attention shall be paid to carbon leakage. From a sectorial point of view, industrial sectors which are at risk of carbon leakage because of the nature of their activities also require some form of protection. This is to protect the jobs that they provide in European Member States against the prospect of externalising their production, which would simply displace emissions to outside the EU.

Efforts to achieve a framework for a symmetric global mitigation action are key to tackling this issue, along with short-term concession-type measures or specially designed trade measures. This effort could also start with international cooperation of the 'willing' regions or even on a sectoral level. Other approaches to prevent carbon leakage range from well-known and already applied measures such as the free allocation of emission rights in the ETS (in ways that simultaneously incentivise energy efficiency in these sectors) to well-known but politically-difficult and contentious measures such as border adjustment taxes on high-carbon-content products produced outside the EU (in compatibility with the World Trade Agreement rules, notably Art. 20, which relates to the environmental protection aspects of international trade) to potentially innovative new concepts such as carbon allowance contracts-for-difference or a carbon-reduction investment fund.

Investing in R&I for advanced and highly efficient production practices can create opportunities to increase competitiveness in zero-carbon technologies and techniques. Energy-system-integration approaches could help to create more markets for new energy technologies, but also help industry to contribute to overall energy efficiency.

The global green technology market is estimated at EUR 5 trillion. The EU is well-positioned on de-carbonisation technologies and business solutions and has the potential to address this market. 'Green production' labels or certification, supported by standard EU lifecycle assessment schemes, and corresponding trade and tax regimes can support EU industrial leadership.

The EU still has the potential to capture global market shares in emerging zero-carbon equipment and services. The demand for these sectors is constantly growing as more countries are taking up more efficient production methods. An emphasis in R&I can lead to cross-sectoral knowledge spillovers, while learning by doing and learning by research dynamics can increase the EU's comparative advantage. Wind turbines are a positive example, and other technologies, such as storage and network infrastructure, can follow. New markets can be pursued not only in equipment and materials but also in the services and financing sectors.

9 Recommendations for R&I

The integrated energy system transition requires that more sectors than only the power sector should become involved, and requires all actors in the energy domain to contribute to making the energy transition happen. In this respect, it is necessary to urge industry, utilities, oil and gas majors and others to assume their responsibilities. This also means they must be involved in the pathways that the EU is going to develop.

In the context of the full transformation to a zero-carbon energy system, R&I is key. It can provide the **knowledge** needed to design and guide the transformation, the **technologies** required to enable this transformation, and the **instruments** to deploy these technologies and implement the transformation. More specifically, investments in R&I are needed to:

- **realise the full potential of integrating the energy system** and linking the development of low-carbon power markets to low-carbon liquid and gas markets (transportation, low and high temperature heat);

- **pursue deep electrification of energy services for industry, transport, and buildings.**

For the second, there exist a wide range of electrification options with varying capital intensities and efficiencies. Better understanding of advantages and disadvantages is required for a successful implementation, including how to reap synergistic benefits and facilitate the integration of variable renewable energies.

This calls for **a next generation of quantitative models with an integrated representation** of all energy networks (e.g. electricity, heating, transport) while considering system stability restrictions and market operation features, accounting for full life-cycle impacts on resources, the environment and the economy.

It is important to **develop improved policies and market designs** (including empirical case studies and step-by-step implementation recipes for regulators) to ensure robust policies and market regulations that reduce the amount of costly trial-and-error iterations. This includes a focus on:

- **market designs** that facilitate **RES** integration, enable **prosumer** participation and incentivise **demand flexibility** to achieve fast power-sector decarbonisation;
- making policies robust against negative **interactions with other policies on EU, national and regional levels**, e.g. the weakening of the ETS price signal due to national decarbonisation policies;
- deeper understanding of **dynamic transition processes, innovation dynamics** and energy market developments (instead of static analyses);
- a wide array of tools, from **large-scale quantitative models** incorporating sophisticated market mechanisms and consumer behaviour to **empirical case studies**, to **step-by-step implementation recipes** for policy-makers, regulators and administrations.

Potential **technological solutions** also exist**:**

- **Bring technologies for 'zero-carbon molecules' to market readiness, such as biofuels with CCS, hydrogen, and other synthetic fuels.** A dedicated mission — including full-scale demonstrator projects — would ensure that the most promising technologies are identified and developed so as to be ready for large-scale deployment by 2030.
- **Develop energy storage and conversion technologies** at all time scales: **batteries, heat storage, Power-to-X**.
- **Improve intelligent networks and infrastructure for electricity, heat and gases** to include spatial issues and benefits of pooling.
- **Identify and overcome non-technical barriers** to otherwise market-ready technologies, e.g. consumer readiness or societal acceptance. Continued support to innovative companies, in particular SMEs, to scaling up and addressing global markets is also required.

Another priority is to design a zero-carbon energy system based on a full understanding of the **co-benefits and externalities** of new technologies and new energy system configurations. This would encompass a number of aspects:

- Investigate the full range of **LCA aspects**, such as material resource needs and **indirect CO_2** emissions from construction, as well as air pollution, land and water use. It also includes **materials scarcity issues**, as the development of whole new systems will require different resources. It is essential to consider this from the perspective of advancing the **EU circular economy**.

- Carry out an evidence-based **socioeconomic** assessment of **employment** and **trade** dynamics for zero-carbon sectors and practices, emphasising **new skill** requirements and EU competitiveness aspects along with growth dynamics through **knowledge diffusion**.

- **Implement the energy digitalisation through the development of an 'Internet of Energy'** to integrate the energy system and connect supply and demand, with a focus on governance and citizen involvement to ensure that prosumers as well as traditional consumers are empowered as well as protected, and negative rebound effects are minimised.

- Advance **open source data collection and provision**, as well as **open energy modelling** to represent the changing and low-carbon energy systems. This includes developing **integrated open models** that cover the interactions between technologies, market operation, policy instruments, the economic sphere, the environmental sphere, and innovation processes.

- Ensure long-term-funding and coordination of **open databases**. This will allow the Commission to better monitor the transformation process, become less reliant on third-party data collection, and enable Member States and/or research institutions to emulate analyses and do their own research.

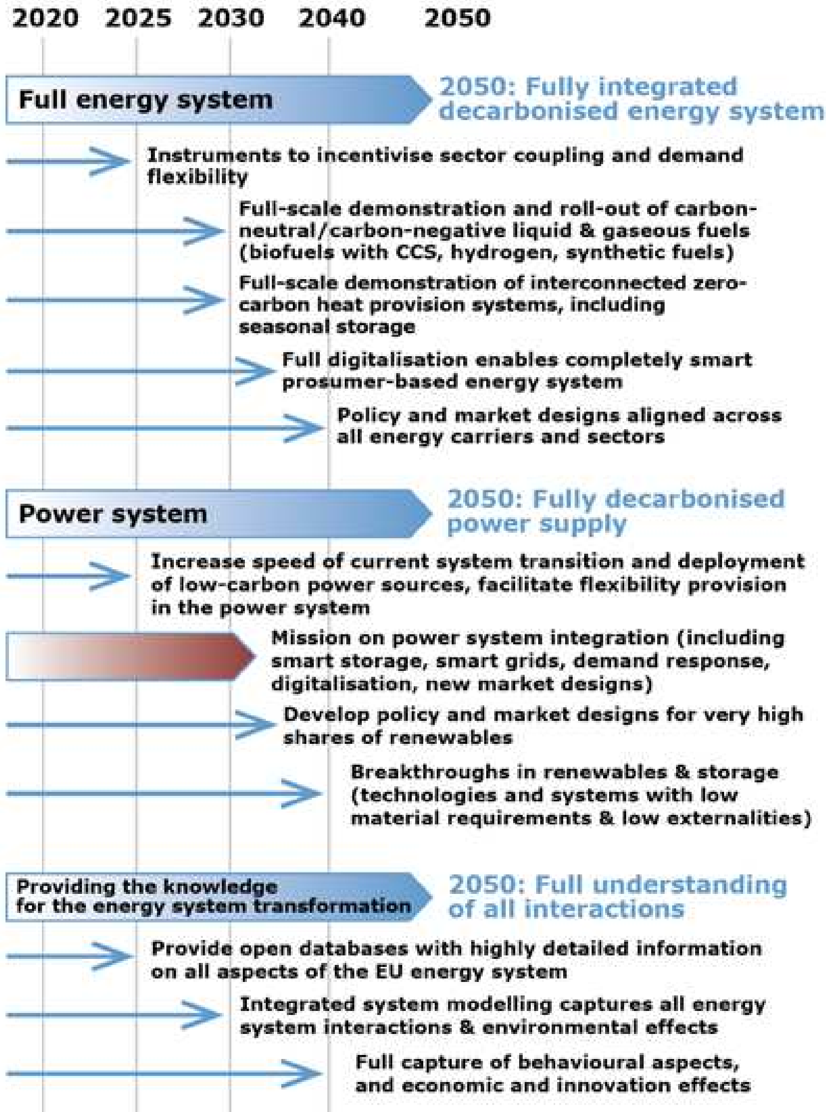

Figure 4: Possible R&I roadmap towards a decarbonised energy supply sector.

CHAPTER 3

DECARBONISING THE TRANSPORT SECTOR IN EUROPE,

CLEANING ROAD, RAIL, SHIPPING AND AVIATION MOBILITY SERVICES

1 The contemporary state of transport in Europe

Transport services within the EU-28 Member States were responsible for 26 % (895 $MtCO_2e$) of total domestic CO_2 emissions in 2015 (European Commission, 2018). Adding emissions from international aviation and marine navigation (in sum, 274 $MtCO_2$-eq) increases the full share of transport to 31 % of total EU-28 CO_2 emissions. CO_2 emissions from aviation (international and domestic) increased by almost 80 % between 1990 and 2015, which is far higher growth than emissions from any other transport mode. Across all domestic transport services in the EU-28, CO_2 emissions increased by 17 % between 1990 and 2015. The major share (82 %) of national CO_2 emissions (domestic emissions and those from international aviation combined) is attributable to road transport (Figure 5)[10]. Passenger transport services were responsible for about two thirds of the national transport CO_2 emissions, with cars being the major source of these emissions. Besides emissions from cars, 20 % of the national transport sector CO_2 emissions were emitted by heavy-duty trucks and buses, and 10 % by light duty trucks.

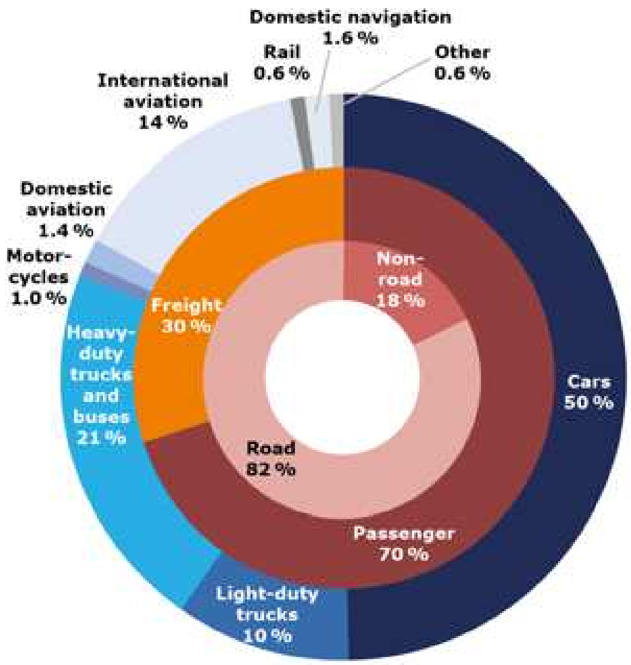

Figure 5: EU-28 national transport sector CO2 emissions (including international aviation) in 2015. Sources: European Commission, 2018; UNFCCC, 2017; European Environment Agency, 2018.

[10] In this figure, the reporting of emissions by transport mode refers to statistical data based on DG ENER (EU Commission, DG ENER, Unit A4, Energy datasheets: EU28 countries, updated 14.02.2018) in which emissions from international maritime transport (134 MtCO2, or about 4% of total EU GHG emissions) are excluded from quantity reported as national total emissions (incl. international aviation). A discussion of emissions mitigation related to international maritime transport is covered in section 2.3 of this chapter.

Transport services and transport-related industries are essential sectors for Europe's economy, enabling growth and prosperity as well as employment in the EU. Transportation services alone constitute 2.9 % of total EU-28 VA. If manufacturing of transport equipment is also included, this share increases up to 5.1 % of total VA[11]. Further including support activities for transportation and postal services brings the overall contribution of the transport industry to 7.2 % of total EU-28 VA in 2015 (European Commission, 2016). Respectively, the transport industry represents 6.4 % of total employed persons (14.6 million persons), while employment in transportation services accounts for 3 % of total EU-28 employment, and manufacturing of transport equipment about 1.4 %. This indicates that land transport services employ more people than the overall manufacturing of transport equipment, while they produce roughly the same VA in the European economy.

While European manufacturers are established as major players for transport technology worldwide, new markets with new equipment producers are growing rapidly in emerging economies. With around 22-23 million units in 2016, about 25 % of the total global light vehicle engines and gearboxes were produced in over 90 production locations across Europe (including Russia and Turkey), worth about EUR 65-70 billion. Even though more than 95 % (global figure for 2016, KPMG, 2017) of the production involves internal combustion engines (ICEs) without electrical hybridisation, the major growth area is electric vehicles. Globally 1.2 million cars (battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV)) were sold in 2017, with half of this amount sold in China (EV-Volumes, 2018). Production capacities for electric vehicles have grown rapidly in China, which was able to produce 95 % of the electric vehicles sold domestically, assisted by very restrictive policies towards foreign BEV manufacturers. Conseuqently, China is not only dominating the electic vehicle (EV) retail market but is also a leading production centre.

Despite the tremendous efforts made in the past, the transport sector's environmental performance is below expectations, not only for GHG emissions but also concerning other environmental and health impacts from pollutant emissions. While the carbon monoxide (CO) and non-methane volatile organic compound (NMVOC) emissions declined by more than 80 % from 1990 to 2015, NO_x and SO_x emissions decreased by 40-50 % in this timeframe and $PM_{2.5}$ emissions dropped by 40 % between 2000 and 2015 (EEA, 2018). Even so, the transport sector is the main source of the EU's NO_x emissions, with more than 55 % (2015) resulting from domestic and international transport activities. Over the last two decades, air pollutant emission reductions from road transport have been lower than originally anticipated, partly resulting from higher growth in the transport sector than expected. This was compounded by accelerated growth in diesel-based vehicles, which cause higher specific NO_x and PM emissions than petrol-fuelled vehicles, in particular considering that diesel cars produce more pollutant emissions than they were supposed to.

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[11] Transport sector-related figures for VA depend on the sectoral accounting schemes applied, i.e. whether equipment manufacturing and support postal services are included or not. Here, we provide disaggregated values depending on which businesses are included. Since different sectoral accounting schemes are used across different literature sources, comparability might be limited.

Beyond particle emissions, which are currently monitored and whose environmental and health impacts are well understood, there is increasing concern about severe health effects from ultra-fine particles. These particles are found in the exhaust of petrol-operated internal combustion engines. Due to the small particle size (<100 nano-meters) they are not measured with traditional instruments. However, they can easily enter the human body and cause substantial health damage. In general, emissions of air pollutants are the most significant environmental cause of premature death in the EU, and lead to respiratory diseases, major healthcare costs and lost working days. The World Health Organization (WHO) attributes a significant share of the 100 000 premature adult annual deaths due to air pollution in Europe to transport (World Health Organization, 2018). Other negative external effects caused by transport systems are related to noise, fragmentation of ecosystems, land occupation and accidents. Road congestion plays a critical role in this because it has social, economic and environmental implications. Delays caused by congestion, in particular in urban areas, not only reduce the quality of mobility and hence quality of life but also represent economic damage estimated for 2013 at over 1 % of the EU's GDP (European Commission, 2017).

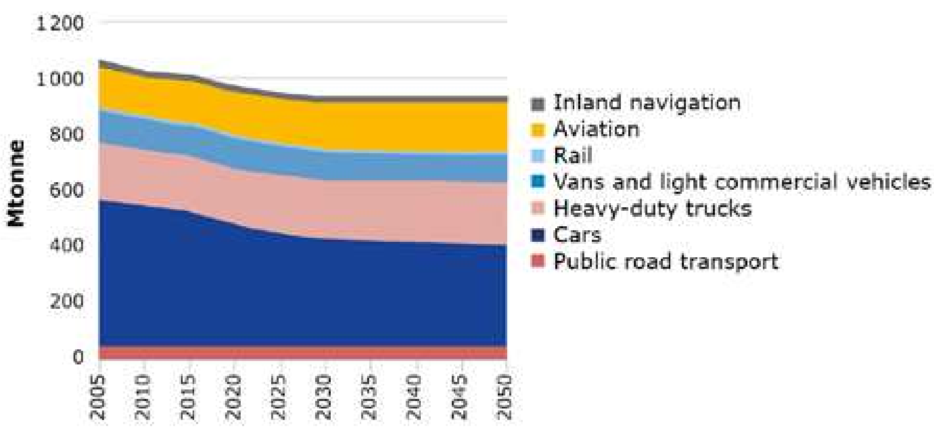

Figure 6: Evolution of EU-28 national CO_2 emissions to 2050 by mode in the EU Reference Scenario 2016. Source: PRIMES model, Reference Scenario (European Commission, 2016).

Without substantial regulatory intervention a rapid reversal of the developments observed over the past seems to be unlikely. An indication of future developments for the transport sector under the condition that no additional policies were to be implemented after 2020 is provided in the EU Reference scenario 2016 (Figure 6). The Reference scenario 2016 should not be interpreted as the most likely outcome; it merely presents a trajectory of the energy system if policy action remained frozen. According to the projections of the PRIMES model, CO_2 emissions from the transport sector would remain broadly stable until 2050. Some autonomous progress of the energy efficiency of vehicles along with a low penetration of advanced car powertrains are offset by the increase in the transport activity. The majority of the emissions would still be generated from cars, heavy-duty trucks and aviation. In the absence of additional policies and measures for the period beyond 2020, slow technological progress is assumed to take place (mainly resulting in low cost declines for electric vehicles). At the same time, electric vehicles recharging infrastructure develops slowly, as a result of absence of policies and low technological progress. Under this framework of assumptions, the Reference scenario shows a tentative uptake of electric vehicles (battery electric and plug-in hybrids); their share in the total fleet of cars does not exceed 6% in 2030. As a result, conventional diesel and gasoline cars remain the dominant vehicle technology.

2 Transport sub-sectoral decarbonisation opportunities

With a focus on technology, this section highlights the main decarbonisation options on a sub-sectoral level. New mobility patterns, including demand reductions and modal shift, are in the last section of this chapter.

2.1 Land-based transport

- *Passenger transport*

Low- and zero-emission vehicles need to become the default option for new car purchases, enabled by the broad roll-out of the corresponding charging and re-fuelling infrastructure. According to (UNFCCC, 2017) 850 Mt CO_2 were emitted by road transport vehicles in 2015, which corresponds to 95 % of the EU-28 domestic CO_2 emissions of the transport sector. The majority of road transport is due to passenger transport, in particular related to private cars. To reduce these emissions, one promising approach is the transition from vehicles with ICEs to electric drive trains operated as BEVs, PHEV or FCVs, accompanied by low-carbon electricity generation. This transition has just started, representing a small market share with average annual sales of BEVs and PHEVs in Europe[12] of 168 000 vehicles between 2013 and 2017 (EAFO, 2018) and on average 580 units of hydrogen FCVs in this time period (Hybridcars, 2018). Compared to the total car sales in 2017, BEVs and PHEVs represent a market share of around 2 %. Barriers to the transition are the higher capital costs of EVs, the limited product portfolio of BEVs, lacking hydrogen infrastructure and concerns related to the density of charging stations, while shorter travel ranges of BEVs compared to conventional cars could constrain the quality of existing services provided by EVs. Referring to current records for 2018, there are about 155 000 public electric charging positions in Europe (EAFO, 2018). To fuel hydrogen FCVs, there exist about 106 hydrogen refuelling stations across Europe (FuelcellWorks, 2017). To scale up EV market penetration to about 7 % (roughly 20 million cars) by 2025 in Europe, around two million publicly-accessible charging points are required (European Commission, 2017b). Policy can support and incentivise investments in charging infrastructure through setting targets for the number of available stations in buildings, public roads and urban areas. One particular issue refers to missing charging infrastructure for people living in multi-family houses where installation of sufficient charging stations has often a low priority with house owners or planners. Legislation has addressed this issue with the adopted revised Energy Performance of Buildings Directive (EUR-Lex, 2018), which now includes EV charging-related requirements for certain types of buildings. Besides residential buildings (new construction and major renovation of existing buildings), non-residential buildings are also captured through the revised directive.

[12] EU-28, Iceland, Norway, Switzerland and Turkey

However, BEVs' market penetration is still marginal, and supporting policies would be needed to facilitate a broader deployment of EVs and other low-carbon transport options. Such policies could either provide incentives to mitigate the market barriers which new technologies face (e.g. in terms of competitiveness compared to conventional technologies or related to acceptance by consumers) or policies can be prescriptive (e.g. a forced phase-out of ICEs). Norway represents an outstanding example of a successful uptake of EVs throughout the last five years. In Norway, the gap between technology readiness and poor market penetration was bridged using strong economic stimuli, including subsidies for charging infrastructure and substantial registration tax benefits for electric vehicles over gasoline and diesel engine cars (IEA, 2018).

For a broad roll-out of EVs across Europe, a number of issues related to technical, regulatory and economic aspects, system integration and standardisation, and consumer behaviour need to be better understood and resolved. Charging plugs for passenger electric vehicles have been required to be standardised under Directive 2014/94/EU, and plugs for buses are expected to be standardised in 2019. However, in practice, and in particular for e-mobility users travelling longer distances, difficulties arise due to the broad spectrum of EV charging system hardware, service providers, standards and protocols, and different payment systems. Compatibility of different systems as well as cross-national collaboration between infrastructure service providers and regulatory bodies to use charging infrastructure more efficiently could lead to a broader and faster roll-out of e-mobility (NeMo, 2017). Moreover, it needs coordination between stakeholders in electricity systems (e.g. distribution system operators, meter data managers, meter operators) and mobility service providers to remove market barriers for EV usage (NeMo, 2017). For instance, to optimise the interconnection and communication of EVs with power and energy storage systems, R&I actions should address innovative communication between or within battery management systems, leading ultimately to advanced standards for integrated battery systems.

Smart and digitalised systems are key to reducing the impact on the electricity network, reducing requirements for network capacity reinforcement and expansion and improving services for the passenger transport industry. Digitalised services facilitate integration of batteries embedded in e-mobility within the electricity system (e.g. via vehicle-to-grid technology), control data traffic and transport capacities, empower autonomous driving and enable bi-directional data exchange on different devices (e.g. EVs, batteries, management systems). These services are expected to improve the abilities to better manage EVs in the electricity system and to contribute to an advanced operation of the distribution grid by reducing the peak load or reducing the need for network reinforcements. Digitalisation can improve users' and consumers' experience with EVs and new transportation methods (e.g. autonomous driving). However, there is a risk of assuming that digitalisation will automatically lead to environmentally friendly mobility systems. This is not the case, and decarbonisation of the transport sector fails if R&I related to digitalisation just addresses enhanced convenience of mobility services or if it even leads to an increase in transport demand (rebound effect) with marginal improvements in environmental performance. Clearly, digital solutions need to be developed with the specific goal of providing mobility services at lower energy consumption and reduced environmental impacts. Moreover, it remains to be investigated which advanced digital applications contribute to effective avoidance of transport of goods or passengers and to lowering the overall transport demand.

Building up the battery manufacturing industry and battery recycling processes is 'a strategic imperative for Europe in the context of the clean energy transition' (European Commission, 2018). Batteries are at the heart of the EV production chain. To prevent technological dependency on Europe's competitors, and to capitalise on jobs and economic growth, Europe needs to ensure an adequate market share in battery technologies. This requires a set of concrete measures to support the development of an innovative and sustainable battery ecosystem for both existing and new battery technologies. When it comes to new battery technologies, R&I should cover the full value chain and development should be compatible with innovative changing systems. Innovative charging of batteries comprises, for instance, ultra-fast plug-in chargers, and wireless inductive charging with its advanced possibilities of dynamic electric vehicle charging (DEVC), which allows charging while driving. R&I efforts should aim at quickly reaching a higher technology readiness level of all-solid-state lithium-ion (Li-ion) batteries (e.g. with polymer or ceramic electrolyte). For existing technologies, Europe needs to promote scaled European battery cell manufacturing and a full competitive value chain. First steps in this direction have been initiated by the European Commission with a number of measures, including the foundation of the European Battery Alliance. Based on information from the European Institute of Innovation and Technology, the European Commission states that 'from 2025 onwards Europe could capture a batteries market of up to EUR 250 billion a year, served by at least 10 to 20 gigafactories' (European Commission, 2018).

Large-scale deployment of battery electric cars raises the question of the availability of critical raw materials and the sustainability of batteries (European Commission, 2018), which calls for R&I related to advanced battery chemistries, as well as innovative production and re-use concepts for Europe. Key areas for improvement are the following:

- Improving existing battery chemistry as well as development of batteries with new battery chemistries: Current Li-ion battery systems use cobalt (i.e. cobalt oxide) as a cathode material, which is a raw material only available worldwide in a few regions (mainly the Democratic Republic of Congo and China), often ones with poor records in environmental protection and human rights. New battery cathode material compositions under investigation are, for instance, lithium-nickel-manganese-cobalt and lithium-nickel-cobalt-aluminium oxide, which both aim to reduce the cobalt amount. Further R&I efforts need to focus on an enhanced TRL for batteries with alternative materials for transport applications or new battery technologies such as redox flow and high temperature batteries.

- Establishing European raw material sources: R&I is needed to map and explore available raw material resources in Europe and other world regions. To ensure sustainability while exploring new resources, development of efficient measurement criteria for assessing the environmental and societal impacts of mining activities could facilitate this process by accelerating the permission process essential for opening new mines. Outside the scope of R&I, EU diplomacy is an important aspect in securing the supply of raw materials.

- Battery recycling: Recycling of automotive Li-ion batteries is not yet established. However, only a decade after the roll-out of e-mobility, large-scale dismantling and recycling would need to be in place. Little R&I is performed on the development of pilot lines for dismantling and sorting processes suitable for large volumes of batteries. The collecting and recycling processes need to be improved to recover new materials used in batteries. Intelligent process designs and labelling of batteries could allow automatic sorting of different battery chemistries.

Sustainability of battery usage can also be enhanced through second-use of batteries, possibly through the quantification of second-life criteria and assessing battery reliability, safety and performance at the end of first use. The development of a standard platform for intelligent management of batteries in both first-life and second-life application is a research area which has hardly been investigated so far.

Hydrogen fuel cells represent an alternative power supply for electric drive trains (i.e. compared to battery systems). The importance of hydrogen fuel cell EVs comes into focus when considering that battery EVs alone could not satisfy all the needs of the whole market. Initiatives such as the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) and the H2020 research programme support the development of hydrogen fuel cells in Europe. Still, integration of fuel cell systems and on-board hydrogen storage into a passenger vehicle remains a challenge due to requirements of passenger vehicle safety, occupancy factors and current cost levels. The current approach for on-board storage focuses on high-pressure hydrogen storage. Alternative storage technologies available in the future (beyond 2020) could operate at lower storage pressure enabled through cryogenic systems or novel bonding materials (metal hydrides and sorbents) while improving safety and costs. The US Department of Energy has formulated ultimate storage targets of USD 266/kg H_2 by 2025, which compares to about USD 500/kg H_2 today (Stetson, 2016). Furthermore, current technology for measuring the accuracy of metering hydrogen is at best +/-3 %, when for better public billing purposes higher accuracies, for example +/-1 %, are required. Further challenges related to hydrogen supply concern the reliability and costs of hydrogen compressors, as well as ensuring the quality of hydrogen gas at the nozzle and satisfying high requirements of fuel gas purity levels for automotive fuel cell applications. Apart from technological development, new business models are needed to influence positively the competitiveness of hydrogen technologies in the market.

Hydrogen also represents an option to decarbonise rail transport where further electrification is not economic. Around 53 % of the EU rail network is electrified. With electrification costs around EUR 2m/km (costs for the Midland Main Line in the UK as presented by Dickerson, 2018), electrification is not a cost-efficient solution for routes with low traffic. The choice of technology in non-electrified routes depends highly on the speed of the service and distance of the route. While battery electric trains are a more suitable decarbonisation option for non-electrified routes with lower average travel speed and short travel distances, hydrogen fuel cells can meet the requirements where speeds and range are higher — 160 km/h and 260 km/h, respectively. Hydrogen fuel cell trains are also more expensive than diesel ones (+30 %) because their energy costs are currently higher and they are less efficient than electric trains. However, their GHG emissions are 45 % lower than diesel, even if hydrogen is produced via steam methane reforming. These emissions can decrease to almost negligible levels when using green and low-carbon hydrogen. Hydrogen rail is an area that can contribute to economic growth due to the leadership of EU rail manufacturers. In addition, new rail technologies based on magnetic levitation and reduced pressure tubes are being investigated for commercialisation (Hyperloop). The EU can still capitalise on the opportunities that this presents by researching critical materials relevant in magnetic levitation systems, human factors, health and safety, as well as other engineering designs and improvements. In turn, this could shift demand from aviation and other transport modes for long distance travel and freight transport to rail.

- *Freight transport*

Heavy-duty (including buses) and light-duty vehicles respectively represent around 25 % and 11 % of all domestic transport-related CO_2 emissions of the EU-28 (UNFCCC, 2017). Steered by relevant policies and regulations, decarbonisation options in freight include a combination of operational strategies, new business models, driving behaviour changes, low-carbon technologies and modal shifts.

Improvements in operations can yield substantial energy and carbon savings which can already be achieved in the near-term. Examples of these technologies include the use of telematics for real-time routing and scheduling software, intelligent transport systems and innovative business models. Often logistics fleets provide reverse logistics services to avoid empty back-haul trips (23 % of heavy goods vehicles ran empty in 2015, European Commission, 2017). Lifestyle deliveries provide flexibility around deliverers' availability, and at least in urban areas, most of these use very low-carbon transportation modes such as walking, cycling or biking. Beyond the new operation modes for transport systems resulting from different lifestyle approaches and consumer needs, driving behaviour can reduce fuel usage and hence emissions. Avoiding harsh acceleration and braking can be promoted via driver training or with driving assistance technologies. Connected and highly autonomous vehicles (level 5) are expected to yield the best driving performance possible while enabling new vehicle designs resulting in lighter, more aerodynamic vehicles with larger loading capacity. In the meantime, lower levels of automation such as vehicle platooning and predictive cruise control can produce more moderate benefits. In the long run, logistics services with connected and autonomous freight vehicles (level 5) might increase fuel economy, reduce CO_2 emissions and improve operational efficiency and profit margins as the lack of human drivers will exempt these vehicles from the EU Working Time Directive. As no recreation breaks will be needed for drivers and longer journeys might be possible, vehicles could be operated 24/7. In some cases, freight vehicles will collect multiple loads on route and deliver them in transit, minimising the need to return to distribution centres to park vehicles overnight. This will result in lower mileage and associated emissions.

Challenging the demand for freight services presents great potential. Collaboration in the supply chain reduces the need for redundant freight services. An outcome of the growth of e-commerce is the entry of new e-retailers that often have poor vehicle utilisation in last-mile deliveries (Allen et al., 2017. Similar to the mobility-as-a-service trend, the logistics sector is also experiencing an 'uberisation', where customers can share vehicle capacity to reduce costs and reduce the carbon intensity of freight by using apps that facilitate those arrangements (crowd-shipping). It is necessary to continue research on the interactions of logistics flows with mobility as a service (MaaS) in urban areas, product as a service business models and the influence of the circular economy in logistics flows due to their potential to reduce GHG emissions.

The opportunities to decrease emissions using low-carbon technologies are multiple and comprise vehicle technologies, decarbonisation of fuels, powertrain technologies and, depending on the vehicle sector, alternative transport refrigeration systems (Velazquez Abad et al., 2017). Among the first are all technologies that influence aerodynamic drag, rolling resistance, acceleration and gradient. There is a broad range of very-low-carbon fuels (e.g. first- and second-generation biodiesel, bioDME and biomethane) that can make a significant contribution to reducing GHG emissions from freight transport. However, none of these can entirely eliminate air pollutant emissions from combustion. Battery electric powertrains seem well suited to low loading capacity and low mileage as there is a compromise between range and vehicle payload due to the size and weight of the batteries. This might suffice in an urban context but is clearly insufficient for long-haul freight. In contrast, hydrogen proton exchange membrane fuel cell vehicles can currently deliver similar operational characteristics to those of diesel trucks in terms of torque, power, range and refuelling time (Staffell et al., 2018).

In the near term, both the hybridisation of powertrains and dual fuel vehicles are good interim solutions to overcome operational constraints on the way to full electrification. Promising hybrid technologies for trucks are diesel/electric drivetrains and fuel cell range extenders for electric vehicles, while dual-fuel technologies mainly refer to internal combustion engines operated on diesel/biomethane and diesel/hydrogen. An alternative to battery-based electrification would be partial electrification of highways with overhead lines or a conductive in-road electricity supply, as is currently being field-tested in Germany and Sweden (Moultak, 2017; ERoadArlanda, 2018). With such systems, no large-scale batteries are necessary for long-distance transport purposes. Small batteries or combustion engines would be needed only to travel to and from the electrified highways. Depending on the electrification system, and in particular if in-road or on-road systems are used, smaller vehicles, such as cars, could benefit from the electrification of roads, in addition to large vehicles (trucks and buses).

Promotion of modal shifts from road to maritime shipping, inland navigation and rail saves emissions. Road is the main mode of freight transport in the EU, representing over 51 % of all tonne-kilometres transported in 2016, while sea represents almost 33 %, rail 12 %, inland waterways 4 %, and air transport a mere 0.1 % (European Commission, 2018). As other modes are less carbon-intensive per tonne kilometre, a modal shift from road to rail, inland navigation or shipping is always environmentally beneficial if operationally feasible. The EU has set a goal of a 50 % shift of medium-distance freight journeys to rail by 2050 (European Commission, 2011). To achieve this goal it is necessary to deploy transhipment terminals in ports and multimodal terminals in rail and inland navigation. However, a segment of the deliveries (e.g. port to road, road to rail) almost always requires road haulage and the changes between modes can be time consuming. Often the waiting time of trucks in ports is excessive. Reliability is another of the big challenges in modal shifts as passenger rail transport has priority over rail freight when congestion on the network occurs. R&I efforts need to address enabling factors for modal shift in freight transport further and to develop better multimodal solutions for long-distance transport of goods.

Similar to the mandatory maximum average CO_2 emissions for new cars and vans in the EU, the European Commission has just published a CO_2 standards proposal to increase fuel efficiency and reduce emissions from new heavy-duty vehicles. By 2025, average CO_2 emissions from new HDV will have to be 15 % lower than in 2021, increasing to 30 % by 2030 (European Commission, 2018). Setting mandatory targets for road freight vehicles in each vehicle class will steer innovation from truck manufacturers, in a similar way as the Euro 6 emissions standard has done to reduce air pollutants. Regulations permitting longer and heavier combination vehicles can also decrease the carbon intensity of deliveries. Several trials have been carried out around Europe, which is particularly important to increase the penetration of battery electric trucks, due to the volumetric and gravimetric penalty of batteries on vehicle payload.

2.2 Aviation

With a share of 13 % of the CO_2 emissions related to domestic and international transport services in the EU-28, emissions resulting from aviation are about one fifth of the emissions attributable to road transport. However, compared to road transport, aviation emissions have grown much faster over the past two decades (about 50 %) and are forecast to grow by a further 45 % between 2014 and 2035. With just 7 % of the world's population, European flights account for around 25 % of global air traffic. In terms of overall impacts on climate change of aviation, it needs to be considered that the impact of emissions due to aircraft operation in the upper troposphere and lower stratosphere is higher than the impact of the same amount of emissions on ground level (Fuglestvedt et al., 2010). This additional impact can be quantified by a so-called CO_2 uplift factor, which takes into consideration the net climate contribution of present and future aviation emissions as a multiplication factor for the climate forcing contribution associated with the respective CO_2 emissions. However, there is no universal uplift factor, due to the different atmospheric impacts of aviation emissions resulting from different engine technologies and atmospheric conditions, for instance (Dessens et al., 2014; Cox et al., 2018).

Enable advanced and sustainable biofuels to become competitive on fuel markets to support cost-effective decarbonisation of aviation. In addition to enhanced technologies and higher-performing operations, 'drop-in' liquid biofuels or biojet fuels are an effective option for decarbonising the aviation sector as other forms of renewable energy are not suitable for powering large aircraft over the forthcoming three decades. Compared to today's production costs of over USD 1/litre for conventional jet kerosene, biojet fuels are more expensive (2-4 times, depending on process and production capacity). While the technological feasibility of alternative jet fuels is proven, reducing cost, increasing availability and feedstock sustainability remain important prerequisites for successful market uptake. A full shift from kerosene to biofuels for just today's consumption in the aviation sector would require five times more biofuels than the current biofuel production for road transport. This illustrates the fuel supply-related challenges of using biofuels for decarbonising aviation. It is important to underline the necessity of compliance with high environmental and social standards on the global scale when producing biofuels, with regard to emissions from land use change, water usage, soil degradation, biodiversity, land and labour rights and food security. European policy is promoting global market-based measures currently being negotiated under the umbrella of the UN's International Civil Aviation Organization, and pursues internationally harmonised policies reflecting suitable and acceptable sustainability criteria.

Beyond biofuels, other options for the decarbonisation of aviation are limited and refer mainly to the usage of alternative low-carbon synthetic fuels, efficiency improvements and alignment of measures between demand and offer in order to tackle the increase in air traffic. Improved aviation efficiency relates to weight reductions, advanced engine concepts, new aircraft designs, improved air traffic management, ground level operations and cruise speed reduction. Future aircraft weight reductions are expected to be quite significant, due mostly to the further replacement of metals with carbon fibre reinforced polymers. A relative weight-related share of composite material of more than 50 % is expected to be deployed in 2050, reducing the average airplane weight by 23 % compared to the 2004 fleet (Cox et al. 2018). Advanced airplane concepts, such as blended wing body aircrafts, would not only require the re-design of ground-level infrastructure but also analysis of consumer acceptance of such novel airplane technologies. Compared to the car industry, for instance, the time needed to introduce new technology is longer for aircrafts. The time for development of a new aircraft is around 10 years and their introduction in the marketplace — for a significant percentage of the fleet — will spread over a period of around 20 years.

Measures to reduce emissions in aviation must extend beyond current technology efforts to include fiscal and behavioural measures addressing air traffic demand, such as carbon travel budgets for industry and governments (see also the section on mobility patterns). Current fuel taxation schemes favour aviation over other transport modes, making air traffic comparably cheaper. Adjusting aviation fuel taxation to be comparable to the taxation of other transport services provides a first step towards a shift to more environmentally friendly transport modes. With life-cycle CO_2 emissions per passenger and kilometre of high speed rail being lower by a factor of about nine compared to air transport (Gao at al., 2016), a modal shift from aviation to high-speed rail could be a valid option for many European countries.

2.3 Maritime transport and ports

Along with aviation, maritime transport is a transportation sub-sector that is not only rapidly growing but that thus far has received limited attention in terms of its CO_2 emissions impact. One reason is that, as with aviation, implementing low-carbon technologies is more intricate and costly than in other (sub-)sectors (IEA, 2017). Domestic and international shipping accounted for 13 % of the EU-28 transport-related emissions in 2015, with about 90 % of all energy used in shipping activities attributable to international marine navigation. The vast majority of shipping activity derives from the transportation of goods in large sea vessels, as opposed to passengers in ferries and cruise liners, but cruising is a rapidly expanding branch of tourism, with concomitant environmental impacts. Most shipping relies on the use of heavy fuel oil, which is both carbon-intensive and highly polluting in terms of emissions of e.g. particulate matter and SO_2. Progress in strategy formulation to reduce GHG emissions was made in April 2018 with the agreement of all member countries of the International

Maritime Organization (IMO) to halve CO_2 emissions from international shipping by 2050 in comparison to 2008 levels (IMO, 2018). Yet the details of this decarbonisation strategy urgently need to be specified, including in terms of how and when to achieve a carbon-neutral shipping sector. Besides measures to reduce energy and emissions intensity of shipping activities, new demand patterns and coherent international policies are required to limit emissions in this sector (see also the section on mobility patterns).

First initiatives for reducing the carbon footprint of shipping would be to reduce the speed of ship transport. This may be an effective measure that could be immediately deployed if additional ships can be operated to ensure a constant transport capacity at lower speeds. However, an in-depth analysis should be performed with regard to how speed measures against scale. According to the International Transport Forum in 2018, 27 % of fuel requirements could be saved if speed was reduced by 10 %. Other effective CO_2 mitigation options concern efficiency improvements, among which are drag reduction and propulsion optimisation, and the use of low-carbon synthetic fuels such as ammonia, hydrogen and biofuels instead of heavy fuel oil. To let shipping reach its required contribution to achieving global climate change control, it will ultimately need to be decarbonised entirely. For that purpose, many more approaches need to be investigated, including more speculative ones such as adding the use of sails to propelling machines. Merit-order research is required to map decarbonisation alternatives and determine time intervals for their optimal implementation.

Options for achieving a zero-carbon shipping sector abound, but all bear intrinsic drawbacks and hurdles to be overcome. Options include advanced biofuels, electric propulsion with electricity stored on-board in batteries, nuclear power, fuels cells with hydrogen or other synthetically produced (renewable) fuels stored on-board. Among technological measures, propulsion improvement devices are expected to provide the most significant fuel savings (up to 25 %), followed by an improved slender design (10-15 % fuel reduction) and light-weight materials (up to 10 %) (International Transport Forum, 2018). Alternative approaches to reducing the carbon intensity per ton-mile travelled are possible by designing bigger vessels. If the current international marine fleet is replaced by bigger vessels, emissions could be reduced by up to one third on a global level (International Transport Forum, 2018). Estimates indicate that a 50 % increase in a ship's cargo capacity increases the fuel consumption by only one third. A factor of major concern related to shipping technology innovation is the fact that vessels are designed for a typical lifetime of 30 to 40 years, which begs the question whether a large part of the current fleet requires retrofitting to improve energy efficiency or, alternatively, should be retired early if we are to meet the goals of the Paris Agreement. Further measures to decarbonise the shipping sector concern the ship-port interface, including the reduction of waiting times and the electrification of ports to enable ships to be connected to the grid when moored.

Aside from efforts to reduce GHG emissions from ships themselves, due attention needs to be given to decarbonising all activities in and around ports between which the vessels navigate. Equipment for loading and unloading as well as other harbour infrastructure can be decarbonised by electrification and usage of biofuel-run engines or hydrogen-fed fuel cell devices and vehicles. This could allow all (dis-)charge activities in ports to become zero-carbon. Given their large surface areas, ports are often also well suited for hosting a large range of possible renewable energy technologies, such as solar thermal stations, PV panel fields and wind turbines, to mention just a few. Clearly, much more techno-economic, socio-economic and logistics research is required to investigate the technologies as well as the policy tools that enable reduction of the GHG footprint of shipping and ports across Europe.

Electrification is to play an earlier role in the decarbonisation of domestic shipping than in that of international marine navigation. Depending on different purposes (freight versus passengers) and distances travelled (national or international) different technologies and fuels may enable shipping to be rendered carbon-neutral. While for some purposes (e.g. local and regional passenger ferry transport or inland navigation) electrification by the use of batteries may prove to be the optimal choice, for other purposes (e.g. intercontinental cargo shipping) hydrogen with fuel cells, biofuels, liquid biomethane or synthetic or renewable fuels — or a mix of these options — may be the cost-efficient solution. From a technical point of view, electrification of short sea shipping and inland navigation is a feasible decarbonisation option, but further investigation of the operation of batteries is needed in view of the safety requirements for waterborne transport. For some long-distance marine navigation purposes, nuclear propulsion could be imagined as this option can rely on a submarine and icebreaker experience base. Drawbacks, however, include the production of radioactive waste, accident risks and concerns over proliferation of nuclear materials (von Hippel, 2016) as well as negative attitudes and perceptions of society. Hydrogen fuel cell ships can also be a solution for isolated regions with a surplus of renewables and poor connections to gas and power networks

3 Transport sector decarbonisation: systemic implications and new mobility patterns

Beyond sector-specific mitigation options as described in the previous section, this section highlights the transformation of the transport sector from a systemic perspective, considering interdependencies with other sectors of the energy system and the wider economy as well as innovative mobility concepts leading to new transport demand patterns. In general, it needs to be kept in mind that introducing and promoting new vehicle technologies and alternative fuels needs to be evaluated from a life cycle perspective — i.e. taking into account vehicle production, operation and end-of-life — to quantify climate mitigation potentials and resulting co-benefits and potential trade-offs. Results of recent research illustrate the substantial differences in the overall environmental benefits of electrification of transport activities with either battery electric or fuel cell vehicles depending on the CO_2 intensity of electricity and hydrogen production (Bauer at al., 2015; Ellingsen at al., 2017; Berrill at al., 2016). Since production of batteries and fuel cells is currently associated with substantial environmental burdens, it is also of high importance to decarbonise manufacturing processes and the power sector as such, not only from a European but from a global perspective (Cox, Mutel et al., 2018; Ellingsen et al., 2013). Complex fuel supply chains, e.g. synthetic fuels generated from hydrogen and CO_2, can exhibit very low overall energy efficiencies and therefore lead to comparatively low GHG reduction as well as to high demand for renewable electricity (Zhang et al., 2017).

3.1 A roadmap towards a zero-emission EU transport

Model-based decarbonisation scenarios, quantified by the PRIMES energy systems model as part of the EU release of the Clean Energy for All Europeans proposal, have explored synergies between transport and the rest of the energy system (including power generation, agriculture, etc.). These scenarios deliver an 80 % reduction in total GHG emissions in 2050 compared to 1990. Transport-related CO_2 emissions decrease by 60 %, which is compatible with the targets proposed in the strategy for low-emission mobility (European Commission, 2016) (compare upper panel in Figure 7). The GHG emission reduction in transport is driven by a significant uptake of low-emission private vehicles as a result of more ambitious targets for car manufacturers, timely development of recharging and alternative fuel infrastructure and further reduction in battery costs. Enhanced production and optimised harvesting, supply chain logistics and mobilisation of potential of advanced biofuel technologies, thanks to effective R&I, deliver biofuel quantities for the road freight and aviation sector. While these scenarios are placed at the lower end of emission pathways that are consistent with the long-term target of 2 °C (van Soest et al., 2017), further emissions reduction would be necessary to go well below 2 °C climate stabilisation, as indicated by the Paris Agreement. However, significant amounts of unabated GHG emissions in transport were found to remain by 2050. In the near term, improvements in ICEs will provide a bridge or extend the transition to real, long-term sustainability. The only real solution is a non-fossil, zero-(net)-carbon energy carrier that can be produced and delivered and then carried and used in a vehicle with acceptable characteristics (e.g. range) and cost. **Traditionally, battery electric and hydrogen fuel cell vehicles have been considered as competitive options.** Nevertheless, dedicated market segments in transport can accommodate both options. The complementarity between hydrogen and electricity needs to be unlocked to bridge the gap to totally curb unabated GHG emissions that would otherwise remain in the transport sector by 2050. The use of hydrogen as a fuel for the heavy-duty vehicle market segments could help to overcome the technical constraints of electricity while at the same time decreasing GHG and pollutant emissions. Hydrogen would need to be produced via low-carbon pathways such as electrolysis from renewable or nuclear power or through alternative hydrogen production processes (e.g. biomass gasification and carbon dioxide capture and utilisation or storage (CCUS) or thermochemical water splitting) to ensure a minimal emissions impact on a well-to-wheel basis. The large penetration of intermittent renewable energy resources, as part of the decarbonisation of the power generation sector, implies that excess renewable electricity may be produced at certain times within a day. Transforming electricity produced from renewable energy into hydrogen to be used in demand sectors (including transport) highlights the role of hydrogen as an electricity-based storage option.

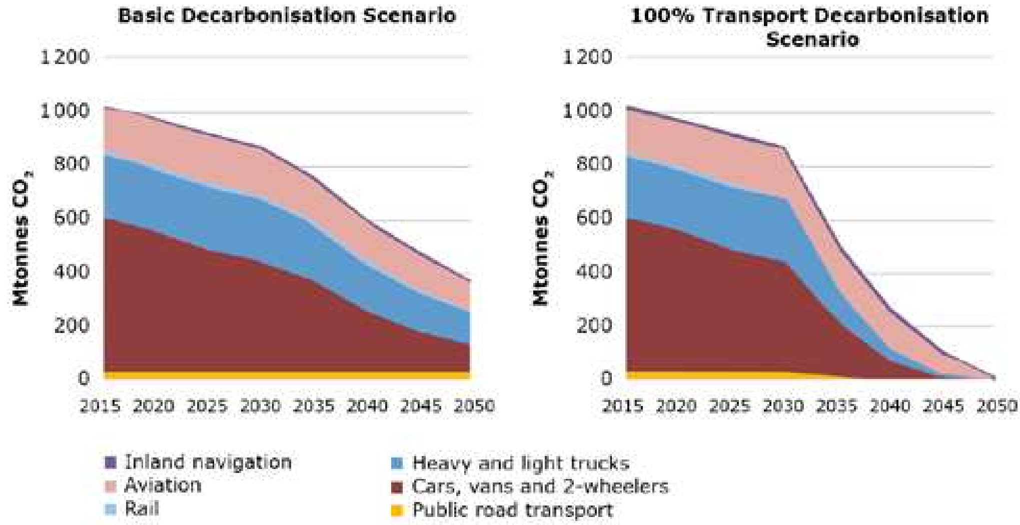

Figure 7: Evolution of the EU-28 transport sector CO2 emissions in the basic decarbonisation scenario delivering a 60 % emissions reduction in transport and in a 100 % transport decarbonisation scenario. Sources: PRIMES model, ASSET study on sectoral integration — long-term perspective in the EU energy system (De Vita et al., 2018).

Using hydrogen in heavy-duty vehicle segments will free up significant amounts of biofuels which otherwise would need to be blended with diesel to power those vehicles. Under such a strategy, biofuel production could be used to fuel entirely the most inflexible transport sectors such as aviation and, to a lesser extent, shipping. Targeted production of a single biofuel product (i.e. bio-kerosene) instead of a diversified portfolio of products could unlock significant economies of scale, rapid technological progress and reduced risk for the investors.

Considerable uncertainties exist though regarding the future evolution of hydrogen fuel cell investment costs, which depend on economies of scale. Studies suggest that the total cost of ownership of fuel cell vehicles can reach parity with battery electric cars by 2030. Uncertainties also exist regarding hydrogen refuelling and distribution infrastructure, as well reliability of fuel cell systems in new niche markets such as rail and heavy goods vehicles. The affordability of the new vehicle technology and fuel options is a prerequisite to ensuring that citizens will continue to enjoy personal mobility. A shift from OPEX to CAPEX is expected to take place in the long-run, since the new vehicle options are more capital intensive but offer significantly reduced running costs. However, new business models such as mobility as a service and collaborative logistics have the potential to reduce transportation costs. A recent model-based analysis (De Vita et al., 2018) depicts the importance of a hydrogen-based sectoral integration in the most promising sectors, including transport. This pathway can lead to an almost 100 % reduction in transport-related CO_2 emissions by 2050 by effectively combining three main energy carriers — electricity, hydrogen and biofuels. Under such a stringent decarbonisation scenario, where all sectors largely deploy their emissions mitigation potential, the importance of electricity to decarbonise energy demand increases substantially, leading by 2050 to more than a doubling of today's electricity consumption in Europe. In the decarbonisation scenario, around 600 TWh are needed in the transport sector in 2050 to fuel electricity-based mobility technologies directly, while even 10 % more is supplied to the transport sector as hydrogen, which is mainly produced with electrolysers.

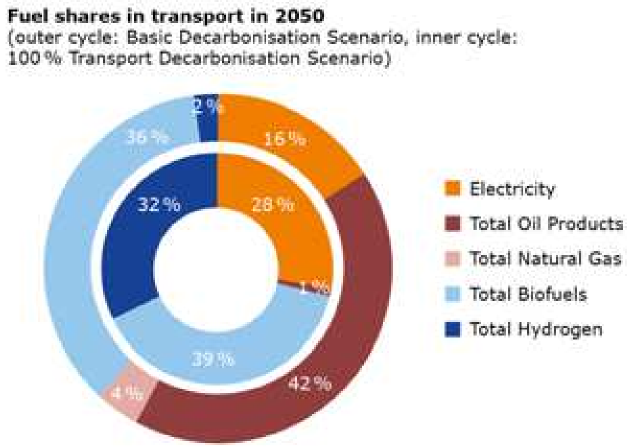

Figure 8: Fuel mix in the EU-28 transport sector in the basic decarbonisation scenario delivering a 60 % emission reduction in transport and in the 100 % transport decarbonisation scenario. Sources: PRIMES model, ASSET study on sectoral integration— long-term perspective in the EU energy system (De Vita et al., 2018).

Transport decarbonisation should not negatively influence the competitiveness of EU businesses. Inflated freight costs would drive consumer prices upwards and increase the costs of intermediate consumption in the domestic production of goods. Price-induced modal shifts from road to non-road freight transport modes would need to be carefully designed to avoid over-taxing specific sectors. The inclusion of heavy-duty trucks in the EU ETS has often been discussed but never implemented. There are doubts as to the feasibility of such implementation due to high transaction costs (Aarnink et al., 2013).

A recent analysis on the **impacts on employment of the penetration of electric vehicles** shows that the number of jobs will increase, provided that the manufacturing of batteries takes place in the EU and not outside the EU (Hill et al., 2018). However, most of the current and near-term manufacturing capacity is being deployed in China and Korea. In fact, new low-carbon transport technologies may trigger positive economic effects in other sectors, such as the upstream sector. According to Smith et al., 2017, a positive cross-sectoral economic effect was found for the case of the UK when shifting the British automotive sector from fossil fuels to hydrogen while replicating the strong domestic upstream supply linkages of the current UK gas and electricity supply sectors.

Besides possible positive macro-economic and employment effects, decarbonisation of transport services offers substantial environmental co-benefits. The ultimate switch from ICE to electric motors (using electricity from the grid or produced from a fuel cell) in road transport will almost completely eliminate relevant air pollutant exhaust emissions such as particulate matter and NO_x and improve air quality in cities. Even if exhaust emissions are removed completely, some pollutant emissions remain from vehicle operation, e.g. because of breaking and abrasion of tyres. The positive externalities (e.g. fewer medical costs, increased productivity) associated with the reduction in pollutant emissions need to be factored in when accounting for the benefits of the transport decarbonisation strategy.

Decarbonising transport has very large consequences on the EU trade balance through reduced imports of crude oil and oil products. Under a 'well below 2 °C' decarbonisation scenario, the transport sector would complement fossil fuel substitution in other sectors, leading to an overall reduction in energy import dependency from 56 % in 2015 to 27 % in 2050 (De Vita et al., 2018). Oil products would only be needed as feedstocks for industrial production processes and non-energy purposes. Comparing imports of oil products between the basic decarbonisation scenario and the 100 % transport decarbonisation scenario (Figure 8) reveals that import expenditure of about EUR 93 billion can be saved. As such, the reduction in fossil fuel imports resulting from energy sector decarbonisation significantly improves Europe's energy security situation.

3.2 Tightened coupling of the transport and the power sector

Often, in the past, the interrelations between different sectors of the energy system were either limited or non-existent. However, the situation may change remarkably in view of the effort needed to curb energy- and transport-related GHG emissions, with electricity being an important resource for the transport sector, either used directly or indirectly as input for hydrogen production. A sectoral integration strategy needs to be pursued, where combined actions in more than one sector would lead towards a low-carbon transition and at the same time exploit new synergies and opportunities that may arise.

Developments in the transport sector, as regards market uptake of electromobility, would need to be closely aligned and coordinated with the effort from the power generation perspective (i.e. increased renewable energy penetration). Electromobility stands as the most promising solution to lead to the decarbonisation of private transport mobility. Using electricity as an energy carrier in transport is expected to generate additional demand for electricity in the system and compensate, at least partly, for a decrease in electricity consumption from households, resulting from energy efficiency obligations. At the same time, the electricity which would power electric vehicles needs to be produced at the lowest possible carbon emissions. This requires not only building new power plants but also implementing smart grids, demand-side response approaches and enforcing electricity interconnectors among EU countries. Policy action that will ensure market coordination among the various actors involved (e.g. car manufacturers, power generators, consumers, providers of infrastructure, etc.) will need to be set in place already well before 2030. A continuous policy presence in the horizon up to 2030 is needed to ensure the successful interplay between the relevant market actors and lay the ground for a broad transport transformation process up to 2050.

The integration of grid electricity-based EVs in the European electricity systems requires coordinated efforts to build up the corresponding electricity infrastructures (i.e. enforcements in the distribution grid) as well as electricity market structures that allow smart system integration and improved system flexibility. This will bring up new cross-sectoral linkages, for instance at grid level through vehicle-to-grid (V2G) technology, with the potential to expand transport services to energy management services. To do so, there is a need for a power market that allows the integration of storage systems embedded in EVs into the grid, including appropriate measures for vehicle owners to compensate for battery degradation due to more frequent charging cycles. More R&I is needed, for instance to develop bi-directional chargers to support the rollout of V2G solutions and to enable ultra-fast frequency responses. In addition, power system dynamics and appropriate market designs and regulation should be investigated in more detail to better understand network operation and business models that create long-term products for electricity supply and balancing services. This includes analysing the influence of dynamic pricing on market, as well as assessing the aggregation of EVs in all energy market timeframes and the empowerment of market players with balancing responsibilities.

For an effective GHG emissions reduction over entire transformation pathways, a systemic approach is needed for electricity as well as for other energy carriers. From the perspective of non-private transportation, batteries for long-distance road freight transport and aviation may prove insufficient due to technical constraints (e.g. low range, autonomy, weight, etc.). Biofuels produced from non-food feedstocks — 'advanced fuels' — are acknowledged as major candidates for mitigating GHG emissions. The technological maturity of production processes and the availability of ligno-cellulosic feedstock in sufficient quantities are currently the main barriers that need to be overcome in the future. Strong policy action will be necessary to trigger investments and decrease associated risks. R&I will hold a fundamental role in delivering advanced biofuel technologies. Enhancing feedstock supply, reducing conversion costs and improving the efficiency of the biomass system supply chain through R&I are expected to support the transition to a sustainable bioenergy system. Measures that set mandates on the production of biofuels from non-food based sources and caps on the maximum production from food crops can provide some certainty to the investors.

3.3 New mobility patterns

Beyond the multiple technology options for substituting fossil-fuel based mobility services with clean transport, a change in demand patterns for mobility services is needed to attain deep emissions reductions in the transport sector. In this context, the European Commission's concept for the development of sustainable urban mobility planning (SUMP) should be regarded as a model approach for comprehensive local or regional transport planning[13]. This means, on the one hand, reducing demand for transport of passengers and goods, and on the other hand, shifting the choice of transport modes towards systems with lower climate impacts. Demand for mobility is influenced by lifestyle and the values consumers attach to transport services as well as the trade-offs with other values. Developments over the recent past indicate several trends, including growing urbanisation, accelerated globalisation, and an increasing role of digitalisation in daily life activities with implications for the transport sector.

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[13] The SUMP concept is complemented by Commission guidelines and comprehensive information on SUMPs in the 'Mobility Plans' section of the Eltis urban mobility observatory: http://www.eltis.org. It includes, *inter alia*, a self-assessment tool for cities, information on national frameworks, a SUMP city database and best practice examples.

Digitalisation can enable smart transport systems, with opportunities to reduce emissions but also with the risk of re-bound effects. For individual mobility with cars, there are several possibilities to operate the traffic system in a smarter way. Through intelligent transport system solutions, where cars communicate with each other and with a central traffic coordination system, travelling routes and car parking can be optimised. Increasing attention is currently given to the development of autonomous driving systems, be it with partial, conditional or even full automation. Even though such intelligent transport systems with optimised traffic control could reduce congestion and environmental impacts, there is a potential risk of re-bound effects creating additional traffic in urban areas and leading to a similar level of congestion as without smart traffic control. Nevertheless, intelligent transport systems offer the possibility to facilitate the operation of surface-bound public transport (trams and buses) by prioritising public services over passenger car transport. This would slow down the average car speed in cities and could even double the average effective travelling speed of buses, which is about 15 km/h today in urban areas, which then translates into increased passenger transport capacities for public transport (Kurrer and Tarlton, 2017).

An emerging mobility option, particularly in urban areas, is the concept of MaaS, which allows bundling of different transport means, public and private, into one easy-to-use package for the customer. This service addresses the demand for intermodal mobility, where consumers can book services involving multiple transport modes. The service is provided to the customer via mobile applications and payment is handled via a digital wallet. In railways, several of these options are already available but can still be integrated in a smarter manner, for example using train traffic control, ticketing, security and passenger counting. The transition within the European economy from goods-producing industries towards service-oriented businesses also increasingly affects car manufacturers, which are becoming providers of mobility services where customisation is key to success. Car manufacturers have identified MaaS as an upcoming business opportunity to retain share in a changing mobility market. Since MaaS is only possible with user-friendly digitalised applications, car manufacturers are partnering with ICT and telecommunication providers to tailor their MaaS products. According to Accenture, the German MaaS market could reach 20 % of total individual car transport by 2027 (Accenture, 2017). The large-scale deployment of MaaS would result in reduced private car ownership. However, overall transport system and market implications, as well as related emission reduction potentials need to be researched more extensively. In principle, shared mobility offers the advantage of higher occupancy rates and intensified usage of transport technologies, which allows quicker stock turnover and positive implications for the deployment of innovative low-carbon technologies.

Beyond novel motorised transport systems in cities, urban planning allows urban mobility infrastructures to be rethought and space needed for transport (roads, parking space, etc.) to be freed up for other services and activities (e.g. businesses and leisure) to make cities better places to live. There is an opportunity to design cities with a focus on the quality of transport, potentially with more space for walking and cycling complemented by a well-functioning public transport infrastructure. Co-benefits of more physical mobility activities are related to increasing public health and well-being. With increasing urbanisation, where congestion of roads in cities is becoming (or is already) a serious limitation in the quality of life, reinvigoration of public transport is a must, complemented by other shared mobility. To increase the convenience of non-motorised light traffic, the digitalised availability of information on different transportation connectivity options is important. For instance, current apps allow people to find places of interest in city centres, using digital map information in most advanced cities. Information on which local train to catch and in which trains bicycles are allowed is a service offered in many towns and by many local train operators through personal smartphones.

With a growing population in cities, R&I on urban spatial planning can facilitate the indentification of urban structures that allow a reduction in mid-distance commuting, which represents a significant amount of passenger transport and, hence, source of GHG emissions today. In order to assess different city approaches, multiple criteria have to be considered such as business location and employment, housing demand, travel speed, transportation network structure and urban emissions stemming from commuting. Some of the criteria may have opposing effects. Denant-Boemont et al., 2016, observe direct benefits for big cities of the value of induced travel savings for an unchanged residential location, while job decentralisation modifies residential choice due to deceases in average land rents, which reinforces urban sprawl. They state that ‘a polycentric city is not necessarily the most desirable urban topology to promote’ because the spatial extension of the city has a significant impact on commuting flows and transport-related emissions. Since cities have different characteristics, there is a need for careful policy implementation to ensure a city’s sustainable development. In a case study on an urban area in Germany, Schwarze et al., 2015, arrive at the conclusion that centralisation (densification) has positive effects on the energy-efficiency of the transport system. Comparing the impacts of different urban city layouts, they identified a higher relevance of policies making car driving more expensive or slower and policies making public transport, cycling and walking more attractive in improving the mobility system’s sustainability.

Related to (urban) freight transport, innovative ideas and solutions need to be further developed to identify collaborative and integrated business models that increase loading factors in logistics and reduce transport-related emissions without sacrificing the quality of their services. Examples of emerging concepts are as follows:

- platforms that allow pooling of vehicles (e.g. trucks) used for freight, such as Pamyra (Pamyra, 2018);
- enabling urban rail-based freight transport using a combination of trains and cargo trams with the existing infrastructure, as demonstrated for the VW production site in Dresden;
- underground automated freight transport systems for delivery between urban freight hubs, as well as including intermediate storage of goods (Cargo Sous Terrain);
- zero-emission last-mile deliveries by utilising zero-emission vehicles for local logistics, such as cargo bikes and potentially also autonomous cargo delivery robots and drones;

- for long-distance freight transport between Asia and Europe, a shift from shipping to railway transport could be one future option, supported by the joint development of a trans-Eurasian railway system (International Transport Forum, 2018).

Apart from the ambition to improve the environmental footprint of transport services, a critical question relates to the possibilities to avoid further increases in transport demand or even to reduce transport demand in future to limit climate change impacts. This is of particular importance for transport services with substantial expected growth rates in the future and long technology development lead times, as is the case with aviation and shipping. If GHG emissions reductions in other sectors of the European economy are not to be equalised by emissions increases related to aviation and shipping, measures to reduce the amount of transport services for these modes need to be deployed. This requires exploring alternatives to these transport services, as well as corresponding market interventions that promote a shift towards the alternatives. In general, aviation demand is subject to high price elasticity. That not only means that higher prices will significantly reduce aviation demand, it also shows that many flights taken have low economic value. This implies that at least price equality of aviation fuels with other fuels should be pursued, but also tackling aviation with carbon pricing. Such policy measures are lacking at the moment, and other demand developments can be observed. Looking at current trends and future prospects for airborne transport, an increasing emergence of new business models with improved convenience for travellers can be observed. Examples are subscription-based aviation, frictionless travel experiences, air taxi services and flight-sharing (Duncan and Bragadish, 2017). Complementary to pricing and taxation mechanisms for air traffic, R&I would be needed to identify and design real alternatives to aviation in Europe which offer the same or even better service and travel experience. One systemic alternative is a pan-European high-speed rail network, which might turn into the most powerful integrating factor for our continent in the decades ahead. Related to the avoidance of transport demand, digitalisation will play a key role offered by new businesses capturing immersive telecommunication and additive manufacturing, for example. Concerning passenger transport, one has to acknowledge that mobility has considerable personal and social benefits which need to be addressed when developing digitalised alternatives, in particular based on telecommunication (Mokhtarian, 2009). Having adequate alternatives in place which increase people's freedom to choose non-travel alternatives would be essential in addition to a change in attitude towards air travel and long-distance goods transport. Behavioural aspects of consumer choices need to be understood much better to establish schemes that raise awareness of the externalities of aviation and shipping, as well as to implement effective regulatory measures. Such schemes could refer to a minimum-distance rule for aviation or a personal air-travel budget, for instance.

Dedicated policies would be needed to facilitate a shift in transport patterns and to promote the uptake of lower-carbon automotive technologies for freight transport, including mandatory targets for synthetic fuels and hydrogen within the EU Renewable Energy Directive and national fuel obligations, compulsory targets for alternative fuel and recharging infrastructure in the **Directive** 2014/94/**EU** on the deployment of **alternative fuels infrastructure** more stringent targets for GHG emissions and air quality emissions standards for heavy good road vehicles. Similar approaches could be applied to the maritime sector and aviation to steer technology innovation. While the EU ETS applies to intra-EU aviation, shipping is currently excluded (Carbon-Pulse, 2017). The enlargement of cap-and-trade schemes to capture further transport modes could steer innovation if a sufficiently high certificate price level exists. Also, adjustments in, fiscal policies can have a strong impact on shifting demand from fossil fuels to low-carbon fuels. Compared to fuels for road transport, the 'red diesel' used by non-road mobile machinery (e.g. port, airport, farming and railway vehicles) is less taxed. Increasing taxation from these freight modes improves the business cases for implementing lower carbon solutions.

Given the international dimension of the aviation and shipping sectors, strong coherent international policies are needed to decarbonise these sectors. International commitments capturing the main regions involved in providing or demanding sea and air transport services are required. For EU policymaking, addressing emissions from international aviation and shipping requires coordination with other large emitters outside Europe, as well as engaging with corresponding international umbrella organisations. For aviation, new efforts should complement existing measures such as the International Civil Agency Organization's Carbon Offset and Reduction Scheme for International Aviation (CORSIA), which encourages aircraft operators to offset emissions over and above their average emissions from 2019-2020. Related to the emissions from international shipping, IMO has arrived at a major achievement with the agreement to cut emissions by half by 2050 compared to 2008 levels. The current medium-term emissions intensity goal (-40 % carbon intensity improvement in 2030 compared to 2008) appears to be rather modest given that in 2015 the carbon intensity of international shipping already dropped by more than 30 % from 2008 levels, due to the global economic downturn. Going beyond the individual sectoral approaches for aviation and shipping, policies on GHG emissions from aviation and shipping could be enforced and aligned under international climate policy agenda. For instance, emissions from international aviation and shipping could be directly captured by the countries' nationally determined contributions as stipulated in the UNFCCC's Paris Agreement, and be subject to the national mitigation measures and countries' long-term global climate change mitigation strategies.

4 Recommendations for R&I

Clustered into four main domains (society/consumers, technology, systems/sector integration, and policies) are R&I recommendations addressing future transport sector decarbonisation options that need further investigation. For R&I on technology, EU funding instruments such as the Future and Emerging Technology (FET) Flagships could be of particular potential relevance.

R&I on society and consumers *s*hould address the linkage of mobility and lifestyle/business models as well as individual and societal impacts in decision making. How does consumer behaviour and the way businesses are run impact future demand for transport services and how is the choice of transport technologies influenced by social norms and individual behaviour? Possible topics are as follows:

- Analysis of future mobility demand patterns and understanding of lifestyle impacts on individual choice of transport services, modes and technologies: This includes, for instance, the development of highresolution urban spatial planning techniques for modern low-carbon/low-traffic city layouts, the analysis of drivers of different transport demand patterns and potential rebound effects of clean transport), as well as R&I on behaviour/behavioural change on the basis of consumer-centred policy pilot projects.

- Advanced methods for integration of consumer behaviour in techno-economic assessments: These would allow an integrated assessment of the interplay between consumers, their needs and technology requirements from a systems perspective.

- Investigation on how digitalisation can change transport demand patterns and energy consumption: These could include telework, 3D-printing, increased online shopping, ICT-enabled smart traffic control and usage of truck transport capacities (5G), (semi)autonomous driving and car-sharing.

- Development of consumer-dedicated information measures and tools: These would increase consumers' awareness of the availability of low-carbon mobility options and alternatives to transport services in general.

R&I on transport technology is required to improve the competitiveness of low-carbon transport technologies and to design technologies to allow for their proper system integration and to comply with consumers' requirements. Specific R&I topics concern the following areas:

- R&I is needed not only related to the **electrification of common land-based transportation systems** (e.g. passenger cars) but also for the segments that receive less attention, for example the decarbonisation of industrial vehicles (yellow machines), trucks (e.g. overhead lines) **and the electrification of ports & short distance water-based transport** (e.g. ferries). For electric vehicles, R&I should also address the **standardisation of charging systems** to overcome adaptation barriers on the consumer side.

- **New battery chemistries as well as the re-use and recycling of batteries** should be explored to improve their life cycle sustainability, reliability, safety and cost performance. An aim could be to lift batteries from TRL 4 (all-solid-state lithium technologies) to TRL 7 within the next decade.

- Assuming battery electric vehicles will be largely rolled out for individual passenger road transport, R&I is needed to identify efficient hydrogen carriers (e.g. liquid hydrogen organic compounds) to enable hydrogen in other mobility market segments that are difficult to electrify such as rail, road freight, emergency vehicles and shipping. What would the corresponding business cases look like, and what is the trade-off of in using hydrogen in vehicles directly versus producing synthetic fuels based on hydrogen?

- R&I on new ships and airplanes is needed to further reduce the specific fuel consumption per transport unit. This comprises development of **new airplane and ship designs to increase transport capacities**

as well as new materials (e.g. composite materials) and improved aerodynamic designs. Furthermore, R&I should focus on the **sustainable production of biofuels and synthetic fuels** as equivalent substitutes for fuel oil and jet fuel. In particular, R&I is needed to ensure and enhance the EU production of lignocellulosic feedstock through investment in new crops, the identification of efficient agriculture, waste and forestry management techniques, optimised harvesting and supply chain logistics;

- Analysis is needed of **international and transcontinental transport infrastructure requirements** and new technologies to substitute short-distance EU air traffic with high-speed rail as well as to shift long-distance freight transport based on road or ship to rail freight transport.

R&I on systems/sector integration needs to be strengthened, given the interdependencies of the transport sector with other sectors of the energy system as well as with the wider economy and its importance for the future of industrial development in Europe:

- Investigation should be carried out on what is needed to make an energy system with very high shares of renewable energy and high shares of e-mobility work, including **research on electricity grid enforcements on a spatially detailed level** (i.e. distribution network) and digitally supported smart **integration of EVs in the power grid** to unlock the potential of e-mobility to provide flexibility to the electricity system, e.g. through vehicle-to-grid options.

- Research is needed on the design of **electricity retail markets** with large shares of embedded e-mobility and novel markets for shared mobility, including innovative tariff models for EVs.

- R&I should be developed on sustainable **hydrogen supply, comprising production, storage and transport** to address the specific question on how the conversion efficiency (over the entire conversion pathway) can be improved to use as little energy as possible to produce H_2/synthetic fuels, including new materials such as MOFs as catalysts, for instance. It is relevant in this R&I field to gain knowledge and experience on the realisation of **sector coupling projects along with H_2 and CH_4 network design and operation,** i.e. to build new hydrogen networks versus using the existing gas network versus decentralised production. A spatially detailed analysis would allow consideration of different consumer groups (e.g. industries) and their requirements in terms of gas supply and gas quality.

- Under the question 'What would be needed so that EU industries benefit from the decarbonisation of transport?', R&I related to the implications of new mobility structures in a macro-economic context is recommended, taking into consideration new transport **service business models** as well as new production chains for transport equipment production. The latter could be facilitated by a **value chain mapping of automotive supply chains and the EU vehicle manufacturing industry**, including hydrogen supply chains and battery R&D. This could ultimately serve to develop an advanced production line for battery and car manufacturing. R&I could be dedicated, for instance, to the development of modular battery storage packages, suitable both for EV and for stationary storage. Given the deployment of new transport technologies and equipment manufacturing in Europe an **assessment of the international raw material availability** would be needed, including the investigation of material streams under global climate change mitigation efforts in order to ensure globally sustainable production cycles.

- From a macro-economic perspective, research **on employment effects associated with the transformation of the transport system** should receive more attention and should also consider changes in the labour market resulting from increasing digitalisation and automation (e.g. autonomous vehicles) of mobility.

R&I on policy measures should complement the other three R&I areas to develop effective mechanisms and instruments to enable development of intellectual property, commercialisation and thus realisation of low-carbon transport structures. Possible specific topics and criteria for policy-related research comprise the following:

- How to improve and implement comprehensive **urban policy packages** (including urban planning, congestion taxing, public transport provision and many more) that transform urban spaces and urban transport, with a focus on increasing public health and well-being while reducing CO_2 emissions.

- Research on full internalisation of all transport-related externalities as well as synergies and conflicts in air pollution policies and CO_2 mitigation.

- Analysis of **effective measures to reduce air travel and shipping demand** (carbon accounting policies, carbon emission quotas for airlines, campaigns to promote alternative transport modes): This closely links to the questions of consumer behaviour and new business models for air-transport and shipping companies to enable a shift from aviation and sea-born transport to (high-speed) rail where feasible. In addition, research and innovative regulatory measures should be investigated to promote a modal shift of freight transport from road to waterways within and across the European countries.

- Assessing and designing the policy landscape with a technology neutral approach, correcting counterproductive existing policies (e.g. fuel subsidies, incentives for commuting; 'flat tax' for highway use instead of 'pay per demand') and avoiding discrimination between particular powertrains and energy carriers.

- Research on the re-configuration of the taxation scheme and fiscal and capital market implications as the transport sector shifts from an energy-intensive towards a capital-intensive market when deep decarbonisation is pursued.

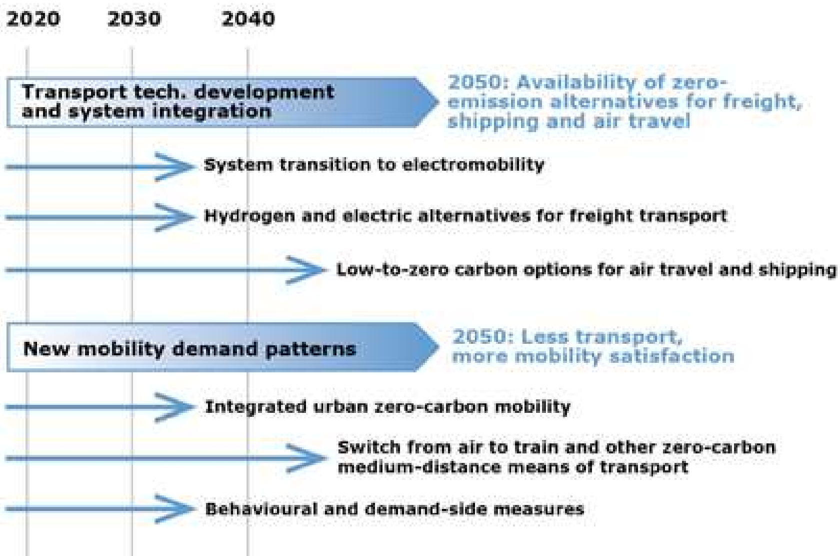

Figure 9: Possible R&I roadmap towards a decarbonised transport sector.

CHAPTER 4

INDUSTRIES: TACKLING PROCESS EMISSIONS, INCREASING ENERGY AND MATERIALS EFFICIENCY AND HARVESTING DIGITALISATION FOR DECARBONISATION

1 Introduction and context

According to the UNFCCC inventory, in 2016, industry represented 21 % of the EU's total GHG emissions, of which slightly more than half came from direct fuel combustion and the rest from industrial processes and product use. In addition, electricity consumption in European industries accounts for 36 % of total consumption, indicating the sector's high indirect emissions. European business and industry are making steady progress towards decarbonisation, with direct GHG emissions in 2016 falling by 38 % from 1990 levels, due in particular to reductions in fossil fuel consumption in energy-intensive industries. Industrial energy management systems, participation in the EU ETS framework and the adoption of new, advanced technologies have all contributed to the sector's emission reductions. Furthermore, decarbonisation of the energy sector is contributing to lowering the indirect emissions of the European industrial sector. Overall, such improvements cannot be attributed simply to the delocalisation of production to non-European countries.

Novel lower-carbon production technologies, fuel switching, and material and energy efficiency improvements are contributing significantly to the downward trend in emissions. Indeed, European companies are exploring business opportunities for low-carbon investments, while capitalising on the technological trends shaping their industries, such as digitalisation (e.g. Internet of Things (IoT), cloud computing), energy storage, automation (e.g. robotics and artificial intelligence), advanced materials, and more. Among these firms are several prominent European companies across a range of diverse sectors. For instance[14], car manufacturers such as BMW are leveraging new technologies, including vehicle electrification, new lightweight materials, renewable energy, material reuse and mobility-as-a-service. Logistics companies such as Deutsche Post DHL Group are deploying cleaner vehicles across their fleet and embracing digitalisation to better plan and improve process efficiency. Energy companies like Engie are seeing digitalisation (e.g. smart grids) across hardware, software and infrastructure across Europe as the driver for change in their sector. Private investment firms such as SUSI Partners or the Green Investment Bank are providing green financing for renewable energy, energy efficiency and energy storage projects.

However, current mitigation efforts in the industrial sector need to be accelerated to first achieve compliance with the Paris Agreement and then to bring European industries to carbon neutrality. As indicated in the Roadmap to 2050 (European Commission, 2011), almost 25 % of the remaining emissions of the decarbonisation scenario in 2050 come from the industry sector. Obviously, this poses important challenges for industrial sectors in

[14] For the four examples mentioned in the text we acknowledge and are grateful for the participation of top officials from these companies in the HLP discussion session dedicated to industry.

general, and for energy-intensive industries in particular. While the trend in the reduction of industrial emissions is moving in the right direction, it is falling much shorter than it should if it is to be in line with the Paris Agreement. Furthermore, decarbonisation challenges need to be pursued not in a vacuum, but rather together with other SDGs. The issue of industry decarbonisation is complicated by the fact that companies operate in an environment that is characterised by disruptions and pervasive uncertainty, as well as by the need to enhance European competitiveness, employment and economic growth. Furthermore, businesses currently face the challenge of operating in a post-crisis environment, in which investors are becoming more risk-averse. In this context, the business cases for investment in energy efficiency have limited attractiveness. Notwithstanding the significant differences among the many industrial sectors, investments in energy efficiency tend to be less appealing than core process investments for European companies since they are characterised by longer payback periods.

Yet, the deep decarbonisation challenge for European industrial sectors can be turned into an unprecedented opportunity if existing green technologies are more consistently deployed and R&I investments are strategically targeted towards the development of breakthrough, zero-carbon industrial technologies and business models. The development of a circular economy can be harnessed to transform the way in which we make, source and consume products and services. Examples of circular design, use and recovery include businesses such as product and process design, tracking facilities, support for life cycle, sell and buy-back, lifetime extension, product as a service (based on delivering performance rather than selling products) and sharing platforms (Carra and Magdani, 2016). In this respect, both public R&I programmes and policy play a key role as they cannot only focus business and industry on decarbonisation but must also consider solutions that allow for deep decarbonisation while enabling employment, prosperity and stability through growth. To this end, even European energy-intensive industries can benefit from the market expansion of products that enable emission reductions, such as insulation materials, efficient lighting and lightweight materials. This is a prize many businesses are positioning themselves for, with the aim of promoting export from and growth in Europe.

Employment in eco-industries has increased by 20 % in Europe since 2000 and now provides 4.2 million jobs (European Commission, 2017a). The link between green growth and business opportunities or job creation can be illustrated by the case of the Netherlands. Using expert judgement on future trends in resource prices, and an increase in reuse, collection, and recycling of products and waste, it has been estimated that the circular economy can create an additional value of 1.4 % of GDP a year corresponding to 54 000 new jobs – or 0.6 % of overall employment (TNO, 2013). Similarly, the EU bioeconomy has great potential: in 2010, it had a turnover of nearly EUR 2 trillion and employed more than 22 million people, corresponding to 9 % of total EU employment (European Commission, 2012). Green production/products can also be a springboard for EU economic competitiveness. Despite the overall trend of the growing presence of emerging economies, most notably in China, in the global market of clean energy technologies, Europe has maintained large shares in specific technologies, such as wind turbines, and has the potential to dominate in others. Nevertheless, European R&I initiatives must accelerate urgently in order to enable gains from first-mover advantages as EU competitors are already increasing their R&I expenditure significantly (Paroussos et al., 2017).

For example, while battery packs for electric cars are largely imported from Asia, thereby limiting the value-added Europe can get from the deployment of electric cars and electricity storage, a positive prospective can be developed as new battery and component plants are announced in Europe.

A noteworthy aspect of the decarbonisation of European industrial sectors is gaining the support of both employers and workers through the development of educational formats as well as best practices. The Paris Agreement includes a commitment to the 'imperative of just transition', because governments acknowledge that the transition to a low-carbon economy will only go fast enough when the world of work – employers and workers – is behind it. Similarly, unless the actions to deliver the Paris Agreement also deliver social benefits that leave no one behind, it is unlikely to gain the public support necessary to urgently mobilise. High on the European business agenda is the concept of the 'future of work'. In this respect, it is crucial to highlight that future profitability and employment will be impacted not only by structural changes from climate action in Europe, but also from other technology and disrupting societal developments, which include automation, digitalisation and artificial intelligence. All of these aspects should be appropriately accounted for in future decarbonisation strategies.

Business-enhancing decarbonisation should be promoted through a well-rounded, fact-based and effective strategy addressing the short-, medium- and long-term challenges faced by the European industrial sectors. Decarbonisation objectives should be drafted, including considerations on future global markets, and should be deeply embedded in European industrial policy. Another very relevant issue for European businesses is to assess the economic opportunities emerging from tackling the dual challenges of Paris and the SDGs. A 2014 McKinsey study (McKinsey, 2014) found that 44 % of business leaders of organisations with a strong sustainability focus on their corporate social responsibility strategy cite growth and new business opportunities as reasons for tackling sustainability challenges. In addition, the adoption of advanced processes and technologies enables long-term cost-savings by industries and improvements in energy security and trade balances through reduced imports of fossil fuels at the EU level. Innovation is a key enabler.

The EU should structure R&I actions for the decarbonisation of industrial sectors around four key pillars: energy efficiency and material savings, deep electrification, embedding industrial processes in the circular economy, and innovation in zero-carbon breakthroughs for process-based emissions industries. These priorities, which are discussed in detail below, represent a more ambitious plan than that described in the recently released report highlighting the joint contribution from 11 European Energy Intensive Industries (EIIs) to the European Commission's strategy for long-term EU greenhouse gas emissions reductions (Institute of European Studies, 2018). Indeed, we believe that it is necessary to raise the bar in terms of innovation efforts to sustain the energy transition in the industrial sector. We believe that industrial sectors need to be deeply engaged in all phases of the innovation process, promoting the deployment and diffusion of new technologies leading to carbon neutrality. Only in this way can we ensure that European industry can reap all the co-benefits associated with such a deep structural transition and avoid being locked into technologies which, in the long term, may not be fully aligned with the deep decarbonisation target.

Specifically, in the short term, two objectives should be pursued: increased energy efficiency through the deployment of already available low-carbon technologies, and the deep electrification of industrial processes. Electrification will contribute to lowering emissions insofar as the electricity is produced using a zero-carbon energy source. Important energy savings can result from the deployment of a wide range of existing technologies, while continuous R&I can further improve energy and carbon efficiency and reduce capital costs and the respective payback period. Examples of such commercially available technologies and processes include waste-heat recovery, coke-dry quenching, combustion system improvements and more. Such short-term strategies should target not only major industrial firms, but also the many and diverse SMEs in Europe that carry out 20 % of total R&I (IEA, 2015). SMEs typically have larger reduction potential than the large energy-intensive companies (Saygin et al., 2010). This potential can be approximated with generic efficiency improvements, such as efficiency and decarbonising power and heat.

In the medium term, industrial processes must be deeply embedded in the circular economy, namely in the slowing, closing and narrowing of material and energy loops. This will have to be achieved through, for instance, long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, recycling and upcycling. Putting emphasis not only on the supply side (e.g. efficient processes) but also on the demand side (e.g. for raw materials), by extending product lifetime can actually reduce industrial emissions by almost 56 % by 2050 (Material Economics, 2018). Supply-chain redesign, waste-to-energy, circular business models, reduction of waste and recirculation of materials are all essential parts of the roadmap towards carbon neutrality in the difficult-to-decarbonise sector of heavy industries. Innovation is a key enabler of moving towards a cost-efficient circular economy, making IT, microsensors, automation, robotics and chemical catalysts components of everyday production processes. Circular economy R&I priorities should be firmly incorporated in the low-carbon agenda.

In the longer term, breakthrough zero-carbon industrial technologies need to enter the market. These should be promoted and fostered through concerted, long-term R&I public and private investments as well as higher CO_2 prices. This is particularly relevant for process-based industries, such as chemistry, steel and cement, which face particularly hard challenges with respect to decarbonisation, as cost-efficient, near-zero-carbon technological options and processes are currently not available on the market. A promising development in this respect is the use of green hydrogen in steelmaking, ammonia production and refining. Specific R&I programmes need to be designed to target the development of disruptive technologies which can decouple production from process emissions in energy-intensive sectors.

2 Priority 1: Energy efficiency and material savings

Although a wide range of low- and zero-carbon technology options are currently available for industry, many have yet to be sufficiently deployed. This is clearly demonstrated by the McKinsey abatement cost curve analysis (McKinsey, 2009; Figure 10) which shows a range of technologies with negative abatement costs that can simultaneously bring both emission and cost savings. Examples include efficient lighting, motor systems efficiency and clinker substitution by fly ash. To better understand the priorities, the abatement curve should be updated and elaborated on specifically for Europe. As an example, the IEA (2013) finds that in the short to medium term (to 2025), steady progress in implementing incremental improvements (e.g. best available technology, BAT) and deploying best practice techniques (BPT) could provide substantial energy savings and emissions reductions in the chemical industry compared to business as usual practice (IEA, 2013). Improvements in efficiency across several types of industries can be achieved by greater electrical equipment and the implementation of captive cogeneration units. Certain commercially available technologies, like advanced-process control in the petrochemical industries and immersion cooling, also present a quick payback period. Low-carbon technologies — including the deployment of bio-based chemical facilities and improved performance of catalysts and related process technologies — can also reduce emissions. To summarise, although the potential to reduce energy, cost and emissions is vast, the available technologies have yet to be fully employed.

Many of these technologies have not yet reached significant levels of market penetration due to a large number of market and non-market barriers. These include access to finance, awareness of benefits, long-term policy frameworks, and volatile energy prices. For instance, in many cases, the initial investment can be a barrier even if the life-cycle costs are reduced, as requested payback periods can range between one to three years. This is particularly the case for SMEs which face difficulties in accessing financial resources and have limited in-house skills and expertise to identify opportunities and available techniques.

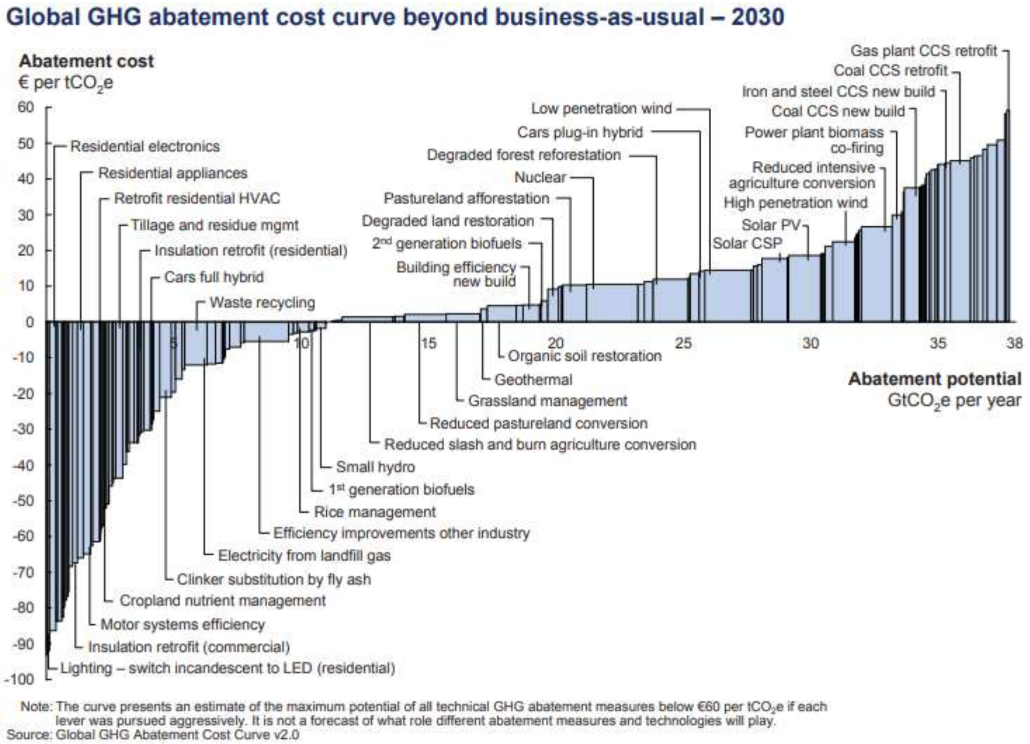

Figure 10: McKinsey abatement cost curve. Source: McKinsey, 2009.

R&I programmes need to identify such barriers for the industrial sectors and devise effective ways to overcome them. Properly designed R&I can help overcome barriers linked with, among others, misleading perceptions (including costs and benefits, but also safety), the development of proper skills, the design of new business models, and cost reductions in existing technologies that will enable lower payback periods. Technology maturity is another barrier which can be overcome by providing funding for demonstration projects and reducing risk aversion from management. Finally, R&I programmes will help to shrink the knowledge gap, which is linked to assessing the extent to which commercial claims regarding efficiency improvements are true. Here, it is important that the EU provides unbiased assessments of the performance of certain low-carbon and energy-efficient technologies.

R&I programmes can also help address issues linked to strategic and financing constraints. Policies which increase the predictability of long-term cash flows (e.g. delinking low-carbon energy prices from volatile fossil-fuel markets) will spur more rapid deployment and reduce prices for energy consumers. However, additional efforts will be required on de-risking, e.g. to make up for the incompatibility of the venture capital (VC) mode of operation with innovation in deep tech which requires patient capital. Corporate tax structures that affect the depreciation period of investments may be a disincentive to replace existing equipment and are an additional area for research. Furthermore, innovative financing mechanisms, including green bonds and energy-performance contracting schemes, can address existing market failures. The effectiveness of other types of incentives, such as accelerated depreciation on R&D assets, R&D tax relief, and patent-related incentives, should also be explored.

SMEs, which account for the majority of the European economy's productive activity, also face significant barriers to the development and deployment of low- and zero-carbon solutions[15]. For SMEs, equally important to VC funds are traditional R&D investments, such as the H2020 programme, and supporting the establishment of centres of expertise (eco-systems) for taking these innovations to the market. As shown in its interim evaluation (European Commission, 2017b), the H2020 programme has already gone a long way in improving access to finance for innovative SMEs. Simplification has also progressed, but efforts need to be continued.

R&I is also needed for continuously improving the energy efficiency of existing production processes as well as exploring lower carbon energy pathways. This is not limited to energy intensive sectors. Many technologies are available today, but the potential for cost reduction remains, enabling more companies to adopt them. R&I programmes should be geared towards cost reduction, improving performance and reliability of close-to-market decarbonisation technologies in order to scale up their deployment. Advanced analytics and other energy management enabling technologies should also be a key priority. High-efficiency motors reducing energy demand, as well as dependence on rare-earth metals, innovative pumps and compressors, pre-heating and drying processes are also constantly developing and can reap cost benefits from dedicated R&I. Other priorities for short-term cost reductions include condensing heat exchangers, electric arc furnaces, and more. This requires an update of the abatement curve to inform policymakers as to which are the most promising technologies.

In this context, there is large scope for supporting public policies, including but not limited to R&I investments. In this respect, resources should be devoted to the study and design of policy measures, such as, for instance, a framework ensuring a long-term high CO_2 price that will support decarbonisation in industry. Research into the potential, efficiency, costs and impacts of industry decarbonisation policies should be continued. Particular attention should be paid to issues such as strengthening the ETS and complementary policies to make the CO_2 price more stable and higher, but also to financial instruments facilitating industry to move capital at scale. Other market-based mechanisms, such as white certificates, can also be assessed as they can target energy savings directly. Accounting/fiscal rules to support investments in energy efficiency (off-balance sheet vehicles) should be implemented, and support provided for basic research and capital-intensive developments in sectors of strategic importance for Europe (e.g. artificial intelligence). The comparative effectiveness of incentives such as cash grants, low interest loans, tax allowances and tax exemptions could be further investigated.

Support is needed for public-private partnerships in innovation hubs for testing, prototyping and demonstrating these high TRL (4-7) decarbonisation technologies. As described by the IEA (2018), there are many examples of innovative technologies at the pre-launch stage for all energy-intensive industries. To name but a few, top gas recovery blast furnace

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[15] All but 0.2 % of enterprises which operated in the EU-28 non-financial business sector in 2016 were SMEs. They employed 93 million people, accounting for 67 % of total employment in the EU-28 non-financial business sector, and generating 57 % of value added in the EU-28 non-financial business sector. Almost all (93 %) of the SMEs were micro SMEs employing less than 10 people (European Commission, 2017a).

and advanced smelting production processes are close to commercialisation in the steel sector, advanced grinding technologies in cement production, and black liquor gasification in the paper sector.

3 Priority 2: A programme of deep electrification of industrial processes

The second, short-term step towards successful decarbonisation requires a radical transformation of some European industrial sectors where it is possible to convert some of the energy input for processes to electricity use. Given the large decarbonisation which will characterise the energy sector, the electrification of industrial processes will ultimately substitute on-site fossil-fuel combustion with zero-carbon electricity. Advanced system and process innovation can deliver high levels of electrification substituting carbon-intensive, heat-related demand. Hence, electrification needs to be the focus of immediate action and should be developed in line with plans for a wider energy system in Europe. Large-scale opportunities can offer long-term solutions to sectors which are difficult to abate, such as hydrogen use through electrolysis to replace coke in the iron and steel industry, and as feedstock in the chemical industry.

Electrification would significantly reduce emission reductions in 'classical' sectors like steelmaking with electric furnaces. Indeed, one of the key challenges for energy-intensive industries concerns heat-related processes such as, for instance, clinker processing of Portland cement in cement kilns. Power-to-heat can provide solutions for both high- and low-enthalpy process heat (e.g. electric arc furnaces and plasma heating, respectively), while existing technologies like heat pumps can be used for the thermal upgrade of ambient and waste heat. Compared to conventional heating, power-to-heat can substantially reduce final energy demand, and R&I efforts can further improve these efficiency rates. Beyond energy savings, these processes can also improve overall process efficiency (e.g. through time-saving), production costs and working conditions (e.g. through secure, automated processes). A wide variety of technologies are now in early or more mature technological stages, and are applicable to most industrial sectors, from food and textiles industries to metal and equipment products.

The fact that such a large proportion of industrial GHG emissions come from heat and power production where clean alternatives are currently available indicates the importance of R&I as well as deployment investment which would enable the provision of these carbon-free solutions at competitive costs. Indeed, the reduction in costs of solar and wind power in particular have driven the EU's declining carbon footprint and can be expected to continue to be key drivers for industry, too. Biomass energy is another important source of process heat for industry. Conversely, the costs of carbon capture and storage (CCS), which is another technological option, remain uncertain and application/site specific (Global CCS Institute, 2017). A significant drawback to CCS technology is the reduction of the overall efficiency of the process and the associated increase in energy demand. While early CCS value chains are unlikely to be economical without public support, the prospects for more efficient CO_2 capture and transport networks is a goal that some EU Member States are actively supporting (Global CCS Institute, 2017b). In contrast to many other mitigation technologies, CCS is completely dependent on the price of carbon. As such, early investments that can help bring down the cost of capture will depend on

CO_2 use and R&I investment in applications where the CO_2 is embedded over the long term, such as mineralisation, should be incentivised.

R&I programmes should focus on promoting the further electrification of heat-related industrial processes in order to make use of low-carbon electricity. Power-to-heat technologies, electromagnetic radiation, electric boilers, mechanical vapour recompression, and clean hydrogen for metal and chemical production are examples of close-to-commercialisation or already mature but expensive technologies with large emission abatement potentials, while pilot options for electrification in industry, such as power for separation and replacement of steam drive with mechanical ones, are expanding rapidly. Large sectors which have started such a large-scale conversion already exist in countries where carbon-free electricity is available, like Norway, which is characterised by a significant penetration of hydropower.

4 Priority 3: Embedding industrial processes in the circular economy

In the medium-term, energy efficiency improvements, materials savings and electrification should be part of a broader, longer-term strategy of embedding industrial processes in the circular economy. The medium-/long-term strategy should aim at developing economies which are both 'circular' (closed-loop supply chains and resource-efficient business models) and based on 'sharing' (more efficient ownership models of assets) (Energy Transitions Commission, 2017). The existing stock of materials can be recapitalised, waste can be used as a resource, while business models can optimise material use and find new ways of sharing existing resources. Material recirculation, increasing materials efficiency and sharing business models have been found to have an impressive potential for emission reductions while related important economic co-benefits remain untapped. To this end, the redesign of products and processes that are in line with win/win circular principles can and should be applied more broadly.

This vision implies that most material fluxes currently supporting the economy are converted from linear processes into closed loops. Material recirculation implies very high recycling rates, allowing for only a small input of new materials in the entire industrial metabolism to replace degraded or lost materials. For example, if downgrading and contaminating steel with other metals is avoided, almost 85 % of European steel demand could be met by secondary production, thereby minimising the demand for raw materials and emissions adjacent to the energy-intensive steelmaking process (Material Economics, 2018). Another example refers to construction, where adopting a whole life-cycle approach and working collaboratively from design along the entire construction value chain offers additional opportunities for carbon emission reductions beyond the cement manufacturing boundary. Optimising the use of concrete in construction by reducing waste, encouraging reuse and recycling, maximising design life and increasing co-working spaces and the overall utilisation rates of the buildings stock are key strategies in this area (IEA and CSI, 2018). The public sector should also lead the way through public procurement design that promotes circular processes.

R&I programmes should be geared towards circular and biobased feedstocks in industry. R&I is a fundamental pillar of the regenerative and restorative production and consumption process envisaged in the circular economy paradigm. Nevertheless, to date, efforts have been allocated more towards the decarbonisation of the supply side or energy efficiency and not to reducing the demand for materials. R&I will enable this systemic change by providing solutions for new processes, business structures, policy and financial schemes. For instance, this is the case for R&I efforts on biobased raw materials in the chemical sector, which need to be continued and increased to enable the transition to sustainable chemistry. Furthermore, attention should be devoted to reducing the production costs of low-carbon chemical building blocks which are high compared to those for fossil-fuel feedstocks.

Industrial sectors should prioritise research into product design targeted at waste minimisation, longer lifespans and recyclable materials. The EU can support these efforts through investment in R&I to promote the harmonisation of waste management and processes and by framing a harmonised, ambitious and effective policy framework for waste management. In this context, the construction industry should make strong efforts to reduce consumption of resources and materials. For example, the construction and operation of the built environment consumes 60 % of all materials in the UK, and construction and demolition waste account for over a quarter of all waste created in the EU (Carra & Magdani, 2016). Therefore, R&I investments in urban design and optimisation of the built environment are critical to reduce GHG emissions, given that cities consume three quarters of global primary energy and the same percentage of the world's production of natural resources. R&I programmes for advancing the circular economy should particularly target sectors such as buildings, plastics, electronic equipment, steel production, food and water management, and sharing economies. These efforts can benefit substantially from the further development of IT tools such as common platforms (aka material market places) (WBCSD, 2018).

R&I programmes should also focus on industrial clustering and industrial symbiosis. Industrial waste-heat recovery is a key technology in clustering. Recent developments in heat networks show a shift to multiple source, multiple user heat networks. As numerous potential studies have been carried out on heat networks, R&I funding should be directed to demonstration pilots, demos and facilities. R&I in industrial clustering should also focus on renewable hydrogen production, storage and use. Another industrial cluster proposal put forward by the EU Fuel Cells and Hydrogen Joint Undertaking (FCH JU) relates to the concept of hydrogen valleys. These are industrial clusters where hydrogen supply chains are developed with the aim of supporting the regional or local economy. This is built around sector coupling which links hydrogen production to the energy, heating and transport sectors and is a key concept in decarbonisation of the economy (EPS, 2018).

Further R&I efforts can include the development of carbon capture and utilisation (CCU) technologies that may constitute an additional dimension to the concept of a circular economy. CCU can provide the chemical and plastics industry with solutions to permanently store CO_2 emissions by using captured emissions as a feedstock for polymers and other chemicals or by trapping carbon in cement. R&I can improve the techno-economic performance of CCU and can also derive new ways of using carbon as input to several production processes outside of current practices, ensuring that the carbon is stored permanently and that the processes do not result in a lock-in in fossil-fuel-based technologies.

5 Priority 4: Targeting zero-carbon breakthroughs in process-based emission industries

Process-based industries such as chemistry, steel and cement face particularly hard challenges with respect to decarbonisation, as cost-efficient, near-zero-carbon technological options and processes are currently not available on the market. In these sectors, it will not be possible to reach net-zero emissions without further R&I in breakthrough technologies and processes because the emission reductions necessary to achieve deep decarbonisation and zero-carbon production far exceed the capacity of current BAT. Achieving successful deep decarbonisation means that by 2050, even the energy-intensive industries of cement and steel will have to be carbon neutral. Similarly, all plastics should be renewable and sustainable. To ensure the competitiveness of European industries, the same targets should apply on a global scale.

Specific R&I programmes need to be designed to target the development of disruptive technologies which can decouple production from process emissions in energy-intensive sectors. For instance, renewable hydrogen use, production, conversion, distribution and storage are likely to be game changers in many industrial heat-related processes, in addition to the impact they can have in the transport and power sectors. Low-carbon and green hydrogen can be a key energy carrier which could replace the combustion of natural gas and use of coke in many industrial processes, with potentially minimal GHG emissions. R&I funds should be directed, in particular, at improving green hydrogen production technologies (including new materials and catalysts as well as new processes) and methods (e.g. plasma methods), finding more efficient hydrogen carriers (e.g. solid storage, liquid hydrogen organic compounds) and materials that will enable tanks to store hydrogen at higher pressures (e.g. composites). The potential of hydrogen storage to improve the energy security of the European energy market should be investigated, as should the role of batteries. Similarly, power-to-gas and gas-to-power technologies should be built into whole energy system models to understand the flexibility, resilience, energy security and societal benefits that hydrogen, synthetic gases and renewable power can provide to different industries.

R&I programmes should promote low-carbon and zero-carbon innovation by SMEs. The future energy and industrial systems required in Europe will need to draw on R&I by SMEs. SMEs should be seen as integral contributors to concepts such as Mazzucato's 'Mission-driven innovation' or the approach of open innovation, open science, open to the world (European Commission, 2016). Many of the critical future breakthrough technologies will be developed and utilised by these companies. To boost innovative start-up and scale-up across Europe, the European Commission and the European Investment Fund (EIF) have launched a pan-European Venture Capital Fund-of-Funds programme (VentureEU) with an investment of EUR 2.1 billion in 2018-2020, expected to trigger an estimated EUR 6.5 billion of new investment (European Commission, 2018a). SMEs are adopters and providers of (innovative) decarbonisation solutions as well as creators of economic growth, jobs, and European industrial leadership. They hold the potential for disruptive innovation, both creating new solutions and even completely new markets (blue ocean vs. red ocean, Kim and Mauborgne, 2017). Identifying high-growth start-ups ('unicorns') is a worthy challenge, although not sufficient in itself.

Appropriate support for scaling high-growth business and, very importantly, retaining the value creation in Europe requires a broad suite of tools, around markets (harmonised European Single Market as a means to compete with much larger markets, e.g. in the USA or China), finance (Capital Markets Union), but also skills and, of course, technology innovation.

Public-private partnerships (PPPs) in the early stages of R&I, and specifically in the development of breakthroughs in reducing process emissions, should be promoted. PPPs are an effective and efficient policy mechanism to increase the involvement of industry in R&I and address more effectively the complex challenge of eliminating process-based emissions, market failures, and accelerating the time-to-market of innovations (de Heide et al., 2016). Many countries in Europe have seen an increase in more strategic, long-term, large-scale and multi-disciplinary PPPs (OECD, 2014)[16]. PPPs are mostly relevant in the pre-competitive stage of innovation, and in helping industry to cross the technological and commercialisation 'valleys of death' (de Heide, 2016). PPPs trigger innovation by firms, as they address the willingness of a company to invest in research activities by providing access to expensive research infrastructure and expertise, access to know-how and networks, thereby increasing an innovation project's probability of success, as well as further insight into the potential impact of the innovation process on a company's result. PPPs require a complex financing structure, which depends on the stage of development and activities. The funding mix can include EU funding (H2020, European Regional and Development Fund, European Institute of Innovation and Technology), national and regional funding (e.g. innovation vouchers, R&D tax, subsidies, grants) as well as private funding (e.g. VC, angel investment, loans). While PPPs require long-term public funding, as the partnership develops public funding will need to be phased out, with private investments and contractual research taking over. Critically, PPPs use public funds to leverage private investment and enable scaling-up technologies to first-of-its-kind application and proving replicability.

Long-term zero-carbon technology development needs to be fostered alongside strategies for decarbonisation through digitalisation. By 2025, Industry 4.0 will have become business as usual, harnessing digitalisation and artificial intelligence to drive efficiency and decarbonisation. European industry has the capability of playing a leading role at the global level in Industry 4.0. The potential for emission reductions through implementation of solutions such as mobile connectivity, IoT, cloud computing, and automation have not yet been fully assessed, but indications are that there is great potential depending on the policies in place to guide deployment. For example, the Global e-Sustainability Initiative (GeSI) estimates that mobile communications technology is currently enabling a total reduction of 180 million tonnes of CO_{2}-eq per annum across the USA and Europe (GeSI, 2015). This amount is greater than the annual carbon emissions from the Netherlands and equivalent to 1.5 % of all GHG emissions from the USA and Europe. Equally applicable to the industrial sectors is the use of cutting-edge sensors, additive manufacturing (e.g. 3D-printing, rapid prototyping), data processing and analytics to bring

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[16] Examples of PPPs include the Dutch Joint Innovation Centres, Field Labs and Top Sector approach, the Catapult Centres in the UK, the Centres of Competence in the Czech Republic, etc. The Digital Innovation Hubs, which act as a one-stop shop by offering businesses access to knowledge, methods and software, technology platforms and testing facilities, are an interesting example at the EU level.

production into the digital age and enable further optimisation and efficiency. The European Commission already invests significantly in the digitalisation of industry through the Factories of the Future programme, which was established in 2008 under the European Economic Recovery Plan. Such efforts should be grounded in the broader deep decarbonisation strategy for Europe. The impact of Industry 4.0 on the labour market still needs to be fully understood to ascertain that all dimensions of sustainability are satisfied. Within this, the EU should intensify its efforts to foster the development of a European clean-tech ecosystem and topic-specific ‘clean-tech Silicon Valleys’ (e.g. around power electronics). The establishment of a leading European research cluster on artificial intelligence for basic research and applications should be considered. Such cluster should be developed in the form of a network between existing actors and capabilities currently working on future innovations. This should also serve as the basis for the fruitful exchange of lessons learned.

In this long-term framework, supporting policies needs to be put in place, above and beyond R&I programmes. In this respect, policy research to identify the most efficient policy instruments to support the uptake of innovative industrial technologies is of paramount relevance. Public policy must ensure that businesses face effective economic mechanisms, such as robust and meaningful carbon pricing, removal of fossil-fuel subsidies, and provision of additional sources of climate solution funding. Credible and reliable regulatory and market signals and incentives give business the confidence to invest. Furthermore, the internalisation of externalities could improve the business case for lower carbon technologies in industry. In addition to carbon pricing, other crucial public policy levers include, for instance, market redesign and pricing mechanisms, especially in the power market performance standards and other regulations, within the frame allowed by state aid rules; continued implementation of performance standards and other regulations to drive greater energy efficiency; transport systems and urban planning which make it possible to grow GDP rapidly while limiting the growth of energy-based services; and integrated energy system planning to ensure adequate coordination across a diversity of sectors (e.g. enabling much greater use of electricity across multiple sectors).

Innovative funding mechanisms can also contribute to achieving economies of scale which, in the long run, will make innovations cost-competitive with incumbent alternatives. Public effort should be devoted to supporting the development of financial instruments to move capital at scale (e.g. Clean Energy Investment Trust); adapt accounting/fiscal rules to support investments in energy efficiency for both public and private entities (e.g. off-balance sheet vehicles); use EU procurement guidelines to drive decarbonisation (e.g. minimum efficiency standards or public innovative procurement); closely monitor the implementation of the ETS reform and the resulting rise in the carbon price. Continuous de-risking of investment opportunities could also serve as a framing concept for public policy. In this respect, several methods, such as blended finance as well as portfolio management aspects, should be considered. Existing initiatives to build upon/leverage could be the InnovFin financial products provided by the European Investment Bank (EIB), the SME instrument, or the Pilot Action on disruptive innovation in clean energy technologies (European Commission, 2017c).

6 Recommendations for research and innovation

Europe must speed up the deployment of existing solutions. R&I can pave the way to identifying and overcoming non-technological barriers to the large-scale deployment of market-ready low- and zero-carbon technologies. As the abatement curve shows (Figure 10), although many low-carbon technologies are available even at negative costs, this potential remains untapped and has yet to be identified or implemented by most European industries. This means that more R&I funding must be directed to commercial pilots and demonstration plants to validate technologies at the industrial scale and raise the awareness of European businesses. SMEs have an important role to play, which will be enabled when new energy management and financing solutions emerge. Public-private shared R&I programmes for technologies close to market introduction are of vital importance.

Deep electrification of the EU industrial sectors should be promoted in order to substitute on-site fossil-fuel combustion with demand for clean power, particularly in the difficult-to-abate energy-intensive industries. R&I programmes focused on promoting the further electrification of heat-related industrial processes can increase the benefits associated with producing electricity from renewable sources. Advanced system and process innovation can deliver high levels of electrification, while large-scale solutions, such as 'clean hydrogen', deliver more options for increased electrification.

In the longer-term, energy efficiency and electrification processes should be aligned with the development of a circular economy. Circular and shared production and consumption models have large emission-reduction potentials. R&I should focus on providing the business models, technologies and processes that will enable this systemic change.

In those sectors where incumbent technologies have reduced opportunities for improving energy efficiency, R&I should focus on technological breakthroughs. In particular, renewable hydrogen and CCS breakthroughs are needed to bring the costs of these technologies to acceptable investment levels. R&I actions are also needed in particular for disruptive technologies, such as digitalisation, artificial intelligence and energy storage for energy-intensive production industries, as mentioned previously.

Potentially disruptive technologies must be harnessed to advance decarbonisation efforts and strategically position Europe in the global markets. The economic potential of these technologies can be translated into substantial growth and prosperity for Europe. Figure 11 illustrates the R&I roadmap for decarbonisation of different industries in the period up to 2050.

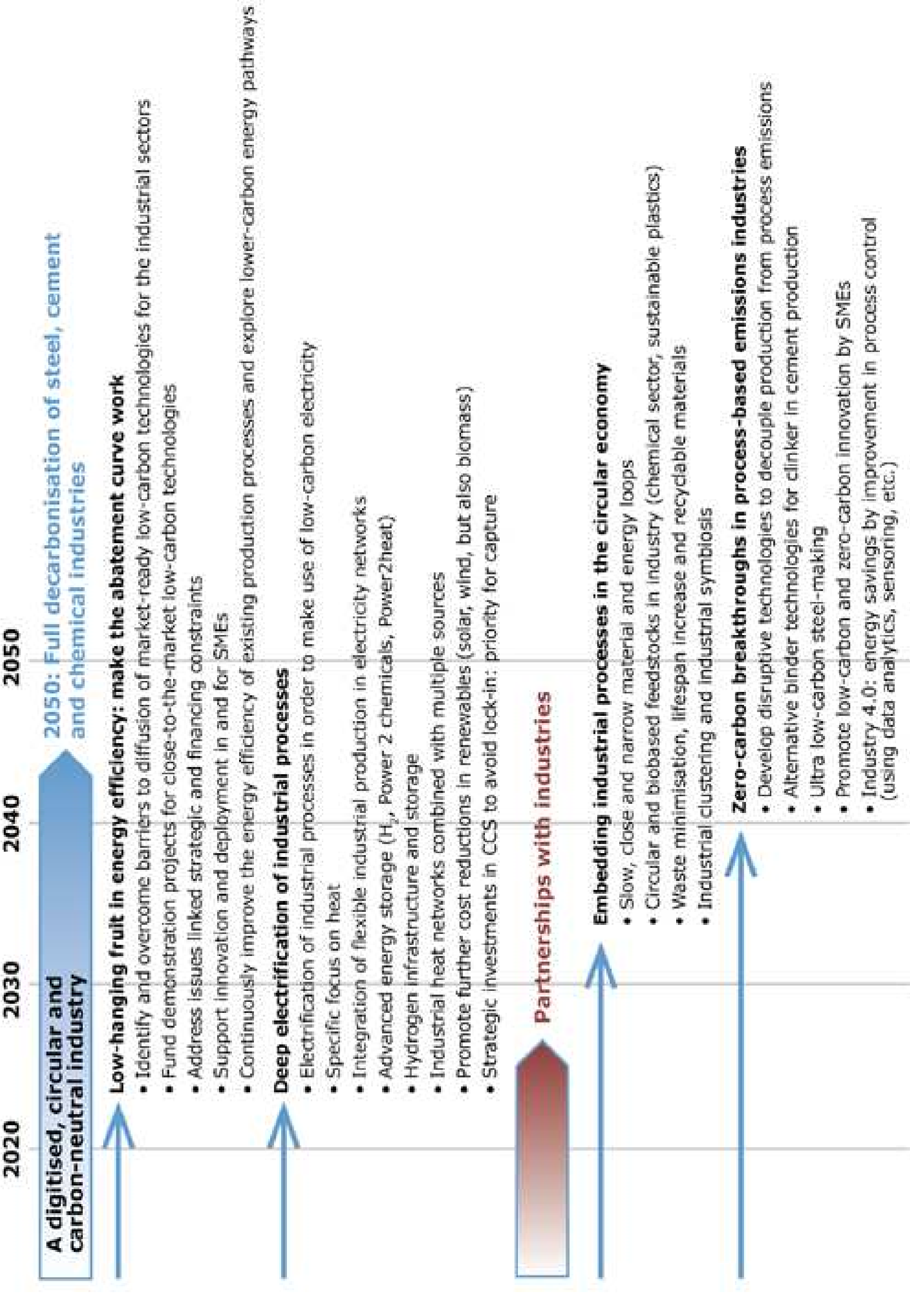

Figure 11: Possible R&I roadmap towards a decarbonised industry sector.

CHAPTER 5

A CIRCULAR APPROACH TO AGRICULTURE, LAND USE AND THE BIOECONOMY: AN OPPORTUNITY TO RESTORE SOIL FERTILITY AND DECARBONISE THE ECONOMY

1 Introduction

The agriculture, forestry and other land use sectors, collectively known as the AFOLU sector, are responsible for just under a quarter (~10–12GtCO_2-eq/y) of global GHG emissions. Europe is the world's fourth largest emitter of GHGs from agriculture and its overall contribution amounts to approximately 12 % of global sectoral emissions. In Europe, agriculture accounts for about 10 % of overall GHG emissions and in absolute terms emits 464 million of metric tonnes of CO_2-eq, coming mainly from non-CO_2 emissions (methane and nitrous oxide — N_2O).

Agriculture and land use have a key role in the decarbonisation effort. Recent analyses of EU-28 decarbonisation pathways indicate that, after 2050, non-CO_2 emissions would constitute a large share of the remaining GHG emissions, thus AFOLU is becoming an increasingly relevant emissions abatement sector. In addition, the AFOLU sector could contribute to decarbonising the energy sector through the development of carbon-neutral bioenergy and biomaterials as well as to the removal of residual CO_2 emissions through carbon sinks.

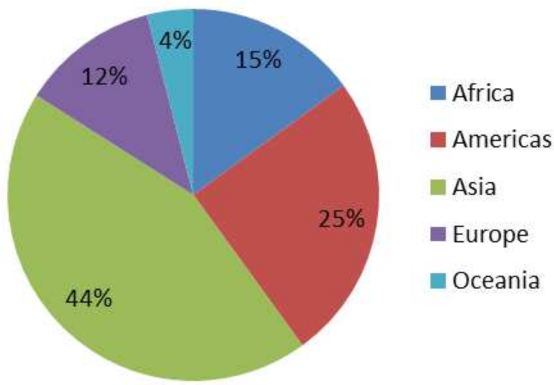

Figure 12: Agriculture, 2001-2011: emissions by continent. Source: FAO, 2014 Agriculture, forestry and other land use emissions by sources and removals by sinks.

Mitigation in the AFOLU sector can be carried out both by **reducing GHG emission intensity** per unit of output (through improved cropland and livestock management), and by **conserving or enhancing carbon stocks** in vegetation or soils (through afforestation/reforestation, bioenergy with carbon capture storage, and enhancement of soil carbon content).

Such mitigation actions in the AFOLU must be carried out in synergy with preserving the quality and functionalities[17] of soils, which is a further sustainability objective strictly interconnected with climate mitigation. For example, land degradation is an environmental issue across Europe but especially in the Mediterranean region. Several Member States have been

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[17] E.g. agricultural production, vegetation retention, filtration, moderation of water flow, energy flow regulation, etc.

impacted by desertification, with Spain severely threatened (up to 49 % of the total country area is highly or very highly susceptible to land degradation). There are also major concerns for Greece, Bulgaria, Italy, Romania and Portugal. Actions to stop and reverse such progressive soil degradation involve the implementation of carbon accumulation practices in soil.

Soil regeneration must start from a responsible use of agricultural land, promoting the creation of new integrated agricultural value chains based on the diffusion of best practices, on the sustainable use of biomass, and on the restoration of organic matter in soils even through the identification of dry farming in marginal and abandoned land. Soil regeneration is both a matter of below- and above-ground biomass and is thus closely connected to the overall environmental management of the AFOLU sector in broader terms, e.g. of forest preservation or livestock management. This kind of soil regeneration could encourage the creation of new income opportunities for farmers working on abandoned or uncultivated land, especially those with negative economic margins, and through the stipulation of supply-chain contracts for the exploitation of crops.

Soil is a non-renewable resource, as it takes over 2 000 years to create just 10 cm of soil. According to the Food and Agriculture Organization of the United Nations, 33 % of global soils are impacted by soil degradation, including salinisation, compaction, acidification, chemical pollution and nutrient depletion. Furthermore, the European Commission's Joint Research Centre (JRC) states that 20 % of Europe's land surface is subject to erosion with rates above 10 $t/ha*yr^{-1}$ [18], while soil sealing (covering the ground with an impermeable material) leads to the loss of more than 1 000 km^2 of productive land each year.

The lack of European harmonisation, mostly due to the absence of a dedicated EU Soil Directive[19], has consequences not only for GHG emissions but also for soil preservation and regeneration, water resources, intensive breeding and antibiotics uses, herbicides and fertiliser use, and compost contamination due to plastics and other waste which is known as 'white pollution'[20].

According to the European Commission, the bioeconomy comprises those parts of the economy that use renewable biological resources from land and sea — such as crops, forests, fish, animals and micro-organisms — to produce food, materials and energy. The bioeconomy is a cornerstone between agriculture and industrial production of food, feed and bio-based products that are functional to both sustainable agriculture practices and soil protection.

The systemic adoption of a circular bioeconomy approach at governmental, agricultural and industrial level provides the opportunity

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18 Tonnes per hectare per year

19 In September 2006, The European Commission adopted a Soil Thematic Strategy including a proposal for a Soil Framework Directive which was withdrawn in 2014, due to the lack of a favourable decision from the Council.

20 Plastics in agriculture are widely used especially for protecting root systems, plants, crops, forage, soil structure and the water table. While improving agricultural systems in terms of productivity, without reliable waste-management practices, agri-plastics can contaminate soils causing 'white pollution' which risks compromising soil fertility and increasing land use with negative effects in terms of GHG, too.

to address the multifaceted challenges posed by land degradation. The bioeconomy is a key lever for promoting cultural, as well as industrial, environmental and social regeneration for a symbiotic society to ensure that the efficient use of resources is given the utmost importance. This can transform local problems into business opportunities, capable of extracting value from the preservation and regeneration of natural and social capital and lending significant economic weight to the externalities generated by the various production and consumption models. Innovative systems using a combination of products from integrated regenerative chains, such as recycled nitrogen and phosphorous, clean sludges, compost, stabilised digestate, biobased biodegradable materials and plastics, biodegradable mulch films and other auxiliary products for agriculture, crop protection bioproducts, biobased biodegradable lubricants, readily biodegradable ingredients for cosmetics and detergents, all represent key deliverables from the bioeconomy.

2 Decarbonising European agriculture: levers and challenges

At the global level, land-based mitigation options, including afforestation and land restoration, represent a potentially large share of the total cumulative abatement potential, and are therefore important elements in climate stabilisation. Mitigations in the land sector must keep pace with emission reductions in the fossil-fuel sector, not offset one against the other.

The vast majority of emission reduction pathways to limit global temperature rise to below 2 °C and all pathways for 1.5 °C **rely on 'negative emissions'** — the removal of carbon from the atmosphere, especially in the period after 2050.

Negative emissions are generally achieved through land-based strategies: carbon sequestration in terrestrial sinks (forest restoration, reforestation, etc.) or bioenergy with carbon capture and storage (BECCS), an unproven technique, not yet commercialised, which involves burning biomass to generate electricity, then capturing the carbon and pumping it into underground geological reservoirs.

Decarbonising European agriculture is challenging as it must be achieved in a context of rapidly growing global food demand (between +50 % and +100 %, according to the latest foresight studies), whilst also coping with the impacts of climate change. The fifth assessment report of the IPCC concludes that: (i) crop yields in temperate regions could be substantially impacted by climate change even for low temperature change; and (ii) the Mediterranean zone will suffer from lower precipitation.

Most agricultural emissions in Europe result from enteric fermentation (methane), microbial processes in soil (N_2O) from the use of synthetic fertilisers, and manure use and management. These emissions have gradually decreased since 1985, mainly due to improvements in nutrient use efficiency, feed use efficiency, and limited growth in the consumption of agricultural products in Europe.

Land use in Europe is a net sink as European forests are being replenished. This trend has been increasing since the 1990s. European land use is also responsible for substantial emissions associated with carbon losses from drained histosols beneath crop land (~100 $MtCO_2$ according to FAOSTAT).

The carbon sink of European forests is threatened by climate change, as it has been reported that forests can become a net source of emissions in case of high global temperature rise. Therefore, an important axis of the European decarbonisation strategy should be to protect the carbon sink in forests.

Overall, agricultural emissions in Europe are characterised by a large share of non-CO_2 emissions — methane and nitrous monoxide, which needs to be converted to CO_2-eq using specific standards. Emissions from the AFOLU sector are also difficult to monitor because they are dispersed across a wide range of sources. Furthermore, they depend on bioclimatic parameters that are difficult to measure and whose biophysical mechanisms are not always well known.

European consumption of agricultural products is characterised by a large share of animal-based proteins (60 % of total proteins consumed) which are intensive in terms of land and water resources. Environmental impacts of meat and milk consumption are important outside Europe as they rely mainly on feedstock from imported origins (e.g. soybean from Brazil to feed animals).

Food losses and waste are particularly large in Europe amounting to 280 kg/person/y, according to Gustavson et al., 2011, the second highest rate of food losses and waste per capita in the world. Potentials for waste reduction are substantial as most food waste at the household level is avoidable.

The European contribution to the global mitigation effort of AFOLU emissions is both a matter of emissions within EU boundaries and induced emissions outside the EU through the global agricultural commodity markets. While European international agricultural trade is balanced in terms of euros and slightly in deficit in tonnes, it is not clear as to the levels of emissions imported or exported from Europe.

Finally, **it is important to take into account the existing regulatory environment** related to the decarbonisation of European agriculture (common agricultural policy, Water Framework Directive, Waste Framework Directive, Nitrates Directive, Climate and Energy Package and European Biodiversity and Bioeconomy Strategy) to better understand policy interactions and dynamics for all low-carbon options.

3 Decarbonisation strategies: soils as a carbon sink

3.1 Demand and supply-side options to decarbonise European agriculture

Supply-side options to mitigate agricultural emissions include: improved feed and dietary additives, improved breeds with higher productivity, modified livestock diets to reduce nitrogen excreta, improved precision of fertiliser application (right amount, right fertiliser, right time and right placement), and increasing cropping intensity through multi-cropping or inter-cropping. All these options improve resource-use efficiency (nutrient, feed, water) which represents an important avenue towards mitigating agricultural emissions in a cost-effective manner. Additional options may include the treatment of manure in anaerobic digesters to produce biomethane and generate heat and electricity and to reduce methane losses from manure storage, thus at the same time providing further tools to decarbonise the energy sector and avoid GHG emissions.

The development of integrated environment/climate/agricultural production practices, such as agroecology and organic farming, allow crop production to be optimised per unit area, taking into account the sustainability aspects. Focusing on soil fertility and closed nutrient cycles, these approaches promote crop rotations and favour nature-based solutions over chemical-based solutions to treat pest and disease and to enhance soil fertility. Whilst they show many potential benefits in terms of biodiversity and nutritional value, improved soil and water quality per unit area, and enhanced profitability, their feasibility is contested as they may produce lower yields and thus require larger land areas to produce the same output as conventional production systems. However, yield comparisons with conventional agriculture are challenging as agro-ecological or organic agriculture relies on a synergetic approach with other crops and the environment, which is not necessarily directly or immediately measurable.

Supply-side mitigation measures imply profound changes in agricultural practices and land use. Access to market and credits, technical capacities to implement mitigation options, accurate monitoring of emission levels and institutional frameworks and regulations are some of the main obstacles. Issues related to rural development and supply-chain organisation can be other obstacles.

Environmental and societal challenges are also becoming increasingly important as regards abatement efforts in the AFOLU sector. Large-scale bioenergy production raises important issues about possible adverse effects on biodiversity, food security, water use and access to land, and the scientific debate on the overall benefits of specific bioenergy pathways remains unresolved (IPCC, 2014b). The promotion of bioenergy production in Europe may imply the conversion of natural ecosystems outside the EU boundaries through international trade. This so-called indirect effect has to be carefully accounted for in the environmental assessment of bioenergy production.

Mitigation options may also imply trade-offs between local and global pollution (e.g. a bioenergy plant using local wood resources or large livestock facilities) and between mitigation and adaptation.

Consumption-based measures, such as changes in diet or a reduction in food loss and waste, offer a substantial mitigation potential (1.5–15.6GtCO$_2$-eq/y on a global scale), greater than supply-side measures. They may enable both a reduced use of inputs and larger areas for afforestation/reforestation or bioenergy production. Changes in diet may be associated with valuable co-benefits such as improving dietary health.

A more balanced diet with lower meat consumption would have relevant implications on GHG emissions and other environmental issues (e.g. water consumption). According to Weber and Matthews, 2008, consumption-based measures provide a strong 'opportunity for consumers to reduce their environmental impact due to their high degree of personal choice, and a lack of long-term "lock-in" effects which limit consumers' day-to-day choices'. However, they may be difficult to enforce for social acceptance reasons linked to habits, taste or cultural representation.

Mitigation measures for agriculture and land use, developed within the bioeconomy framework, may be associated with socio-economic and environmental co-benefits provided they are sustainably implemented.

Therefore, bioenergy should be integrated in food production, notably through suitable crop-rotation schemes, or use of by-products and residues. Mitigation options designed to enhance carbon stocks in soils may also have a positive impact on food security by improving land quality. Other potential co-benefits include, for example, human health and well-being through better-adapted diets, clarification of land tenure, synergies with other international agreements, including the United Nations Convention to Combat Desertification (UNCCD, 2011), or the Convention on Biological Diversity (CBD, 1992).

New approaches for transforming and reorienting the role of agriculture and business towards land regeneration can have important consequences, not only on the social pillar of sustainability, but also for GHG reductions. The exploitation of innovative geographic information system (GIS)-based tools, smart sensors, precision-agriculture principles and, above all, the implementation of circular economy principles could help promote more resource efficient and sustainable farming practices that reflect the regional diversity of farms across Europe.

3.2 The role of organic carbon in soil

Degradation of the Earth's land surface through human activities is negatively impacting the well-being of at least 3.2 billion people, pushing the planet towards a sixth mass species extinction, and costing more than 10 % of annual global gross product through loss of biodiversity and ecosystem services (IPBES, 2018). Soil degradation is part of land degradation and includes, among others, loss of soil through erosion at a rate faster than it is formed, and depletion of soil organic matter. Therefore, the human pressure exerted on soils is increasingly alarming. The degradation of soil is emerging as a fundamental element of global environmental change.

The world's soils hold approximately 1 500 ± 230 Gt of carbon down to 1 m depth (excluding carbon in permafrost), which is twice the amount of carbon in the atmosphere. In European soils, 70-75 GtC are stored in the first 30 cm of soil. However, close to half of all agricultural soils in the world are estimated to be degraded (i.e. depleted in soil organic carbon, among other factors), leading to foregone annual grain production which could reach USD 1.2 billion globally (FAO, 2006). The continuation of this trend could lead to a global yield decline of 10 % (FAO and ITPS, 2015). Land degradation poses a threat to agriculture, and climate change may accelerate the rate of degradation with major impacts on food security and the well-being of small farmers. In recent years, loss of organic matter has become increasingly important for the soils of the Mediterranean area, for instance.

Land use conversion and soil cultivation have been major sources of GHGs since the onset of settled agriculture. As much as 40 % of the planet's total land area has been converted into agriculture and plantations to produce grains, vegetables, fruit, milk, and meat to feed 7.3 billion people in 2015. Over the past two centuries, soil organic carbon, an indicator of soil health, has seen an estimated 8 % loss globally (176 GtC) from land conversion and unsustainable land management practices (IPBES, 2018).

Thus, enhancing soil organic carbon (SOC) could be key to mitigating climate change and contributing to food security. SOC storage in agricultural soils could contribute to meeting the joint goal of reducing the impact of agriculture on GHG emissions and climate change (UN SDG 13) and delivering zero hunger (SDG 2). In March 2017, the jointly organised Global Symposium on Soil Organic Carbon by the FAO and its Global Soil Partnership, IPCC, UNCCD and WMO highlighted the crucial role of soil carbon in achieving food security, especially in future climate change scenarios.

Smith et al. (2016) estimated that **soil carbon sequestration has an achievable potential of negative emissions by 0.7 GtCeq/y at the global scale,** emphasising it has a potentially lower impact on land, water use, nutrients, albedo, energy requirement and cost than many negative emission technologies. While this actual potential is not sufficient to offset all anthropogenic emissions, nevertheless it is substantial and would offset the fossil-fuel emissions equivalent of the EU. Large-scale modelling studies have estimated a biophysical potential about 0.5-2 f $GtCO_{2}$-eq in the EU, which is storable in a centennial time horizon by applying different sets of agricultural practices.

Changes in SOC content are generally nonlinear. Thus, SOC changes are usually fastest during the first years following the adoption of a new practice and hardly exceed a few decades until a new equilibrium is reached. In addition, the rate of C gain is usually lower than the rate of C loss. In this 'slow in — fast out' temporal scheme, the quantity of SOC that can be stored in a given soil is finite and saturates after a few decades.

The ability of soils to store carbon depends on many factors, including: (i) the intrinsic characteristics of soil (e.g. mineralogy, the abundance of fine silt and clay fractions); (ii) type of land use (e.g. forest, pasture, crop land); (iii) land management, including agricultural practices; and (iv) climate, through its impact on net primary production, respiration and decomposition of organic matter. It should be also noted that carbon and nitrogen biogeochemical cycles are strongly coupled and that, on average, the carbon-to-nitrogen ratio in soil organic matter is equal to 12.

This means that there is no universal management practice or technology that is appropriate for all farming systems.

Re-carbonisation of soil and the terrestrial biosphere by 'sustainable intensification' implies producing more food using less land, water, chemicals, energy, and minimising GHG emissions. SOC stock is under constant changes at different timescales and, if widespread, relatively small changes in the flow of carbon into or out of soils could have a significant impact on a global carbon budget.

All these elements have led to the development of **several international initiatives on soil**, including the 4 ‰ Initiative — soils for food security and climate (http://www.4p1000.org) — which was launched by France during COP21 as part of the Paris-Lima Action Plan and is supported by the United Nations Food and Agriculture Organization. Its overarching goal is to help contributing countries and non-state organisations to develop evidence-based projects, actions and programmes, to promote and encourage actions towards reducing GHG emissions by protecting and increasing SOC stocks, the target rate of a 4/1000 (0.4 %) SOC increase per year being the aspirational goal. It aims to avoid loss of organic matter from soils and enhance soil carbon sequestration with the ultimate aim of improving food security, and adapting and mitigating climate change. The Initiative comprises two parts: an action plan and an international research and scientific cooperation programme.

4 Organic carbon in the soil: not only a carbon sink but also meeting the challenges of desertification and land degradation

4.1 Agricultural practices and avenues for implementing soil carbon strategies

Within the agriculture sector (excluding bioenergy and improved energy use), about 90 % of the total technical mitigation potential is based on SOC sequestration options. The variations in SOC at the ecosystem scale are the results of the flux of organic carbon partitioned below-ground, the human appropriation of above-ground carbon (e.g. through harvest and animal products mainly) and the carbon losses at ecosystem scale (e.g. due to soil erosion and fire). Therefore, management strategies to increase SOC could fall into three different categories: (i) soil conservation; (ii) carbon management; and (iii) agricultural and forestry intensification.

Soil conservation requires reducing C losses from the ecosystem, e.g. by avoiding fires, and reducing erosion and leaching. For instance, no-till, cover crops, or direct drilling into mulch can all be used to protect cultivated soils from erosion and will have consequences for plant production and harvest, through soil moisture and nutrients.

Carbon management aims to increase the ecosystem carbon balance by accumulating above-ground biomass (e.g. in forests, in agro-forestry) and by sequestering SOC (in all ecosystems). Protecting SOC stocks requires avoiding adverse land use change and management practices (e.g. deforestation, ploughing grasslands, soil sealing, etc.), and avoiding drainage and cultivation of organic soils (e.g. drained peatlands). Avoiding overgrazing, balancing soil organic matter decomposition with the supply of manure, crop residues and litter, and increasing mean annual net primary productivity all enable an increase in SOC in agricultural systems.

Agricultural practices which can be used to store additional SOC include crop species and varieties with greater root mass and with deeper roots, use of N-fixing legumes in N-deprived soils, use of cover crops during fallow periods, use of crop rotations providing greater C inputs, increased residue retention, and the addition of amendments such as compost and biochar.

The mitigating effect on GHG emissions associated with the use of compost in agriculture has been addressed in several studies and in experimental research. The available results suggest that compost use in the agricultural sector increases SOC and tends to neutralise GHG emissions caused by cultivation, thereby increasing soil fertility and resiliency.

The use of straw for energy generation in parallel with optimisation of the cropping system can achieve compelling environmental performance showing that a favourable balance can be found between the use of crop residues for soil and for energy.

Experimentation is required at scale, both at the local and then the regional level, to explore the potentials of SOC-enhancing strategies and to address specific problems or societal challenge under real-life conditions. This could take the form of regional demonstrators bringing together farmers, firms and academia to foster a systemic approach, while also supporting new entrepreneurial initiatives and open innovation.

The question of creating a specific market for soil carbon should be investigated. To this end, inspiration can be drawn from the carbon market in Alberta in Canada. This trading scheme has been functioning since 2007. Since 2014, the protocol for offsetting carbon has included conservation cropping which is based on practices that increase carbon storage. This experience has shown that finding the right balance between reliability and simplicity in monitoring the reduction in emissions is key for the success of this strategy. Fostering R&I in this field could help to develop new practices and models able to increase carbon storage, while also enhancing the marketability of pre-existing schemes.

A connected challenge relates to communicating the benefits of SOC sequestration through the consumer supply chain. Creating a new value chain should contribute to the general objective of finding the right incentives for spurring SOC-enhancing practices.

Promoting sustainable agriculture is of huge relevance since the agricultural sector represents the basis of the bioeconomy. It is no coincidence that recent standards, certification schemes and international initiatives indicate, among the various requirements, sustainable management of organic soil.

4.2 Synergies and limitations of SOC-enhancing strategies

In addition to reducing GHG emissions and sequestering carbon, smart soil management that increases organic matter and tightens the soil nitrogen (N) cycle can yield powerful synergies. SOC plays a fundamental role in the fertility and productivity of terrestrial ecosystems, supporting important soil-derived ecosystem services such as soil quality, water filtration, erosion control, nutrient cycling, habitat and energy for soil organisms. Indeed, carbon is the main component of soil organic matter (more than 58 %), which is important for maintaining soil fertility and soil quality and their benefits as regards providing a range of ecosystem services. SOC sequestration policies would generate additional revenues for farmers by increasing yield, keeping larger areas of agricultural land in production, and reducing fertiliser needs.

The demand for mineral fertilisers can be reduced by combining organic inputs, thereby cutting the emissions associated with the application and the fossil energy necessary for their production. Also, a reduction in the use of inorganic fertilisers results in a greater control of eutrophication and water quality.

However, there are scientific, political, and socio-economic issues with the large-scale implementation of soil carbon-enhancing policies, including:

- scientific evidence of the benefits of increasing SOC across a range of different soils, agro-ecosystems and climatic zones is still insufficient;
- the finite capacity of the soil C sink: the 'maximum potential' of SOC sequestration corresponds to the 'soil C sink capacity' which depends on a range of factors including texture, mineralogy, depth of soil, etc.;
- carbon sequestration tends towards a new equilibrium implying a diminishing increment in SOC as time elapses;
- some limitations to SOC sequestration may occur because of a lack of nutrients such as nitrogen and phosphorus;
- adoption of management practices (e.g. residue retention, cover cropping, controlled grazing, converting agriculturally marginal lands to perennial vegetation cover, and soil amendments) would require financial resources;
- SOC permanence is also a key issue that needs to be addressed from a multidisciplinary perspective;
- one important question is how long it may take to reach the ceiling economic potential;
- greater adoption of adequate practices is also a key issue, especially in Europe where they are already widely used by farmers.

5 The rationale of the circular bioeconomy

5.1 A circular bioeconomy for a sustainable society

For more sustainable development, as regards land, soil, water, biodiversity and human beings, it is of paramount importance to drastically change production processes, consumption models, and recycling and disposal of biological resources.

Integrating the bioeconomy into the circular economy model is key for developing a sustainable society, since the circular bioeconomy is the cornerstone between agriculture and industrial production of biobased products that are functional to both sustainable agriculture practices and soil protection.

This bioeconomy model includes the 'sustainable regions' notion introduced by the European Commission's Bioeconomy Panel. Sustainability is not a worldwide concept but it is linked to the qualities of local areas, to their specific economic situations, because a solution which may be absolutely sustainable in one context may have an enormous impact in another. Thus, it is necessary to think in terms of local areas, and regions represent the ideal dimension for making a start on the problems specific to those areas and transforming them into opportunities for development.

Reducing food losses and waste at the source, within the bioeconomy framework, should be the priority of a sustainable strategy for future agriculture, with the aim of avoiding land use and fertiliser emissions as well as the many emission sources associated with the supply chain (e.g. refrigeration, transport).

SDG 12.3 focuses on the food-waste sector and sets the target to halve per capita global food waste at the retail and consumer level by 2030 and to reduce food losses along production and supply chains, including post-harvest losses. The management of food waste starts with understanding how much is currently produced and what share of it can be prevented. A detailed analysis at the European level can be found in the EU FP7-funded project FUSIONS (http://www.eu-fusions.org/). In total, 88 million tonnes of food waste is generated in Europe per year, the majority (about 53 %) occurring during food preparation and consumption at home. Based on these figures, 31 million tonnes of food waste would need to be reduced each year to meet the United Nations' SDG by 2030.

For example, in order to provide 1 kg of apples to consumers, 1.28 kg must be produced. Along the supply chain, that 0.28 kg of edible and inedible parts of apples are removed for various reasons. Environmental impacts related to this 0.28 kg of food waste occur during production, processing, retail and distribution, consumer activities (e.g. cooking, storing) as well as food disposal (e.g. composting, waste incineration). The later in the supply chain food is wasted the more environmental impacts are associated with this waste. Therefore, reducing food waste by prevention would avoid such impacts. By preventing food waste at the consumer level, around 26 million tonnes of food can be saved (assuming that 57 % of food waste is avoidable). This would result in a potential reduction of 69 million tonnes CO_2-eq. (corresponding to Finland's total GHG emissions). However, once (hopefully) food waste losses have been reduced, the remaining challenge will be how to handle the unavoidable bio-waste.

Enhanced waste recycling should be promoted. Initiatives for better separation of bio-waste are under way in many European countries, and the European Food Waste Framework Directive is being amended to promote the implementation of food-waste prevention measures.

Italy is an interesting case study for the transformation of bio-waste into compost: the Italian Composting and Biogas Association of composting plants (CIC) estimates that, in 2015, about 4 million tonnes of municipal solid waste and 2 million tonnes of green waste (from parks and gardens) were collected separately in Italy and sent for biological treatment (61 % composting and 39 % anaerobic digestion + composting). With a population of about 60 million (ISTAT, 2014) inhabitants, the organic fraction recovered annually per capita corresponds to about 67 kg compared to a potential quantity of about 170 kg/cap/year. This gap of around 100 kg/cap/year can be easily filled.

5.2 Biobased products for the regeneration of local areas

There is considerable room for improvement regarding the capture and recycling rate of bio-waste. Specific incentives could be introduced for those farmers and companies using compost in their agricultural practices. This would be reflected in an increase in the demand for quality compost and, therefore, in greater efficiency of the management of bio-waste. At the EU-28 level, the amount of bio-waste produced annually is about 96 million tonnes which is around 190 kg/person/year, of which 150 kg/person/year is really collectable; Overall, just 33 % of EU bio-waste is currently recycled.

The quality of compost is key. It is important to consider nutrient composition and physical, chemical and physico-chemical properties as well as disease suppression. Within the EU Member States, standards for compost use and quality differ substantially, partly due to differences in soil policies. Thus, a harmonised process would be welcomed.

Figure 13 shows the recycling of carbon in agriculture, food, biobased products, and compost (going back to agriculture) as an example of both the bioeconomy and circular economy mimicking the natural carbon cycle.

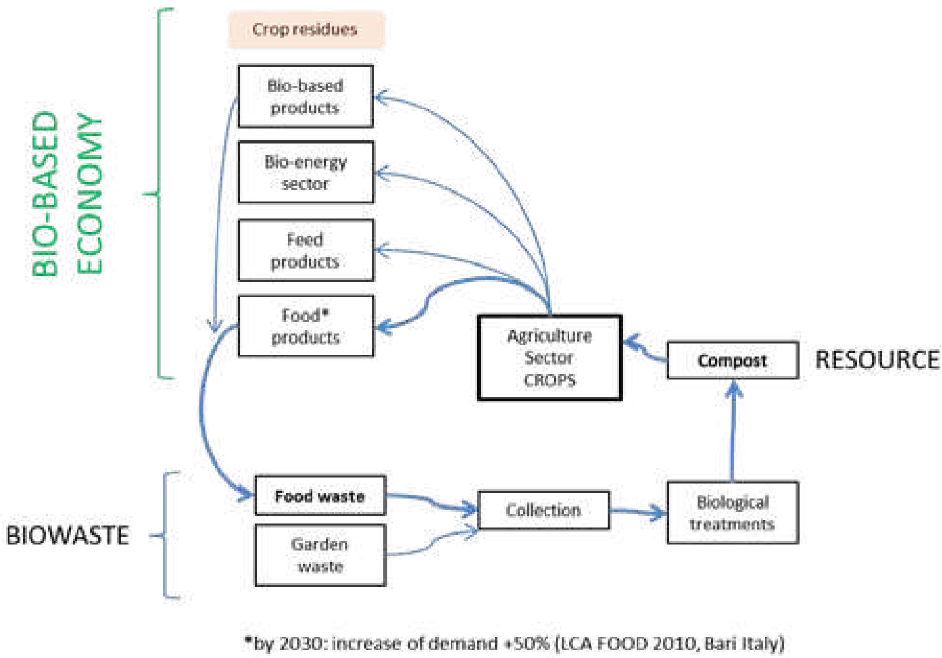

Figure 13: Virtuous circular economy model for food-waste management, compost and sustainable agriculture (rows in bold). Above-ground biomass (crop residues) could be exploited to produce biobased or bioenergy or be returned to the soil partially/totally.

In this scenario bio-based products must be designed in a circular perspective in order to address specific environmental issues, such as water and soil pollution generated by plastics, lubricants, fertilisers, crop-protection products, or the dispersion of cosmetics and detergents residues. Properties such as biodegradability and renewability are desirable for a significant part of these products. To maximise the effects on climate change and guarantee real sustainable development, they have to be the results of a bioeconomy conceived as a feature of territorial regeneration in a society prepared to choose quality over quantity.

More specifically for a sustainable society based on local resources, biodegradability must be seen in a broader context, applying a circular vision based on fair and continuous access and on value creation with use of renewable resources through sustainable processes, respecting the environment, society and the territory. The choice of renewable products which build up the ecosystems and continuously generate value is one of the key issues when regeneration becomes the focus of production processes.

Biobased products such as biodegradable and compostable bioplastics are crucial to promote the better management of organic waste and reduce the risks of its contamination. Bioplastics are also fundamental tools to reduce pollution in those sectors where there is high dispersion rate, such as agriculture or fisheries. The adoption of appropriate standards for biodegradation in different specific environments is key to guarantee that a product can be reabsorbed if released accidentally. Another crucial aspect is that product sustainability/biodegradability is not an excuse for limitless growth: if produced in increasing quantities without limits and without passing through the appropriate treatment plants, even natural products may pose a major threat to the environment.

In a circular bioeconomy perspective, it is of paramount importance that products originate from the development of new local agro-industrial supply chains, creating new case studies and new regional standards and projects. The value chain coming from the regenerative management of forest products is another area of opportunity. Some case studies within Horizon 2020 already exist at EU level with significant investments in infrastructures, and integrated agricultural/forest value chains spurring the development of innovative products for feed, generation of organic chemicals (biochemicals) via fermentation from crop biomass, starch materials, agri-residues, and agro-industrial waste as well as bioplastics.

Bioeconomy could be a great opportunity in those areas characterised by marginal lands, where integrating the cultivation of dry crops with multiple sectors will not only enable soil regeneration (through agricultural best practices, such as the use of biodegradable mulching films, bioherbicides for the control of infestations or biolubricants) but will also encourage the development of multi-product value chains, with the cascading use of biomass and creating new opportunities for production and income. The value chain coming from the regenerative management of forest products is another area of opportunity. This circular approach should make it possible to avoid increasing competition of biomass resources with other biobased products such as lignocellulosic bioenergy products.

Every single area is different and is characterised by its own peculiarities. Territories have their own production system, culture and biodiversity, which could be exploited through interconnected projects with local roots. In this way, it is possible to stimulate the creation of a new, local and virtuous value chain starting from identifying a product and driving the all-integrated system, regenerating resources and rethinking the end of life.

In conclusion, soil regeneration is a key milestone in the development of a more general pattern of regeneration of local areas via the establishment of integrated value chains of quality food, feed bio-chemicals and innovative materials such as bioplastics based on a functioning network of stakeholder relationships and cooperation.

These prerequisites allow the bioeconomy model to act as an effective accelerator for sustainable innovation, transforming the peripheries into strategic centres and a driving force for the EU. This model should be implemented through the building of the so-called bioeconomy infrastructures, establishing a new relationship between the economy, technology and society.

The goal is to achieve a high-level of diversified quality rather than pursuing the undifferentiated quantity, at the same time reconnecting a decarbonised economy with society and relaunching the EU's competitiveness on the basis of continuous innovation applied to local areas, taking into account their traditions, addressing challenges, and developing opportunities.

5.3 Supply of and demand for biomass: how to maintain a sustainable equilibrium

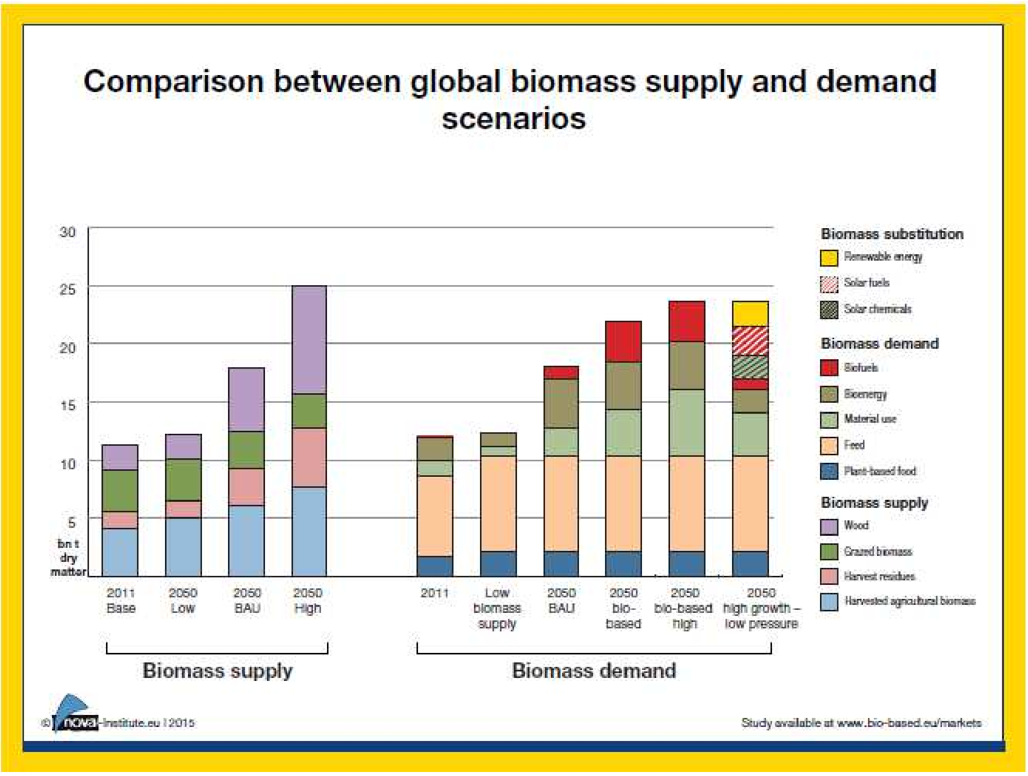

Figure 14: Comparison between biomass supply and demand scenarios (by biomass sources and uses). Source: Nova, 2015.

One obvious question is: 'Would agricultural and forestry feedstocks be enough to feed the future biorefineries for the production of biochemicals and bioenergy without negatively affecting the supply of food, feed and other biomass uses?' An interesting analysis aimed at responding to this fundamental question was conducted by Nova Institut in 2015, where five different demand scenarios were formulated and investigated. These scenarios highlight how under different plausible and consistent assumptions the supply and demand of biomass may develop. Leaving out the assumptions and the details of the study that can be found here (http://bio-based.eu/download/?did=69849&file=0), the research outcome is well summarised in the Figure 14 above, which shows the biomass demand and supply for each sector in 2011 and 2050 (the figures are expressed in billion metric tonnes of dry matter).

All five demand scenarios share the same assumptions regarding the demand for food and feed, whereas for the biobased chemicals and materials, bioenergy and biofuels sectors different demands were assumed.

In the LOW supply scenario, the global biomass supply will scarcely change from 2011 to 2050, while it will almost double in the business-as-usual (BAU) scenario and more than double in the HIGH scenario. Based on these scenarios, the range of global biomass supply in 2050 will be between 12.4 billion tonnes of dry matter (2011 base year) and 25.2 billion tonnes of dry matter in 2050.

The results show that the LOW supply scenario would just be able to cover the demand for food and feed but hardly any of the demand for materials and bioenergy and none of the demand for biofuels or biochemicals.

In comparison, the BAU supply scenario could cover the demand for food, feed, materials and bioenergy and could even leave room for an expansion of biofuels of up to 1 billion tonnes of biomass dry matter. That would be enough to produce about 25-30 % of biofuels needed to reach the 2 °C climate goal, according to the IEA 2012. In contrast, the BAU supply scenario — if combined with the biobased or biobased HIGH scenarios — cannot quite meet the biomass demand from food, feed, materials and bioenergy. The HIGH supply scenario can meet the demand of all scenarios and would still leave enough biomass for further applications. It is noteworthy that in both the BAU and HIGH supply scenarios a relatively high amount of cellulose will be available as the result of greater forest utilisation and an increased use of agricultural by-products. This suggests that for the BAU and HIGH scenarios the amount of so-called 'second generation' raw materials (starch, sugar, fats and proteins) will grow in all sectors.

In both the BAU and HIGH supply scenarios, a relevant net expansion of land for arable and permanent crops takes place and concomitantly there is a considerable threat of a further reduction in biodiversity as well as more GHG emissions from agriculture. Hence, at first glance, these scenarios do not appear to be sustainable.

However, the authors conclude that in the future an equilibrium (meeting the 'safe operating space' criteria) can be met through massive investments in new technologies and system optimisations which enable a higher output with less input and, at the same time, less environmental burdens (i.e. a well-developed bioeconomy). The greening of deserts with deep water recovered by solar energy and fresh water through desalinisation of marine water, the introduction of salt- and heat-resistant crops, large-scale marine cultivation of macroalgae, tailored fertilisation, plant protection and irrigation through precision farming, optimised crop rotation and a combination of crops, soil improvement, modern plant breeding, storage systems and CCU technologies and more would all help to achieve this. This requires consistent political guidance and huge investments in new technologies.

6 Research proposals

Three strategic macro-areas have been identified, each targeting the specific challenges and the R&I efforts required to address such challenges:

MACRO-AREA 1: DECARBONISING AGRICULTURAL AND FORESTRY SYSTEMS THROUGH TRANSFORMATIVE TECHNOLOGIES AND PRACTICES FOSTERING MULTI-DISCIPLINARY APPROACHES TO FOOD, FEED, BIOPRODUCTS AND SOIL REGENERATION

- **1.1 Challenge**: Rapidly growing global food demand (between +50 % and +100 %, according to the latest foresight studies) with increasing pressure on farming systems. Agricultural emissions in Europe are dominated by emissions from enteric fermentation (methane), microbial processes in the soil (N_2O) from the use of synthetic fertilisers and manure use, and management.

  R&I EFFORTS TO ADDRESS THE CHALLENGE*:* Sustainable and resilient intensification of agricultural and forestry systems while preserving biodiversity through the adoption of innovative precision-farming and breeding techniques enabled by digital services, input reduction, implementation of low-impact management protocols, and the application of nature-based and eco-designed solutions (including new sustainable organic fertilisers and biopesticides, alternative feeds for breeding to reduce antibiotics use, etc.).

  Adoption of a systemic view on the links between crop and animal production, animal welfare, ecosystems and human health, interconnecting sectors, existing knowledge and innovation.

- **1.2 Challenge**: Presence of agricultural, forestry and breeding residues and side streams with underexploited potential.

  R&I EFFORTS TO ADDRESS THE CHALLENGE: Developing new processes for the conversion of residues, by-products and side streams into systemic and regenerative bioproducts, food/feed and high-quality organic fertilisers, including the capture and valorisation of CO_2 and clean digestate from bio-refinery and bioenergy plants, to generate negative emissions.

MACRO-AREA 2: NEW REGENERATIVE MEASURES TO OPTIMISE LAND USE AND IMPROVE SOIL QUALITY

- **2.1 Challenge**: Use of virgin land to build new industrial and urban areas, reducing soil availability.

  R&I EFFORTS TO ADDRESS THE CHALLENGE*:* New regenerative processes for cleaning polluted areas and engineering measures for the reconversion of abandoned industrial and urban sites, promoting the valorisation of brownfields rather than virgin land.

- **2.2 Challenge**: High presence of marginal/abandoned/degraded land across the EU in relation to climate change, urban and industrial facilities.

R&I EFFORTS TO ADDRESS THE CHALLENGE*:* Innovative multi-purpose cropping systems for the regeneration of marginal/abandoned/degraded land, taking into account regional specificities and creating value for local areas.

Enhancement of current agricultural machinery and practices to enable farming on marginal/abandoned/degraded land.

- **2.3 Challenge**: White pollution and soil contamination related to the use of plastics in agriculture.

  R&I EFFORTS TO ADDRESS THE CHALLENGE*:* Development of low-impact, innovative products, as well as soil preservation and regeneration schemes, including biobased and biodegradable chemicals/materials/products associated with effective risk-management strategies.

- **2.4 Challenge:** Need for monitoring and evaluating organic matter in soil. Emissions from the AFOLU sector are difficult to monitor because they are dispersed across a wide range of sources and depend on bioclimatic parameters that are difficult to measure and whose biophysical mechanisms are not always well known.

  R&I EFFORTS TO ADDRESS THE CHALLENGE*:* New models and techniques to monitor and evaluate soil-organic-matter dynamics in different soils and developing tools to plan adequate decarbonisation strategies (including the development of international databases where farmers can access data relevant for implementing SOC management programmes).

  Assessment of European agricultural emissions embedded in international trade.

- **2.5 Challenge**: Need for integrated cross-sectorial evaluation systems.

  R&I EFFORTS TO ADDRESS THE CHALLENGE*:* New methods to assess interconnectivity of carbon, nitrogen and phosphorous flows across sectors to maximise environmental and socio-economic benefits.

MACRO-AREA 3: NEW POLICY MEASURES AND SOCIO-ECONOMIC MODELS BASED ON THE SYMBIOTIC SOCIETY APPROACH

- **3.1 Challenge**: Social reluctance to change dietary behaviour and reduce food-waste generation.

  R&I EFFORTS TO ADDRESS THE CHALLENGE: Development of new models based on symbiotic society approaches in cooperation with social sciences and humanities forecasting a proactive role for prosumers towards more sustainable food production and consumption behaviour, preventing waste and food losses and assessing the impact of changing food patterns on the whole supply chain.

- **3.2 Challenge**: Fragmentation of standards and certification schemes.

R&I EFFORTS TO ADDRESS THE CHALLENGE: Harmonisation of standards and development of common certification schemes to facilitate the market for new, high-quality and low-impact products from a regenerative AFOLU sector.

- **3.3 Challenge**: Interconnecting the AFOLU sector with other sectors.

  R&I EFFORTS TO ADDRESS THE CHALLENGE: Development of new business and governance models and training tools interconnecting the AFOLU sector with other sectors in a circular economy framework, taking into account the regional dimension and fostering the linkages between rural, urban and coastal areas to build wider value chains with multiple benefits for all the stakeholders involved.

  Promote circular economy initiatives focused on high-quality bio-waste valorisation where the latter is biologically recycled through transformative technologies aiming to obtain high-quality compost together with other chemicals and products, and preventing leakages of CO_2 and methane.

  Design and implementation of platforms to improve global governance and regional collaboration among actors and across sectors, and to communicate the benefits of SOC sequestration through the consumer supply chain.

  Analyse and assess the benefits and modalities of a trading scheme to promote the market for soil carbon.

7 Recommendations for research and innovation

A drastic transformation of the way biological resources are used in production processes, consumed and subsequently recycled is necessary to comply with the Paris Agreement goals on climate change and for more sustainable development.

As stated above, Europe is the world's fourth largest emitter of GHG from agriculture – its overall contribution amounts to approximately 12 %. In Europe, agriculture accounts for about 10 % of overall GHG emissions and in absolute terms it emits 464 million metric tonnes of CO_{2}-eq mainly from non-CO_2 emissions (methane and nitrous oxide, N_2O). European consumption of agricultural products is characterised by a large share of animal-based proteins which use land and water resources intensively, driving important environmental impacts both within and outside Europe. In addition, Europe has the second highest rate of food losses and waste per capita in the world.

Land degradation and desertification are major concerns across the EU, posing an important societal challenge to Europe and beyond, as soil is a non-renewable resource. Actions to stop and reverse progressive soil degradation and ensure food security involve the implementation of transformative technologies and practices enhancing carbon accumulation in soil.

In the short term, proven best practices on the sustainable use of pesticides, livestock and water and nutrient management plans aimed at reducing fertiliser use should be boosted by the reformed CAP. The deployment at the EU scale of the separate collection and recycling of bio-waste to produce high-quality compost and stabilised digestate and to generate renewable energy will also contribute to staying within the EU carbon budget.

Integrating the bioeconomy into the circular economy model is key for the developing a sustainable society.

In the coming years, the adoption of innovative precision-farming and breeding techniques enabled by digital services, and the application of nature-based and eco-designed solutions (including new sustainable organic fertilisers and crop protection bioproducts, such as biopesticides, alternative feeds for breeding to reduce antibiotics use, etc.) will result in the sustainable and resilient intensification of agricultural and forestry systems while preserving biodiversity.

In addition, new models and techniques will be developed to monitor and evaluate soil-organic-matter dynamics in different soils. Adequate decarbonisation strategies (including the development of international databases where farmers can access data suitable for implementing SOC management programmes) will be deployed, with substantial financial support.

The circular bioeconomy is a cornerstone between agriculture and the industrial production of biobased products that are functional to both sustainable agriculture practices and soil protection.

In the decade 2030-2040, deployment of new business and governance models and training tools connecting the AFOLU sector with other sectors in a circular bioeconomy framework, taking into account the regional dimension and fostering the linkages between rural, urban and coastal areas, will help build wider value chains with multiple benefits for all the stakeholders involved.

Biobased products must be considered in a broader context, applying a circular vision based on fair and continuous access and the value generation of renewable resources through sustainable processes, respectful of the environment, of society and of the territory. Innovative systems using a combination of products from integrated regenerative chains, such as recycled nitrogen and phosphorous, clean sludges, compost, stabilised digestate, bio-based biodegradable materials and plastics, biodegradable mulch films, other auxiliary products for agriculture, crop protection bioproducts, and biobased, biodegradable lubricants, represent key deliverables expected from the bioeconomy.

In this perspective, it is of paramount importance that products originate from the development of new local agro-industrial supply chains, thereby creating new market opportunities.

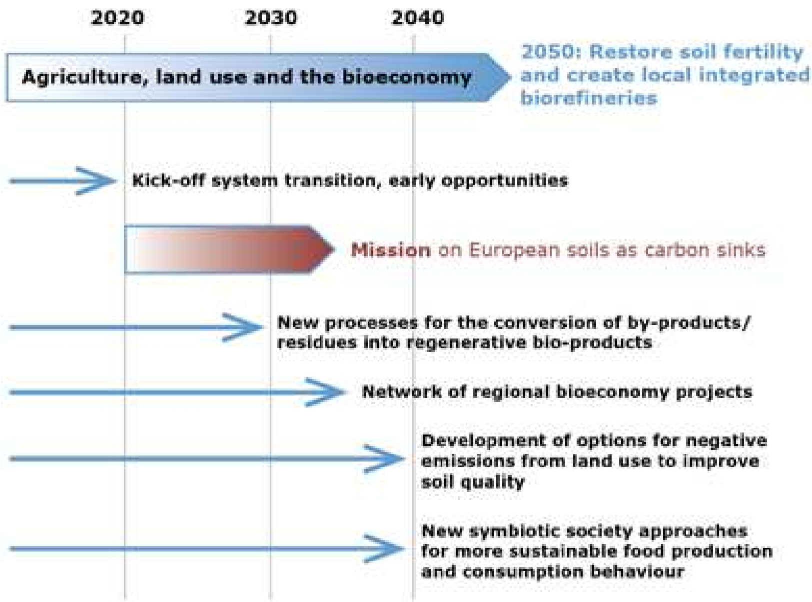

Figure 15. Possible R&I pathways to decarbonised agriculture, land-use and bioeconomy.

CHAPTER 6

THE ROLE OF CITIES IN DECARBONISATION

1 The role of cities and state of play of R&I in the decarbonisation in EU cities

Cities are key actors in the fight against climate change. Globally, they account for 60-80 % of global CO_2 emissions, depending on the estimate. In the EU, around three quarters of the population live in cities (European Commission 2018a) — and this is in the context of growing urbanisation. More people are moving to cities every year, both from within and outside the countries where the city is situated.

Cities are the ´melting pot´ where decarbonisation strategies for energy, transport, buildings and even industry and agriculture coexist and meet. As the density of energy use and infrastructures is much higher in cities, there is high potential for cross-sectoral integration (e.g. waste and energy, sewage and energy, public transport, etc.) and for complex infrastructures like smart grids or multi-energy hubs. Furthermore, more capital and know-how are often available compared to rural areas. In addition, in contrast with rural areas, cities can leverage economies of scale when adopting decarbonisation strategies.

In the zero-carbon transition, integrated urban planning and cross-sectoral governance is crucial. Cities have a key role to play in coupling all sectors and exploiting their great potential as hot spots of zero-carbon innovation — also spurred on by synergetic (and competing) local businesses. In fact, cities are already taking their responsibilities: while the EU set itself the goal to reduce CO_2 emissions by 20 % by 2020, the average commitment of the Covenant of Mayors' signatories was to reduce emissions by 28 % (UNFCCC, 2018).

This chapter gives an overview of how decarbonisation can be achieved in cities, and suggests some action points for R&I. It starts by defining the key drivers of decarbonisation in EU cities, before presenting lessons learned from diverse case studies of Stockholm, Barcelona and Warsaw. Finally, it discusses the key lessons learned and R&I gaps for the future of decarbonisation in cities.

1.1 Drivers of decarbonisation in EU cities — technologies and key concepts

Cities are moving towards integrated planning concepts in order to integrate technical and social systems for low- or zero-carbon cities. Such cities will need to encompass a range of both new and existing solutions. **Several solutions are currently being developed to help cities lower their impact.** These include a broad range of solutions from energy efficiency and local generation of zero-carbon heat and electricity, as discussed in Chapter 2, transport solutions in Chapter 3, community gardening and agricultural change in Chapter 5, and broader concepts of smart cities and the circular economy. The role of each of these solutions can have a different impact across the EU.

One of the key differences among EU cities is the existing building stock. **Buildings in EU cities are heterogeneous across regions**, including differences in the ratio of residential to commercial buildings, the average area of dwellings, and energy use in buildings. Across the EU, the efficiency of new buildings has steadily improved over time. In fact, the EU has set the ambitious target for all new buildings to be nearly zero energy by the end of 2020 and all new public buildings to be nearly zero energy by 2018 (EUR-Lex, 2018). However, most of Europe's existing building stock has yet to be affected by energy-performance requirements (European Commission, 2018b). Heating and cooling in EU buildings account for a large share of the EU's energy consumption. In residential households, heating and hot water account for 79 % of total final energy use (192.5 Mtoe) (European Commission, 2018c). Strategies to reduce emissions from heating and cooling include: more efficient technologies; efficiency in buildings, including climate-smart design and proper insulation; renewable heating and cooling technologies such as biomass boilers and solar heating; district heating and cooling; and better information and control on energy use for heating and cooling.

Energy efficiency is playing, and will continue to play, a key role in reducing the use of electricity and all fuels in cities. Implementing/increasing renewable-energy generation in buildings and transport can also reduce cities' carbon footprint. Several renewable-energy-based solutions can be integrated into buildings, such as solar thermal, photovoltaic and small-scale wind turbines. Furthermore, bioenergy can be produced locally from waste.

In addition, many cities are embracing the 'smart' label to foster the uptake of digitisation potential and ICT applications in the urban context. Usually, a smart city applies to a one that is technologically interconnected through a network of sensors, IT platforms, open data and programs that serve to make city life more efficient and smoother. It is thus a broad term, including various projects within a city, such as placing sensors on roads to optimise traffic flows and allowing for real-time tracking of public transport or the availability of parking spaces, and using waste bins that alert the city when they need to be emptied. Overall, smart city projects have a wide variety of focus areas, such as: (i) optimising infrastructure and physical networks; (ii) smart citizens and data-informed decision-making; and (iii) improving the learning and transition capacity of city administrations. Smart city projects can range from something as complex as using electric vehicles within the city to balance the grid as they charge (Latvakoski et al., 2015), to a simple app that enables users to report road defects to the municipality in order to get them repaired quickly. In transport, smart city concepts can rationalise and reduce emissions related to the movement of passengers and goods across the city. The sum of these individual projects helps to make a city more interconnected and allows its citizens to live in a more efficient way and thus reduce their carbon emissions. An important enabler for smart cities is the implementation of the IoT, in which everyday devices or household appliances are fitted with micro-controllers and the means necessary to transmit and communicate information. IoT can be applied to public services (e.g. for remotely controlling street lighting) and in households (e.g. so that certain appliances only operate during off-peak hours (Bourgeois et al., 2014) or the electric vehicle will only charge when household electricity consumption is at a minimum (Zhang et al., 2016).

Furthermore, **the broad concept of the circular economy is also often mentioned as a way of improving sustainability in cities.** There is no consensus on the definition of the circular economy – which is often seen as an open philosophy concept. In 'Conceptualising the circular economy: An analysis of 114 definitions', Kirchherr, Reike and Hekkert, 2017 provide the following definition: 'A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations.' There is considerable potential for integrating a city's technological systems through the circular economy. Besides being re-used or recycled, huge waste streams can be transformed into heat, electricity, gas, fertilisers, food and other products needed in a city. Different estimations exist on the role the circular economy could play in the EU. Kalmykova, Sadagopan and Rosado, 2017 estimate that implementation of the circular economy could save 6-11 % of the energy used to support economic activity, reducing the demand for primary energy by around 5-9 %, both worldwide and in the EU. The Ellen MacArthur Foundation, (2017) estimates that the circular economy could result in a 32 % reduction in primary material consumption by 2030, and 53 % by 2050 in the EU, compared to today, and could reduce GHG emissions by up to 50 %.

1.2 Drivers of decarbonisation in EU cities — the role of governance

Governance structures in cities across the EU vary considerably. Decarbonisation challenges are equally diverse, and city governments have organised themselves differently depending on the country, geographical location and other factors.

The complexity of urban systems stems from the numerous interactions and interdependencies in cities. Interdependencies in cities are both between scales (cities are part of regional, national and international systems) and different layers (such as the subsurface, infrastructure and occupation layers). Due to these interdependencies and interconnections, patterns and activities within such a complex urban system are only predictable to a certain extent, and depend on a range of actors. Therefore, adaptive approaches are needed for city planning and governance.

The notion of 'governance' (Koppenjan and Klijn, 2004; Torfing et al., 2012) implies that a government is one actor embedded in a network of multiple actors. It is this network of multiple actors that takes decisions and actions regarding complex and pressing policy issues. **Governance starts with a holistic view on urban systems and societal challenges.** It emphasises the importance of dynamic partnerships between public and private actors which can cope with the complexity of cities. Holistic approaches for coping with societal challenges are rare. Existing actor set-up, finance mechanisms, decision-making responsibilities and regulatory frameworks often do not allow a break with sectorial silos. A siloed and short-term urban investment strategy (either driven by public policy aims or private developers) has a risk of being unsuccessful. Planning for decarbonised, circular, smart and inclusive cities requires shared and long-term urban investments that are well embedded in the current urban systems and value chains.

Innovation and urban learning are key to solve pressing societal problems in the urban context. Knowledge of new solutions and the working of urban systems is scattered among many stakeholders. In some cases, city governments, academic partners and industry work closely together to demonstrate new solutions and optimise the urban system. Those partnerships usually emerge around specific challenges or technical opportunities. Their role is to detect innovation opportunities and create the space to develop them from pilot to successful upscaled solutions. In this context, governance can support strategic partnerships among sectors and silos by establishing test environments, setting clear goals and implementing innovative procurement strategies.

Government has a significant task to do in coordinating cooperation among different actors to enable both collaborative circular economy and smart city concepts. For instance, in smart cities, government has a role to play in securing access to IT infrastructures, if technology systems are privately operated and owned. They also have a role in managing the data generated in a city, both by analysing them to improve governance and by taking care of the privacy issues associated with such data.

1.3 Drivers of decarbonisation in EU cities – the role of citizens

Broad citizen engagement is key to successful zero-carbon transition in cities. In response, cities can become incubators of behavioural and lifestyle change. Citizens hold key knowledge on the working of urban systems. Consultations can help to identify and co-design more effective zero-carbon solutions because the citizens' views and knowledge on what works in reality may otherwise be overlooked by expert-driven proposals. Citizen engagement is also an instrument for creating the momentum towards zero-carbon transition by raising awareness, building acceptance, and encouraging citizens' actions.

Citizens are the ultimate consumers of energy, goods and services as well as the ultimate 'users' of the city and its infrastructures. Thus, in the future, climate change mitigation outcomes will depend on behavioural and lifestyle changes (Riahi et al., 2017), as discussed in Chapter 7. In addition to behaviour and lifestyles, citizens can also become active drivers of social and technical zero-carbon innovation. In the past, most of the zero-carbon innovations in various European and global cities have been driven by municipal governments (Castán Broto and Bulkeley, 2013) and have focused on technical solutions in energy and transport. Thus, all other kinds of social and technical experiments with zero-carbon solutions that are primarily driven by the citizens offer an untapped potential.

Either as individuals or households, citizens can, for example, produce part of the energy they consume using renewable sources, such as building-integrated solar systems. They can even become prosumers and feed the unconsumed electricity into the grid. Citizens can actively engage in demand-side management programmes with smart meters and integrated smart home solutions. They can also shift to less-carbon-intensive transportation modes, from cars to car sharing, public transport, cycling, walking or telecommuting.

Information, economic incentives, policy and regulation can be used to nudge citizens towards more active participation in zero-carbon action.

Citizens can enable zero-carbon innovation by becoming the funders of new projects, for example, through participatory budgeting. Citizen-led energy cooperatives and associations can support the realisation of medium-size zero-carbon solutions, such as neighbourhood-level energy projects. Citizen-run projects result in and boost various factors, such as awareness-raising about the need for and feasibility of climate mitigation, enhance the pride in individuals' neighbourhood or city, and improve community cohesion and integration.

1.4 An overview of other climate change impacts of/in cities

Cities are particularly vulnerable to climate change. This includes possible impacts of rising sea levels, more precipitation and higher temperatures (IPCC, 2014). Climate adaptation policies for cities will be needed to adapt to different levels of climate change. Further, some policies could address both mitigation and adaptation aspects — providing benefits for both areas in terms of decarbonisation and increased resilience. Examples include local production of renewable energy, urban farming and greening of the city.

1.5 State of play in EU funding for research on decarbonisation in cities

Today, many EU R&I funding programmes support the decarbonisation of cities. A wide set of EU-funded programmes is available for funding research, innovation, demonstration, and for supporting the deployment of policies or testing new governance approaches. Among them, the Horizon 2020 programme is the largest, while other programmes are targeting public authorities in order to tackle urban challenges (such as the European Regional Development Fund (ERDF) and the URBACT initiative).

2 Case studies

European cities differ in size, climate, economic growth, social life, energy mix, etc. R&I should support the whole range of different conditions that apply to cities.

There are many examples of European cities with a successful record of climate action (Reckien et al., 2018). From these lighthouse cities, lessons can be learned that provide insight into the R&I needs for the future. The decarbonisation efforts in three diverse cities in different parts of Europe have been selected and are described below.

A city in the North: Stockholm

Facts

Location	Capital of Sweden, on the Baltic Sea coast
Population	950 000 inhabitants (1.8 million in the metropolitan area)
Population density	Ca. 3 600 persons/km^2
Ancient history	Founded in the 13^{th} century
Modern history	Construction of full-scale waste-water treatment, metro and district heating in 1930-1950. Experienced great expansion in the 1960s. Strong population growth since 2000.
Major business areas	ICT, life sciences and clean tech.
Jurisdiction	Strong mayoral powers regarding buildings, city roads, land use and water. The city owns most land and gets its financing from income taxes.

The city of Stockholm developed its first action plan to mitigate GHG in 1997 in response to national environmental targets. Today, emissions are 37 % lower than they were in 1990 (44 % if measured per capita). Over the same period, Stockholm's population has grown by 37 %. 70 % of the total energy supply in the city comes from renewable sources. Its current target is to become fossil-fuel free by 2040 and to achieve 2.2 tonnes CO_2-eq per inhabitant in 2020 (2.5 tonnes in 2016).

In Stockholm, low-carbon urban planning is at the centre of the zero-carbon transition. An example is the Royal Seaport eco-district in which zero-carbon solutions are tested before being scaled up to city level. Favouring walking, cycling and public transport over car use is one essential part of urban planning. A 'green parking index' is used to promote new mobility schemes at the expense of private cars.

The actions for reducing emissions in Stockholm have been centred on heating, transport, waste, electricity and gas. The district heating system was developed in the 1960s and now provides heat to around 80 % of the buildings. Over time, oil and coal have largely been replaced by incinerated municipal waste and wood chips as well as heat recovery from the sewage system. This waste-to-energy policy is the centre of the city's circular economy. The latest development includes refrigerated stores and data centres as sources of heat. The district heating company is now looking into large-scale CCS from bioenergy combined heat and power (CHP) in order to create negative emissions. Energy efficiency in the city is also an area of work. For instance, an insulation programme targeting the large residential areas of the 1960s has been started and measurements show that the supply of heat could be cut by 60 %.

The city has promoted biofuel-powered public buses. Further, since 2006, the Stockholm has a road-pricing system with automatic reading of number plates. This 'congestion tax' has reduced rush-hour traffic by 20 %, cut emissions and brought financing to future infrastructure investments. This was a controversial measure when introduced, but it is now embraced by all actors. A network of filling stations for biogas provides fuel for taxis, freight and service vehicles. Electrification is under way, with 700 public charging points. The city's procurement of transport has been used as an instrument to stimulate low-carbon development in the transportation fleet, with a 50 % share of renewable fuel as a requirement for new contracts.

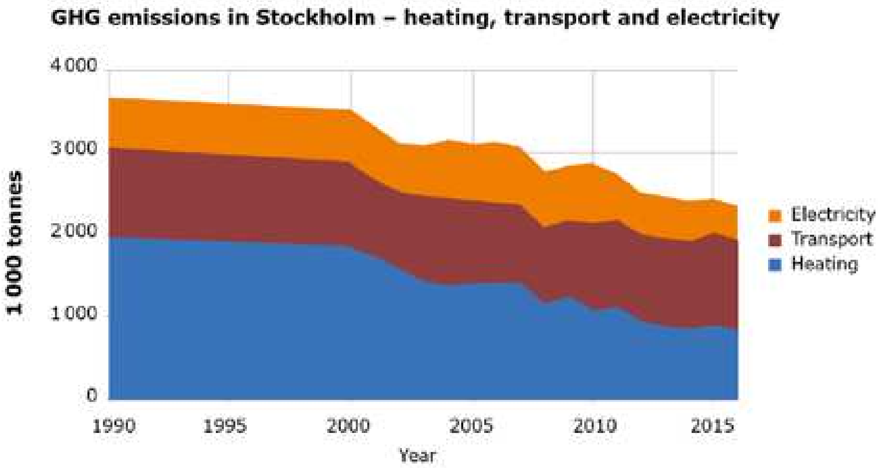

Figure 16: Historical development of GHG emissions in Stockholm per sector; total emissions are down 37 % since 1990. Source: Stockholm local government, 2018.

The city's waste-management system includes source separation for material recovery, energy recovery from incineration and digestion of sludge and organic waste to biogas. Only 3 % of the waste is put into landfill. In 2017, a pilot plant for producing biochar from green waste was inaugurated. The biochar, which is used as a soil improver in the city's tree plantations, is likely to be the world's first urban carbon sink and its operation is economically profitable.

The environmental programme assumes a strong position in the city's governance. Stockholm's Vision 2040 is a long-term complete vision for city development built around the different aspects of sustainability. All environmental sub-targets are reported regularly in the city's integrated management system. The long-term targets are communicated to citizens and local enterprises in order to build momentum.

Stockholm has explored the synergies between decarbonisation and digitalisation. Apart from the energy recovery from data centres mentioned above, open data is provided for app developers, and there is cooperation with the academy and local companies known as Digital Demo Stockholm. Using the latest ideas in IoT and Big Data, new applications are being developed and tested in practice.

Important success factors include the systematic use of targets and measurements, the exploitation of national tax incentives promoting renewable energy, the deployment of demonstration projects within the EU Framework Programmes, and active dialogue with industry, academia and the public. Stockholm was awarded the title of Europe's first Green Capital in 2010 (City of Stockholm, 2015). The city was assessed in 2012 as an international 'green leader'. While Stockholm has progressed in many of the city's decarbonisation challenges, some of the key remaining challenges include how to reduce emissions from the transport sector and from fossil plastic that is incinerated with waste streams.

A city in the east: Warsaw

Facts

Location	East-Central Poland
Population	(2017) 1.758.143 inhabitants (3.2 million metropolitan area)
Population density	Ca. 3 330 persons/km^2
Ancient history	Founded around 1300
Modern history	Rebuilt after WWII, metro lines open in last 20 years
Major business areas	ICT, biotechnology, energy, agri-food, tourism
Jurisdiction	Strong local government policy powers and ownership over public buildings, transport infrastructure, roads and water systems.

Background of action plan, changes and targets

Warsaw has made significant efforts to become more sustainable within a nation that is known for its adherence to traditional methods of energy production (Michał Olszewski, 2018). The Sustainable Energy Action Plan (SEAP) for Warsaw was published in 2011, presenting a version of the EU 20/20/20 goals tailored specifically for the city. When the document was written in 2013, GHG emissions in Warsaw were: 78 % from the energy sector, 15 % from the transport sector, and 7 % from waste management and waste-water treatment. Within the transport sector, individual vehicles comprised 40 % of total travel and 80 % of emissions. According to the plan, and taking 2007 as a base year, in 2020, the maximum energy consumption must not exceed 22.7 million MWh per year (Infrastructure Department of the City of Warsaw, 2013).

The plan promotes action on several issues. As regards the housing sector, Warsaw faces a key challenge that many buildings were built in prefabricated style from low-efficiency materials. The plan addresses this challenge by setting targets for thermally retrofitting all residential buildings and modernising all heat sources, indoor lighting and appliances. The efficiency of the water-heating systems will also be upgraded. The plan also sets goals for the public sector, including retrofitting of public buildings, modernisation of street lighting, replacement of office equipment, and organising information campaigns.

Within the transport sector, the intention in Warsaw is to both modernise transport and road systems and to foster change in how the residents travel, by promoting walking and public transportation rather than car travel. To achieve this goal, a transit authority in the city has been established and several actions are planned, such as the development of trams and subway systems, the improvement of railroad efficiency, the replacement of rolling stock and integration of transit methods, and the improvement of bus transit and optimisation of routes. The local government is promoting public transport by expanding its infrastructure and introducing a common ticket for public transport.

Furthermore, the plan sets a roadmap for modernising the district heating network, adapting the electricity grid for renewables, and enabling prosumers (e.g. citizens producing their own electricity via solar panels) in the city.

By 2014, the following goals had been achieved (Climate Scorecard, 2018):

- transportation modernised with electric buses and trams and energy-efficient trains;
- public bikes schemes made available;
- hybrid rubbish trucks increased to 12.2 % of the fleet;
- housing sector improved with better lighting, appliances and retrofitting insulation.

Warsaw has made significant efforts to introduce a variety of public-awareness strategies to help citizens get involved with decarbonisation efforts. Actions specific to the city include:

- Picnic with Climate: Every year since 2008, the City of Warsaw has organised for families to come together to discuss and take quizzes on climate;
- Tree Day: Every year since 2003, NGO Klub Gaja organises joint tree planting based on local involvement, focused in particular on getting children involved;
- Warsaw Recycling Days: Every year since 2006, the day aims to promote environmental awareness, when citizens may exchange recyclable materials for green items like seeds and flowers.

Overall, the city has significantly improved its sustainability compared to other areas in Poland. Interestingly, public-awareness campaigns and changes in citizen behaviour has played a key role in this change. Behavioural changes were promoted through targeted incentives, which were well received by the local population.

A city in the south: Barcelona

Facts

Location	North-Eastern Spain, on the Mediterranean Sea
Population	(2018) 1.628.936 inhabitants (3.2 million metropolitan area)
Population density	Ca. 16 000 persons/km^2
Ancient history	Founded between 5th and 3rd century BC
Modern history	Expansion to prepare for 1992 Summer Olympics
Major business areas	ICT, biotechnology, energy, agrifood, tourism
Jurisdiction	The city has strong powers and ownership over public buildings and urban land use. However, it has limited power over the city's energy supply and partial powers over the transport infrastructure.

Background of action plan, changes and targets

Barcelona has long struggled with poor air quality, and in recent years has sought to strengthen efforts to reduce local pollution – in parallel with climate change mitigation action. The city sets out its climate roadmap for 2014-2018, which comprises several strategic measures (City of Barcelona, 2012). The strategic measures are divided into sectors, namely: energy and air, public transit and mobility, climate change resilience, waste management, and biodiversity.

While the climate roadmap is important to set out the city's vision on decarbonisation, **in Barcelona, climate action is addressed in all sectors in a transversal way across plans.** The city is addressing, in particular, mobility-related GHG emissions with tailored mobility and innovation plans – which are primarily aimed at reducing local pollution (City of Barcelona, 2014). The plans address three fundamental aspects of mobility to be improved by 2018.

The first is **improving the city's mobile fleet.** To accomplish this, Barcelona has set out a plan to subsidise citizens who wish to trade their old vehicles in for cleaner, newer ones, with the possibility of contributing up to EUR 2 500 per vehicle. Similarly, those who wish to purchase electric or hybrid vehicles may also receive a subsidy from the local authorities. The plan aims to have 15 % of hybrid vehicles in 2020. Furthermore, municipal vehicles are being progressively replaced by electric or hybrid variants.

The second aspect concerns **optimising the number of vehicles in the city's streets and traffic flows**. The first project working towards this is improving car-pooling options by setting up a website to inform the population and establishing a network of high-occupancy vehicle (HOV) users. This is aimed at increasing the coefficient of vehicle occupation in the city in 2020 from 1.18 to 1.4. Another project is working to improve car-sharing options, aimed at establishing a fleet of vehicles throughout the city which citizens can use as required, paying a fee for the service and kilometres travelled. Finally, optimisation of the current taxi network is also under way. In an effort to reduce the amount of time taxis spend in traffic without passengers, more taxi stands are being established throughout the city, and users are encouraged to book before a drive, to optimise taxi drivers' routes.

The third and final aspect is the **management of transport.** Redesign of the bus networks is a key project. Orthogonal routes are being planned together with priority roads for buses, and special lanes for buses and HOVs. Finally, the schedules and frequency of buses are being reanalysed to optimise traffic flow and reduce fuel usage.

In addition, on 1 December 2017, the city introduced a low-emission zone within which cars that do not possess a city-defined environmental label are not allowed to go. This is currently valid only when the air quality is poor, but it will become permanent in 2020.

Furthermore, **the city of Barcelona has several projects addressing the green and circular economy and biodiversity.** A range of actions are being promoted, such as shifting towards renewable sources, electric mobility, waste prevention, increasing green spaces, and support for innovative business (such as bycing — the city's bike-sharing scheme). Barcelona does not only rely on public initiatives, but several companies, designed with a circular economy perspective, are now emerging. E-sharing motorbikes (ecooltra, mottit, taro) are expanding in Barcelona, alongside cooperatives in the farming sector (e.g. promoting competitiveness and reducing organic waste in a localised way) and in the building sector (e.g. promoting flexible, modular and shared spaces) (City of Barcelona, 2018).

Barcelona is a good example of the co-benefits of decarbonisation. Most of the policies designed to reduce emissions in cities do not specifically address climate change mitigation, which features as a cross-cutting issue across policies, but rather focus on improving the local air quality and the city's liveability. Nevertheless, these are key drivers for cutting local GHG emissions.

3 Lessons learned and R&I gaps

3.1 Technologies, smart cities and the circular economy – lessons learned and R&I gaps

As mentioned in the introductory part of this chapter, **European cities are very diverse, both within and among countries.** Even within cities, building stocks in different areas differ in energy efficiency and level of digitalisation. In addition, as noted in the three city case studies presented in this chapter, different cities are adopting different low- and zero-carbon solutions — making a case for the transmission of knowledge on decarbonisation solutions across geographic boundaries to scale up promising solutions in the EU. In this diverse context, it is possible to recommend some R&I actions that would be beneficial for EU-wide action on decarbonisation in cities.

The first recommendation in this context is that there is a need for **R&I to help develop cities as integrated and zero-carbon systems.** To achieve this, cities can work as 'living labs' engaging every actor, from citizens to academia, local businesses and the municipality, to test innovation in practice.

Many technical systems are controlled by the city. Integrating them provides possibilities for more efficient processes, less demand for energy, and greater access for citizens to technologies and methods for decarbonisation. To achieve this, there is a need for R&I to further **develop and test smart cities concepts**. These are crucial for integrating innovative technologies and ICTs in the urban system. Technologies, such as energy-management systems, monitoring sensors, and steering algorithms are meant to improve efficient use of urban (physical) infrastructures. For instance, smart thermal grids, multi-commodity grids, mobility-as-a-service measures, as well as smart lamp posts and smart bins reduce energy consumption. In the EU context, the effectiveness of these measures is continuously being monitored and analysed for each specific urban context, in order to find the best solutions to upscale. Also, electrical mobility (as described in Chapter 3) can be enabled in cities by higher digitalisation of the system.

Although smart city projects are often driven by infrastructure and technology, the major barriers to successfully implementing smart solutions are related to governance (i.e. ownership, business models and incentive structures). In particular, smart city projects usually develop new, innovative infrastructure layers (roads, grids, buildings) within existing urban systems. These new layers have to be connected with the existing infrastructure. Here, there is a trade-off between, on the one hand, choosing to develop highly innovative new techniques that replace existing infrastructures and do not connect well with the old system or, on the other hand, choosing less-innovative solutions that do not significantly challenge the existing interests and system. Several recent examples demonstrate the latter. Due to existing interests and path dependency, innovative smart solutions are designed and embedded in such a way that they do not fully grasp the innovation and carbon-reduction potential. Avenues for future research in smart cities should cover: i) policy aspects regarding how to balance the public and private interests of technical and ICT operators; ii) data quality and data-gathering issues around big data; and iii) ownership and privacy issues in smart cities.

Part of the integration of low- and zero-carbon technologies and strategies in cities will involve exploring **smart urban spatial strategies.** Both for new cities and existing city areas being revitalised or expanded, smart spatial strategies will be needed to integrate zero-carbon technologies and strategies. These include renewable energy sources, energy storage, green areas and other carbon sinks, and would cover cities both underground and overground.

Furthermore, many technological systems will need to be improved and integrated for low- and zero-carbon cities. **In the building sector, R&I on how to improve the efficiency of the existing stock** will be needed. Continuous R&I will be required to promote both the refurbishment of existing non-efficient buildings and the design of innovative strategies for near-zero-energy buildings. That will include R&I on the necessary policies, programmes, technologies and economics to reduce emissions across the wide array of building types in the EU.

Further R&I will also be needed to **understand the role of cities in producing electricity and heat locally.** As cities are hot spots of high-density energy demand, various energy supply and end-use efficiency improvement solutions, from district heating, electrification, local renewable systems, electricity and heat storage, or building retrofitting, can be combined. The exact solutions will differ significantly among the different European cities. Solar, geothermal, bioenergy, waste and wind sources can be harnessed in cities for local electricity and/or heat production. Research is needed to understand their potential and integration in the urban energy system, while the flexibility of different energy systems to be upgraded to avoid path-dependencies and technology lock-ins as energy services require change. As for heating, in addition to the much-investigated renewable heat sources, such as biomass-based CHP or solar thermal units, geothermal energy in cities offers a substantial source of heat (Hirschberg, Wiemer and Burgherr, 2018). Shallow geothermal systems with heat pumps, seasonal underground storages for heat and cold, or deep systems that reach to 3-5 km in depth and produce both heat and electricity can all contribute to zero-carbon cities with a diversified energy supply. Berlin's Reichstag (German Bundestag, 2018) building and multiple geothermal projects in Munich are several examples of successful projects.

R&I will also be needed to explore the benefits of **electrification and biofuels in transport** (see also Chapter 3). Electrified urban transport gives important co-benefits such as improved air quality and lower noise — and integrates well with 'smart cities'. Construction machinery and transport on land and water have the potential to be electrified and integrated with smart cities concepts. At the same time, there is a need to better understand and utilise the benefits of biofuels in the urban transport decarbonisation challenge, thereby also supporting the bioeconomy.

For integrating the above-mentioned systems, **circular or semi-circular economy** can also have several benefits, including less pressure on the environment, enhanced security of the raw materials supply, greater competitiveness, innovation, local growth and jobs. However, the shift to a circular economy poses several challenges, such as financing, understanding the needed economic enablers and skills, and the integration of multi-level governance. Furthermore, in the integration of the technical system, the circular economy should experiment with different technologies, both mature and innovative. Broader research will be needed on those technologies that enable the circular economy. Waste management, digitalisation, district heating and transportation optimisation are some of the topics that best relate the circular economy with technology. On the topic of waste management, synergies and trade-offs between reuse, recycling and waste-to-energy strategies should be further investigated. To overcome the challenges above, there is a need to better understand and research how outputs from one process can feed another in cities — which also depends on their location and size. For this to happen, there is a need to map the efforts towards the circular economy in different countries and cities to understand differences and capture best practices.

Finally, to understand decarbonisation efforts in cities, continuous efforts will be needed to **monitor and collect data** on building efficiency, energy usage and citizens' behaviour. Further research will be needed on how IT can act as an enabler of different decarbonisation strategies in cities — building on and analysing the large amount of data being made available thanks to digitalisation. This will play a key role in collecting and analysing data, and further R&I will be crucial for analysing and gathering meaningful data from the digitisation processes in cities. Monitoring the effectiveness of climate action in cities as a response to new policies and innovations is key for evaluation and cross-city learning. R&I is needed to establish shared decarbonisation indicators that can be applied across cities to monitor, communicate and benchmark progress. Finally, networks of cities could be created to facilitate exchange of experiences and best practices.

3.2 Governance of cities — lessons learned and R&I gaps

Addressing societal challenges in a holistic and integrated way requires cooperation and cross-sectoral alignment. To build on this issue, a particular challenge should be addressed — that the regulatory power of cities is limited. Moreover, the type of power that cities have varies across Europe. This is especially true for the possibility to finance climate action and to stimulate private partners and consumers to do so. **There is a need for R&I to establish how to enable governance of decarbonisation in cities**, which will include several R&I actions.

Best practices in zero-carbon urban planning will have to be mapped across EU cities. In new districts in particular, urban planning allows zero-carbon solutions to be tested so that they can then be scaled up to the rest of the city. One example of this is the Stockholm Royal Seaport. Transport efficiency is a key outcome of such practices. The dense and walkable city, where new developments are located around public transport nodes, is less energy consuming than cities characterised by urban sprawl and car dependency. New and more sustainable mobility patterns can be fostered using careful planning, easy access to walking and cycling, and innovative parking policies. R&I is needed to better understand how new developments in cities can be planned to enable zero-carbon transition.

Given the diversity of EU cities, R&I is needed to support the development and exchange of **financing tools, new incentive models and business models** that can support cities with different powers. Outcomes from such a programme may stimulate the upscaling and replication of successful measures and solutions in other countries. R&I could be used to understand how procurement procedures could be used to support the adoption of zero-carbon technologies or to redefine how public-private partnerships might operate. Strategic public entrepreneurship can be explored as a means of promoting decarbonisation in cities.

Another important area of R&I emphasises the **role of vertical, multi-level governance**. Cities need national policies and EU directives to be successful. This underlines the importance of integrated policy action at the European, national and local level. There is a need for R&I to understand this interplay, and, most importantly, policy action at the European level to enable cities to take action against GHG emissions. EU funding instruments should support cities' specific needs, and should be easier to use. There is also a need to coordinate the different instruments.

Finally, climate is only one of the challenges facing governance in European cities. Social sustainability, integration, job creation and health are all important aspects for mayors in European cities and municipalities. The city of Barcelona case study is the perfect example — in which the climate mitigation policy is highly intertwined with the local air-pollution policy. Further R&I is needed on how to facilitate integration of these complex tasks and to find and promote synergies. In addition, there is a need for **understanding and mapping the co-benefits (e.g. with air pollution and health strategies) and trade-offs (e.g. costs) of climate action in cities with other development goals** in order to coordinate policymaking (Fuso Nerini et al., 2018).

3.3 Citizen engagement — lessons learned and R&I gaps

Different European cities will need to take very different paths and strategies for engaging their citizens in zero-carbon innovation, depending on the locally available technical and social solutions as well as the cities' economic, societal and regulatory contexts. As the previous section shows, the zero-carbon strategies of Stockholm, Barcelona or Warsaw are very different. It is therefore important to understand the differences and similarities among European cities in terms of zero-carbon innovation potential and options, as well as to observe how innovation emerges, diffuses and can be fostered.

To truly tailor zero-carbon strategies to every specific city, **local citizen engagement processes** are irreplaceable. In line with the democratic principle of involving those who will be affected, and in order to come up with realistically implementable and scalable solutions, broad citizen dialogues and visioning processes will be key. Very little is currently known about citizens' visions of zero-carbon cities and zero-carbon societies in Europe and how these visions could be integrated into broadly legitimised and realistically implementable zero-carbon strategies that mobilise citizens' critical capacity (Creutzig et al., 2015). Citizen consultations and digital crowdsourcing of citizens' ideas could help develop such an overarching zero-carbon vision. The UK 2050 Calculator has proved an effective means of engaging citizens in the deliberations over very complex, national-level decarbonisation (Pidgeon et al., 2014).

Although top-down techno-economic assessments indicate the important potential for emission savings through behaviour and lifestyles changes and social innovation (Creutzig et al., 2016), there is comparatively little evidence on assessing this potential against real-world empirical observations and investigating how such potential could be enabled and then scaled up. Large-scale generalisable empirical studies as well as local case studies, such as living labs, are key to unpicking the complexities of zero-carbon actions, including citizens' goals, preferences, habits and norms. Without substantial evidence from social and behavioural sciences, it is difficult to say whether European citizens will broadly accept and actively embrace their new role in zero-carbon cities.

European citizens will become an integral part of the zero-carbon transition, both by embracing the change as well as driving and sustaining it through social innovation. Citizens' perspectives on how their zero-carbon cities of the future should look are key for developing strategies that will be supported and realistically implementable. **New mechanisms for fostering bottom-up social innovation and the adoption of zero-carbon lifestyles should be experimented with.** More research is needed into understanding how information, economic incentives, policy and regulation can nudge citizens towards more active participation in zero-carbon action.

Low-carbon innovations in cities have so far primarily included technical innovations in the energy and transport fields (Castán Broto and Bulkeley, 2013). End-use technologies and social innovations tended to be marginalised in past research compared to larger-scale technical solutions (Wilson et al., 2012). It is therefore key to expand the evidence with **R&I on the full range of citizen-centric technical and societal zero-carbon innovations in cities**, including dietary changes, the sharing economy, ICT, participatory budgeting, and many others. For example, experiences from successful free web platforms for car-pooling, such as AhaCAR in Bulgaria, Greece and Serbia, where the drivers and passengers distribute the travel costs among themselves without anyone gaining financially, could help inform sharing solutions in other cities or even other zero-carbon innovations. Monitoring and evaluation has a key role to play in understanding under what conditions successful initiatives emerge and how they are enabled in terms of financial, natural and human resources. This evaluative evidence should extend from the behaviour of individuals and households to low-carbon peer groups and cooperatives and even to networks of European cities.

Citizen engagement is one part of the overall zero-carbon transition governance in cities, whereby multiple stakeholders in local, regional and national governments as well as in industry and businesses have a role to play. In fact, the analysis of ongoing urban climate experiments worldwide indicates that new governance schemes emerge, for example, with deeper cooperation between private and public bodies (Castán Broto and Bulkeley, 2013). Integrated governance approaches will align and leverage the actions of all the stakeholders and citizens for fast and productive zero-carbon innovation.

3.4 Other areas of R&I

There is a need to understand the **co-benefits of climate action** in cities, across the full range of SDGs. Climate policies can interact and have synergies (or trade-offs) with many development goals (Fuso Nerini et al., 2017). As examples, policies to improve liveability and health outcomes in cities can also result in decarbonisation, and vice versa. Expanding green spaces in cities can enhance the role of cities as ´carbon sinks´. As seen in Barcelona, policies targeted at reducing local air pollution can have clear decarbonisation co-benefits. And climate mitigation in cities can support the mitigation of energy poverty in cities, targeting the 54 million European citizens (10.8 % of the EU population) unable to keep their homes adequately warm in 2012 (Pye and Dobbins, 2015). Actions to improve the efficiency of buildings and the management of energy in households can also help to address the pressing issue of energy poverty in buildings, whilst reducing GHG emissions, too.

Finally, there is a need to **improve the visibility of R&I funding for decarbonisation in cities.** There are many EU-funded R&I actions in cities, but presented on many separate web pages, with different rules and criteria. Local and regional authorities — as well as academics — can lose themselves in the information flow. A one-stop shop, where all the tools available for cities could be explained (amount, criteria, etc.) could help local and regional authorities to navigate this information. To make it as user-friendly and intuitive as possible, this should be available in every Member State to allow local and regional authorities to access a set of instruments that could fit both their needs and their purpose.

3.5 From low-carbon achievements to zero-carbon cities in 2050

A system-level approach, combining all the areas of innovation listed above, will have to move from localised low-carbon achievements to zero-carbon cities. First of all, strong city governance and vision will be needed. The governance will have to set clear zero-carbon targets and accompanying strategies to achieve the strategies. For the transition to happen, citizens' buy-in and engagement will be crucial. All zero-carbon technology solutions will have to be used and tailored to the local context, and all of them combined in a smart city concept. Electricity consumed in cities must be zero-carbon, which means this challenge will also depend on decarbonisation happening in national power systems. Cities will also have to influence the power mix by producing renewable electricity locally. Transport and heating will also have to become fully decarbonised based on a mix of renewable solutions and maximising internal flows. Waste will need to be minimised, and the circular economy promoted. To summarise, there will be no single 'silver bullet' solution for zero-carbon cities, but all the solutions listed above will have to be used in conjunction with and tailored to the local context.

4 Recommendations for research and innovation

R&I on how to develop cities as an integrated zero-carbon system. R&I is needed on how to integrate technical and social systems for low- or zero-carbon cities. Key R&I questions relate to how renewable energy, electric mobility, and efficient and smart buildings can be integrated in a single city 'organism'. This should include how the concept of 'smart cities' and digitalisation can provide the tools for the integration of such systems. R&I should also explain how this integration might differ in cities which vary according to location, size and existing building stock and transportation infrastructure.

R&I on the circular or 'semi-circular' economy in cities. There is a need to better understand how outputs from one process can feed another process in cities. For instance, urban waste must be used and recycled in the most efficient way. Energy, new products and carbon sinks can also be developed in new innovative processes, using local resources. For that to happen, the efforts towards the circular economy must be mapped in different countries and cities in order to understand differences and capture best practices. R&I on this topic should also include how the size and density of a city may affect its 'circularity' and whether or not there is an 'optimal' extent to the circularity of a city's systems.

R&I on how to enable governance for decarbonisation in cities. R&I is needed to support strong governance for decarbonisation in cities. The regulatory power of cities varies across Europe. Several have limited regulatory power for financing climate action and stimulating private partners and consumers to do the same. R&I is needed to understand the regulatory power that cities require to implement local climate action, and how it interacts with national and EU policy. Moreover, R&I is required to support the development and exchange of financing tools, new incentives and business models and partnerships that can support cities with different powers. Finally, R&I is needed to understand how governance can support energy-efficiency interventions in the EU's existing building stock.

R&I on how to engage citizens in cities' decarbonisation strategies. European citizens should become an integral part of the zero-carbon transition, both by embracing the change as well as driving and sustaining it through social innovation. Research is needed to understand the most effective strategies for engaging citizens, and how the location and size of a city can influence such strategies. Furthermore, R&I is required in order to understand how information, economic incentives, policy and regulation can nudge the citizens towards more active participation in zero-carbon action. New mechanisms for fostering bottom-up social innovation and the adoption of low-carbon lifestyles should be experimented with.

All the above should be addressed through a **mission-oriented action** to be launched in Horizon Europe which should include what is indicated in Figure 17.

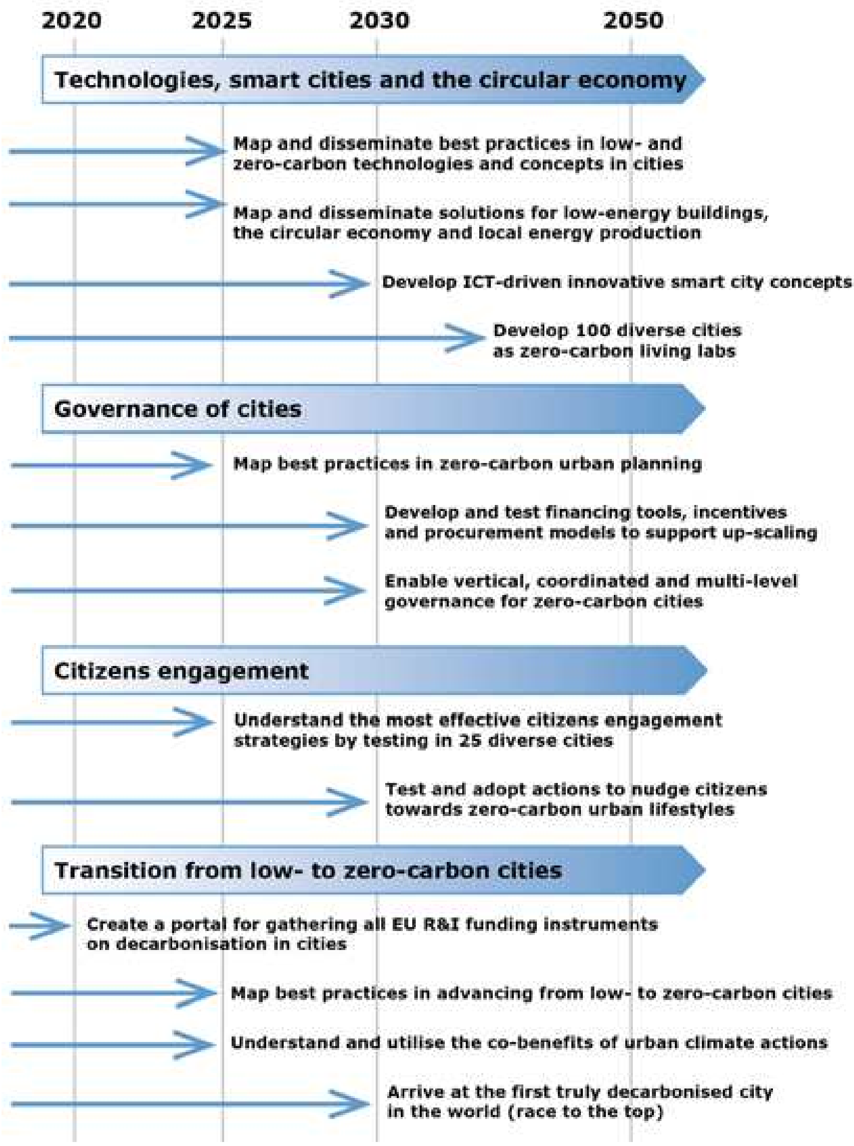

Figure 17: Possible R&I pathways to decarbonisation in cities.

CHAPTER 7

EU CITIZENS FOR THE DECARBONISATION OF EUROPE: THE ROLE OF SOCIAL INNOVATION AND LIFESTYLES

1 What can EU citizens do and how can they contribute to decarbonisation?

A scientific consensus exists stating that it is difficult to reach the targets of the Paris Agreement with technological and policy measures alone, without addressing social changes too. While the other chapters in this report emphasise the role of technological solutions and policies for the decarbonisation of Europe's economy and society, this chapter focuses on the role that EU citizens[21] can play in the decarbonisation of Europe and how social innovation can provide 'bottom-up' solutions, frameworks and incentives to make this change.

The transition towards a carbon neutral economy and society in Europe will require deep changes in its economy, institutions, politics, social networks and people's behaviour. This will create many social challenges that should be tackled with innovations in the socio-cultural sphere. EU citizens can change their behaviour to reduce their carbon footprint and can start initiatives that reduce CO_2 emissions — 'social innovation for decarbonisation'. Behavioural change and social innovation both have their own merits and are separate concepts, but social innovation can also enforce behavioural change.

Social innovation creates the social context for adoption of zero- or low-carbon technologies, products or services and the context in which citizens can change their behaviour. With this, it is an essential element of the low-carbon transition that complements technology-driven approaches. This emphasises the role of both behavioural/social change and technology and brings them together as two sides of the 'decarbonisation coin'. Social innovation activates specifically local social networks for decarbonisation. Through its bottom-up character and the fact that it is rooted in the specific local context, it complements 'top-down' public policies addressing decarbonisation. Social innovation, in general, contains two 'core conceptual elements' (Van den Have and Rubalcaba, 2016): '1) *a change in social relationships, -systems or –structures*, and 2) such changes serve *a shared human need/goal or solve a socially relevant problem*.'

Social innovation is often contrasted with the business type of innovation, but mixed forms of the two also exist. Social innovation is always embedded in the specific local context, which emphasises its European character and relates to the European capabilities and comparative advantage. Because social innovation is seldom a 'stand alone innovation', and is often realised in social networks and/or in combination with certain technological innovations, products or services, its impact on decarbonisation is difficult to measure, and not much data on the actual impacts is available.

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[21] By 'citizens' we mean people in general, in different roles as consumers, initiators, investors and participants in the democratic process.

Behavioural change and social innovation cover a rather broad field that is not limited by geographical scales, domains or topics/subjects. For instance, social innovations can be developed and applied in cities, but also in rural areas, where they can play a role in, for instance, combating poverty or unemployment or promoting social inclusion or decarbonisation, or combinations of these issues. Education can furthermore enforce behaviour or lifestyle change, by delivering information on which behavioural changes are most effective and how to implement them, and in delivering (social) support for the behavioural change.

In this chapter, the roles of EU citizens in behaviour and lifestyle change and in creating social innovations are elaborated.

2 Behavioural and lifestyle change for fewer CO_2 emissions

A plethora of elements create lifestyles that ultimately contribute to climate change — the type and size of housing, comfort expectations for heating or cooling, and daily practices in or outside homes. The location of housing, work and leisure activities as well as the choice of a car, public transport, cycling, walking or aviation for transport lead to very different carbon footprints. Increasing consumption of meat as well as fruits and vegetables that have been transported over long distances and refrigerated for long periods drives emissions upwards. Even more fundamentally, there has been a transition towards large air-conditioned shopping malls that are massive energy consumers and — in contrast to smaller, local stores — reinforce carbon-intensive lifestyles. Although there is still diversity across individual households, recent decades have evidenced a convergence across countries, cultures and households of various incomes towards an energy- and carbon-intensive lifestyle.

Citizens can contribute significantly to fighting climate change in their homes. Globally, lifestyle changes could reduce residential emissions by an extra 13 % by 2050 — on top of emissions reduction by technological measures — as compared to the emissions in the baseline scenarios (van Sluisveld et al., 2016). This 13 % reduction covers measures such as reducing thermal comfort, reducing hot water consumption, capping household size per capita, reducing the use of appliances and switching to smarter ones, reducing waste, and recycling. If behavioural plasticity is considered (i.e. the share of population that could be realistically induced to change), the behaviour changes that are associated with heating, ventilation, air-conditioning, hot water and building retrofitting in the United States could offer residential emission savings of up to 10 % in a decade (Dietz et al., 2009). Beyond these integrated studies that embed ambitious behavioural change in a whole-system perspective, there are only scattered case studies (Creutzig et al., 2016). Some emission reductions only depend on behaviour and are hence easier to achieve, for example line drying instead of tumble drying, turning off lamps or avoiding stand-by mode. Other changes require new infrastructure, such as smart metering, or substantial investment, such as building retrofitting.

Change in transportation choices offers a vast potential too. By 2050, lifestyle changes that reduce vehicle use and foster modal shifts could globally reduce residential emissions by an extra 35 % as compared to the baseline scenarios (also in van Slusveld et al., 2016). A behavioural assessment of the reasonably achievable reductions in the United States estimated more cautious emission savings of 8 % in a decade due to purchasing new fuel-efficient vehicles, low resistance tyres and improved vehicle maintenance and driving behaviour. As aviation is another relevant contributor to climate change, any change in lifestyle that avoids or reduces air travel is key (Girod et al., 2013). Specific case studies and techno-economic assessments at times aspire to much more ambitious reductions, yet they do not offer a full behaviourally-informed system-wide assessment.

Circular, sharing and second-hand economies can increase the overall efficiency of using energy, materials and natural resources and hence reduce emissions. Although the circular economy is a broader concept that crosscuts various activities from consumer to industrial levels, households can systematically reduce the flows of energy and materials by means of reducing unnecessary consumption, and by repairing, reusing and recycling. Interactions across individuals and households as part of the sharing and second-hand economy (Frenken and Schor, 2017) could further help to minimise carbon footprints. The unused goods could be donated, lent, rented or resold. The sharing and second-hand economies not only apply to household appliances or small consumer goods. They can reach more fundamentally to the increasingly popular car sharing or less common co-housing.

The diet choices of European citizens also translate into a vast spectrum of emission outcomes. Figure 18 shows the variation in the per-capita carbon footprint of food consumption in European households (Ivanova et al., 2017). Despite this variation in local cuisines and habits, transition from beef to pork, cod, chicken and, especially, plant-based food offers significant emission cuts. For example, replacing a full beef-based meal with a vegetarian one cuts emissions by over 10 times per meal (Carlsson-Kanyama and González, 2009). Further emission reductions can be achieved by minimising over-purchasing and food waste, consuming less food with low nutritional value and growing one's own food or engaging in community gardening.

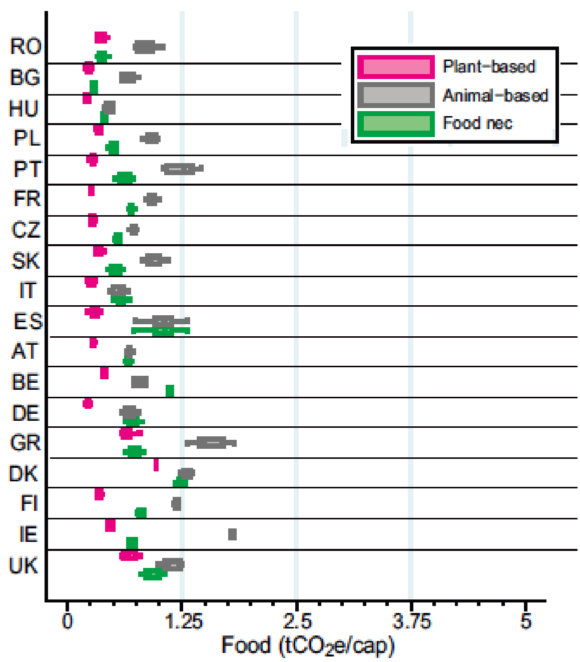

Figure 18: Household carbon footprint of food consumption per capita across Europe. Nec = non-classified food. (Reprinted with permission from Ivanova et al. 2017)

However, the real change in behaviour and lifestyles is difficult to achieve. In theory, most of the behavioural measures to save carbon emissions can be adopted comparatively widely, easily and rapidly in any European country. Many of these changes require behavioural plasticity and are not dependent on regulatory interventions or upfront monetary investment. Yet the increasing wealth of European families as well as the convergence of behaviour across countries currently lock Europe into high-carbon lifestyles. Even if some behavioural measures offer monetary or time savings, these savings can then in return be spent on new activities or appliances that lead to increasing emissions due to rebound effects.

Top-down policies for behaviour and lifestyle change have been typically complemented by public information campaigns. Deliberate strategies with a mix of information, regulation, economic incentives/taxes and social engagement have proven to work in other areas, such as the reduction of smoking or the slow but continuous transition to 'de-motorisation in cities' or healthier living. There are lessons to be learnt from these experiences for the decarbonisation challenge. Behaviour change can emerge quite suddenly, but then take years and generations before it diffuses among the wide population.

There are still knowledge gaps about the contribution of lifestyle and behavioural change to decarbonisation. Although consumption plays the key role in determining the future outcomes of climate change (Riahi et al., 2017), there have been relatively few investigations on which behaviour and lifestyle changes can contribute most effectively to mitigation. Thus it is essential to gather generalisable empirical evidence across behaviour types and countries to estimate the reduction of the carbon footprint through specific behaviour and lifestyle measures and estimate which measures shall be prioritised for the most effective outcomes. Such evidence should include both bottom-up data from real-world case studies and 'living labs', as well as top-down modelling assessments of scaling up the potential impact at continental and global scales.

Multiple disciplines need to collaborate in providing the way forward on how to scale up behaviour and lifestyle change. Most of the research so far has been done in the silos of either technical or techno-economic assessments or in the social, behavioural and economic sciences. Interdisciplinary research that develops new scientific concepts at the interface of diverse scientific disciplines is key. These interdisciplinary collaborations should also be extended to active engagements with EU citizens and other stakeholders for designing low- or even zero-carbon behaviour and lifestyles of the future.

Reaping the benefits of behaviour and lifestyle changes needs evidence on the effectiveness of the policy approaches. There is a tendency in R&I communities to refer to the lifestyle and behaviour changes as mitigation means that require public acceptance. Indeed, some measures, such as reducing the space heating temperature (assuming that the minimum heating temperature is ensured), reducing meat consumption or avoiding car or air travel, still face acceptance issues. Policies for promoting information campaigns, open public discussions, peer-to-peer and community initiatives, nudging and gamification can sensitise European citizens to the need for change and its impacts. Evaluative evidence should be gathered systematically to identify and scale up the most promising policy approaches. This evidence shall come from other fields, such as health or mobility, to reveal the crucial triggers that have caused and sustained behavioural change in the past.

3 New roles for EU citizens

The energy transition and the liberalisation of energy markets create new roles for EU citizens (as consumers but also as prosumers) that involve them directly in the energy transition and through which they can become important change agents. Social innovation can then foster the social organisation of consumers and prosumers, for instance through cooperatives. The liberalisation of electricity markets in the EU tends to reinforce the power of people as consumers by giving them the choice of their supplier. Consumer empowerment in the energy system has become a goal of the European Commission, and corresponds to the ability of consumers to switch supplier easily, to receive an understandable bill, and to have access to a certified comparison tool to make well-informed decisions but also to become more active in the energy system. An active consumer in the energy system develops into a prosumer who is able to generate, self-consume, store or sell electricity. This is a growing trend in Europe which clearly contributes to the decentralisation of the energy system. In 2015, there were 4.8 million EU household prosumers and 620 000 collectives, and it can be expected that around half of EU households will be prosumers (either individually or collectively) by 2050.

Box 1: Social innovation for decarbonisation: the example of Elektrizitätswerke Schönau, Germany

Ursula Sladek started a local citizens' initiative to generate electricity in a sustainable way after the Chernobyl disaster in 1986. This initiative was the first of its kind in Germany to take over the grid as well as electricity supply to the local community, which it did in 1997 (Schönau, 2016). When the German electricity market was deregulated in 1998, the initiatative seized the opportunity to supply all its Schönau customers exclusively with electricity generated from renewable and cogeneration sources. As a result, Schönau does not use power supplied from nuclear and coal-fired plants. What started as a local initiative has now become the ElektrizitätsWerke Schönau (EWS), an energy cooperative with five subsidiaries aiming at sustainable energy production and supply, which by the end of 2016 had 5 100 co-operative shareholders, 164 462 electricity consumers, 12 718 natural and biogas customers, and 110 employees.

On top of the two classical roles in the electricity system, i.e. producing and consuming electricity, a new role for citizens of providing flexibility to the electricity system is becoming increasingly important. Flexibility is essential to maintain a well-functioning system, with increasing use of variable energy sources such as wind and solar. At the household level, flexibility (upwards, and downwards) can be provided via energy storage devices such as batteries (behind-the-meter, or 'on wheels' with electric vehicles) or via electric boilers which can adapt their pattern according to the system's needs, increasing and decreasing the level of power accordingly.

With these new roles, individuals should be able to use electricity in a conscious manner, and to alter their behaviour towards efficiency and

flexibility. Raising awareness about investing individually or collectively in generating assets, but also adopting more flexible patterns of using electricity, is needed to trigger this behaviour. Societal Appropriation (as coined by the EIT InnoEnergy) aims to raise awareness about energy to progressively lead individuals towards a steering role in the energy transition, and to contribute to embedding energy in Europeans' social identities. In the same vein, new companies are emerging that are developing personal coaches to guide users and provide them with tips and tricks to optimise their consumption, help them navigate and choose the offer which suits their preferences, leverage social norms via comparison to others, and nudge them towards more efficient and more flexible behaviour.

4 Social innovation through active EU citizens

Active EU citizens reduce greenhouse gas emissions through social innovations such as grassroots innovation and social entrepreneurship that create local capacity and forms of professionalised or commercialised organisations to support local communities in decarbonisation. Social innovation is rooted in the specific local social system and its needs, and is fuelled by local initiators who act on social needs and are skilled in finding novel ways (business models, ways of collaboration, funding mechanisms, etc.) to solve issues. The social process that is initiated in this way fosters at the same time the local capacity to solve the issue. To get social innovation off the ground requires a lot of energy, knowledge and skills from the initiators. Local businesses, start-ups, community developers and crowd funding mechanisms also have a role to play here and can create local jobs.

Social innovations are not domain specific, unlike policy fields. Social innovations can therefore create a tension with existing policy silos and related policies. For this reason, social innovation is often neglected by policy and policymakers and not seen as a means to reach policy goals. This explains the very low awareness of social innovation among most policymakers. However, social innovations could support many different actions or complement regional- or local-level policies related to the decarbonisation challenge in different fields. Social innovation could be directed towards 'an inclusive and just transition' through empowering and activating the local population in creating new jobs related to energy efficiency and sustainable energy, or through establishing new energy providers (see Box 1). Social innovation could also create new mobility services that meet local mobility needs, and that create a low-carbon footprint. It could also be directed towards changing food patterns towards a lower carbon footprint. Social innovation is therefore an enabler of low-carbon footprints in different fields, such as energy, mobility, food, business and, last but not least, cities, although it is also relevant for the decarbonisation of rural areas (see Figure 19).

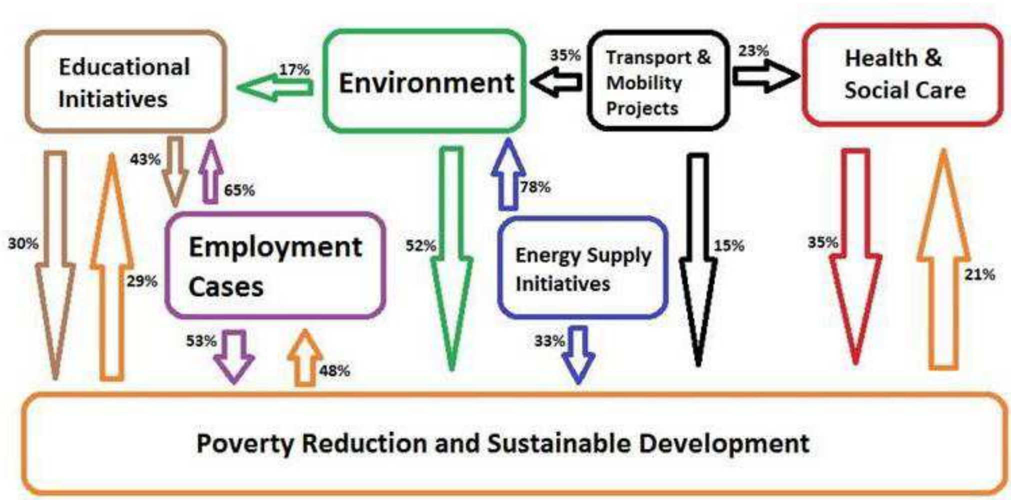

Figure 19: Topics dealt with in social innovation and their relation to societal challenges, based on an analysis of 1 000 world-wide social innovation cases. Source: Howaldt et al., 2016.

As social innovations are developed in a specific local (social) situation, replication to other localities and upscaling of social innovations is a challenge. Specific business models, new forms of organisations or cooperatives, cooperation with businesses and public authorities, and development of targeted replication and upscaling strategies can help to solve this issue.

Grassroots innovation is 'a network of activists and organisations generating novel bottom-up solutions for sustainable development and sustainable consumption that respond to the local situation and the interests and values of the communities involved' (Seyfang and Smith, 2007). Grassroots innovations differ from mainstream innovation in that they possess different types of sustainable development and forms such as cooperatives, informal community groups, social enterprises and voluntary associations (Martin et al., 2015). They face many challenges related to funding and finance, regulations, binding initial members, finding skilled people, connecting to research institutes and diffusion of their innovations (Hossain, 2016). As the innovations are small scale, and very locally situated, they generally have difficulty getting attention from policy makers. Another possible reason for this difficulty is is the lack of actual outcomes that policy makers can use. Setting grassroots innovation higher on the policy agenda through communicating attractive outcomes is therefore one of the main challenges. There are examples of grassroots networking organisations relevant for decarbonisation, such as the Transition Network[22] and the European ECOLISE network[23]. Grassroots innovation could be strengthened by smart public policies empowering non-governmental (NGO), civil society (CSO) or even non-profit (NPO) organisations, who by their nature involve ordinary people in delivering locally needed solutions.

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[22] https://transitionnetwork.org/about-the-movement/
[23] http://www.ecolise.eu/about-ecolise/

Box 2: Social innovation for decarbonisation: the example of Fundacja Łąka[24], Poland

Fundacja Łąka is a Polish social enterprise that is empowering citizens to take an active role in the 'greening' of cities. Increasing urbanisation has led to a loss of biodiversity and deterioration in the natural environment. The few green spots in cities have low biodiversity. Fundacja Łąka stimulates citizens to establish flowery meadows in cities among blocks of houses or in empty places, aiming to reduce CO_2 through natural absorption by plants, reduce local temperatures and increase biodiversity within local communities. Fundacja Łąka sells seeds and 'insect hotels' to interested citizen groups, trains them on how to seed and maintain the 'city meadows' and is involved in educational projects with citizens and CSR activities in cooperation with large companies and corporations.

Social entrepreneurship contains several sub-concepts, which are identified as i) social value creation, ii) the social entrepreneur, iii) the social entrepreneurship organisation, iv) market orientation and v) social innovation (Choi and Majumdar, 2014)**.** The individual, the social entrepreneur, plays a key role in developing innovations that create (local) social wealth. These individuals are able to 'find innovative solutions to social problems of his/her community that are not adequately met by the local system'. Several international organisations such as Ashoka support and promote social entrepreneurship to solve social problems with innovative concepts, creativity and entrepreneurial skills[25] [26]. UN organisations support social innovations: UNDP through its Global Centre for Public Service Excellence Innovation, and UNIDO through the Entrepreneurs for Social Change programme for young social entrepreneurs.

Social innovation has the potential to develop into new businesses on a local, national and even international scale. Market orientation is an integral part of social innovation (Martinez et al., 2017). As a social innovation develops further, and the organisation becomes more mature, professionalised, or commercialised, it can develop into a business-like organisation. Many social innovations shift from a marginal to a commercial organisation over time (Hossain, 2016). Businesses themselves can also develop social innovations, which is sometimes seen as a further development of corporate social responsibility (Mirvis et al., 2016). It has been found that social innovations influence the sustainability of big companies, so the interaction between social innovation and corporate (sustainability) strategies of (big) companies is an interesting topic for research (Hockerts and Wüstenhagen, 2012).

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[24] https://www.laka.org.pl
[25] https://www.ashoka.org/en/about-ashoka
[26] https://www.ews-schoenau.de/

Box 3: Social innovation for decarbonisation: the example of DORÉMI, France[27]

A social entrepreneur, Vincent Legrand, pioneered a large-scale operational approach, the DORÉMI solution, for renovation of houses in a carbon friendly way. The DORÉMI solution relies on a two-pronged strategy: 1) train independent builders in sustainable renovation techniques and 2) group them locally to better negotiate with materials manufacturers and package a simple, global renovation offer to homeowners at a reasonable cost. The solution unlocks the market. Builders reduce their costs and are willing to explore sustainable renovation as a new economic opportunity, owners have access to a simplified, reasonable-cost offer, and a maximised environmental impact is generated by replacing incremental renovation with a global renovation process. Partnerships with local authorities enable external stimulation of demand. With DORÉMI, regions overcome the complexity of the issue and support a highly efficient solution for the environment, reducing heating consumption by four to six times.

Although much knowledge has been developed about social innovation in the past years, there still exist some important knowledge gaps. The actual impact of social innovation on reduction of CO_2 emissions, dependent on the followed approach, is still not very well known as many social innovations have been researched on process rather than on outcome. Therefore, there is a need to evaluate relevant past projects and monitor saved CO_2 emissions of social innovations related to decarbonisation.

Many social innovation initiatives lack a good interaction with science. These initiatives could gain from transdisciplinary approaches in which scientists, social innovators, businesses, public authorities and other stakeholders work closely together on new types of social innovations with a high impact on carbon emissions. This fits in the mission-oriented approach of Horizon Europe.

Replication and upscaling of social innovations is still an important challenge, although progress on this point has been made. There is a need for research on replication and upscaling strategies and actions to gain more insight into applicable mechanisms. The private sector could help in the replication and upscaling of social innovations.

5 Policies to support social innovation for decarbonisation

Although social innovation in general is adequately supported by the European Commission, there are still actions to be taken to exploit its potential for decarbonisation fully, especially on the awareness of policy makers.

The European Commission supports social innovation in various ways, for instance, through its R&I programmes. A policy review paper (Moulaert et al., 2017) was recently published that examined 30 social innovation projects in depth. It that warns of a reduction in the significance of social innovation for

[27] https://www.ashoka.org/en/fellow/vincent-legrand

social enterprise and business, and argues for recognition of a variety of forms of social innovation. It stresses that policies should be refined to support social innovation, bearing in mind the shift from 'government to governance', which calls for a more coordinating and facilitating role for the state. It observes an underuse of social science contributions in the analysis of societal challenges and policies to address them. Beyond activities to support social innovation carried out by DG Research and Innovation, the European Commission also supports social innovation from the entrepreneurial side, providing funding to social enterprises and entrepreneurs via the common instruments suitable for this purpose, such as the SME instrument. The European Commission organises a grant competition published on the Social Challenges Innovation Platform that aims to match social challenges submitted by local authorities to entrepreneurial innovation. By providing EUR 30 000 grants to selected solution providers, the European Commission aims to transform the challenges into business opportunities.

EU policy-making can support social innovation by enacting new legislation or by harmonising existing legislation to address the market fragmentation which obstructs scaling up. In this regard, the European Commission has recently released a Communication in which an action plan for fintech is proposed with a suggestion to create a passport for crowdfunding platforms to help them reach the EU scale. Crowdfunding can stimulate social innovation as a way to engage communities in the development of (local) projects. Kiva is a non-profit platform that expands access to capital for entrepreneurs around the world. Similar to microcredit, this is clearly a way to empower people as social entrepreneurs. A European association, the European Crowdfunding Network, promotes the use of alternative forms of finance, notably to boost the economic and social effectiveness of European structural and investment funds by better engaging people as tax payers and citizens in the allocation of public money.

Many activities on social innovation, thus, have been initiated by the Commission. The question remains: What is still lacking, and what is the role of R&I in this?

One of the bottlenecks for a wider uptake of social innovation is a lack of attention by policy makers to social innovation as a way to reach policy ambitions and goals. There is a need for policies that support social innovation, with a facilitating role for responsible authorities. The European Commission could launch a White Paper that creates awareness among Member State policy makers of social innovation for decarbonisation, by showing benefits and results of social innovation and by highlighting how local and national politicians and policy makers could support and facilitate social innovations for the decarbonisation of Europe's society. Research could be done to develop new policy strategies and approaches that can be applied by policy makers to support social innovations.

Another bottleneck is replication and upscaling of social innovations. Local and regional authorities can play a key role in supporting replication of proven social innovations within their territory. Research could develop the appropriate strategies and replication mechanisms for the further upscaling with and for these authorities, possibly in co-creation with other involved actors.

A point of attention for policy is the unequal distribution of the impact of the energy transition over groups and EU regions. Certain groups or regions in Europe will be disadvantaged by the energy transition (for instance because they rely on a fossil-fuel economy), which requires policy attention to redistribute the impacts of the energy transition. Social innovation could play a role in countering these disadvantages for certain groups or regions.

6 Recommendations for R&I

In the following, R&I recommendations are presented for the short term (2030) as social innovation plays a supportive role on the short term and needs to be adapted to the issues that are emerging on the longer term (that cannot be foreseen now). For the same reason, recommendations for research on behavioural and lifestyle change are also given for the short term.

Social innovation and behavioural change are both part of innovation and societal change at systemic level. It has already been stated that social and technological innovation should be a unity of two parts that complement each other. Examples of cross-overs of social innovation and domains (mobility, energy, food and agriculture, etc.) have been given. Therefore, all system-level innovations recommended in this whole report have to contain a part that is dedicated to social innovation and behavioural research.

Furthermore, a clear link exists with the mission on climate-neutral, 'circular' and liveable cities. This mission has to propel social innovations and behavioural change for the short and long term, aiming to reduce carbon footprints to levels that are in accordance with the Paris Agreement. It should generate a network of successful examples of social innovations and behavioural change strategies to be the basis of their replication and further dissemination and upscaling.

One of the challenges of R&I on social innovation and behavioural change related to reducing the carbon footprint is its interdisciplinary and transdisciplinary[28] character. Scientists from diverse scientific backgrounds (social psychologists, political scientists, engineers, economists, etc.) should work together with social innovators, public policymakers, private innovators, citizens, etc. on new approaches for lifestyle change and social innovation that have a clear impact on the carbon footprint. Interdisciplinary and transdisciplinary cooperation is not self-evident and these benefit from research on effective interdisciplinary and transdisciplinary methods or processes for a better cooperation.

There is a need for concrete information on the impacts (reduced CO_2 emissions) from social innovations and from strategies to change lifestyles. Robust evidence should be gathered in bottom-up real-world case studies as well as top-down model-based assessments to quantify the CO_2 emission reductions that can be achieved at local, regional and the EU scales

[28] Interdisciplinary research delivers new concepts and new insights through interaction among scientists from a variety of disciplines involved in the topic. Transdisciplinary research is even broader and delivers new concepts and approaches through involving scientific and stakeholder knowledge.

through social innovation and lifestyle change. Furthermore, Horizon Europe should focus on setting up research and empirical evaluation of social innovations and promising strategies for behavioural and lifestyle change in the practice of everyday life. A network of 'living labs' in the EU Member States could execute the experiments in a systematic way to distil learnings and change strategies that can be replicated and further disseminated.

R&I is geared towards awareness, developing effective lifestyle programmes and other new approaches to influence the behaviour and lifestyles of EU inhabitants, such as feedback mechanisms on the carbon footprint through ICT applications, gamification, neighbourhood labs or other types of community-based approaches. These new approaches are to be disseminated and implemented in all EU Member States, while keeping good track of their impact through specific monitoring of CO_2 emissions. Research should develop these new approaches, assess their potential for CO_2 reduction and monitor the actual CO_2 reduction. Education programmes directed at disseminating the knowledge needed and developing the appropriate skills, as well as public campaigns, should foster the effective implementation of the awareness and lifestyle programmes.

Europe should actively stimulate social innovation initiatives related to the decarbonisation challenge through developing a specific programme, and through suitable financing mechanisms, both existing and new, such as microfinancing, crowdfunding, etc. R&I should be aimed at monitoring and evaluating the reduction of CO_2 emissions through the social innovation initiatives, identifying best practices and developing suitable upscaling mechanisms.

Replication and upscaling of social innovations are still major challenges, and relevant for their impact. Governance regimes that empower replication and deployment of often locally-rooted initiatives should be developed in co-production with the communities involved. Research should be set up for upscaling within and among regions those initiatives that help to expand the impact of social innovation for decarbonisation. Furthermore, awareness should be created about the benefits of social innovation for decarbonisation through showcasing best practices. Promising social innovation initiatives should be brought to the forefront and to the attention of private businesses, policymakers and politicians to gain awareness within these groups. Policymakers should be provided with portfolios of approaches and strategies to stimulate and promote in their territory social innovations in relation to the decarbonisation challenge.

Social innovations create local jobs. To exploit the entrepreneurial potential of social innovation fully, research should target the skills and capacities that are needed for social innovations that are able to be commercialised, and policies should support capacity building. Certain regions or social groups in Europe will be disadvantaged by the energy transition, for instance, because they lack money, skills or the capacity to change, or because they are still heavily dependent on fossil fuels for their local jobs. Research and (social) innovation should be aimed at the equity aspects of the decarbonisation of Europe, creating (local) capacity to change, and at the same time creating new jobs. From past regional transitions that are similar to those in the decarbonisation challenge (for instance, the transition in the south of the Netherlands from coal to gas), we can learn what kind of transition strategies have worked. Research should take stock of these experiences and experiment, making use of the lessons learnt.

Exchange knowledge and experience on the international level, and learn from this exchange. Many international organisations and networks are active in the field of lifestyle change and social innovation related to the decarbonisation challenge. Cooperation with these international organisations (UN organisations, communities of networks, etc.) should be set up to exchange knowledge and experience, to expand the number of cases that can be researched, and to diffuse the developed lifestyle change strategies and European social innovations to a worldwide community.

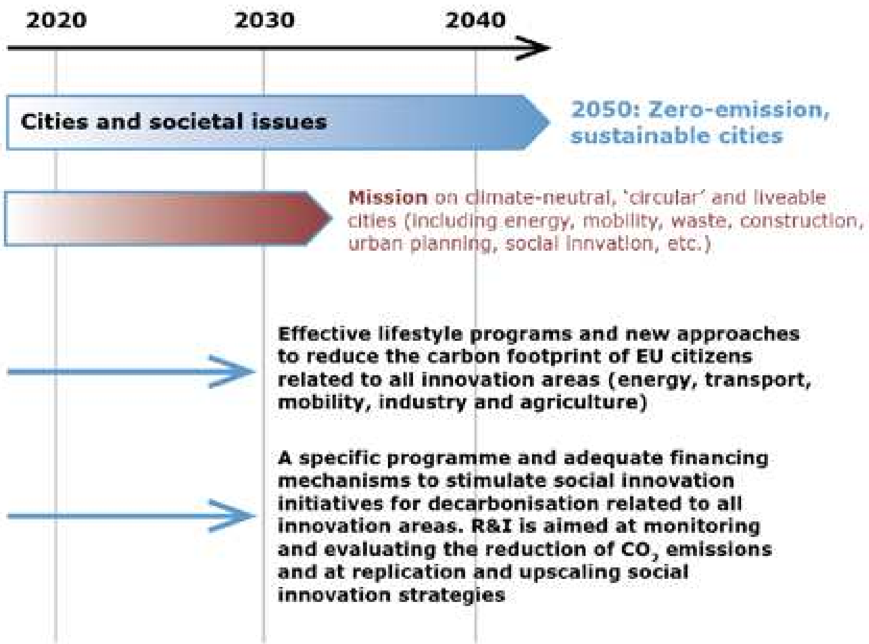

Figure 20: Possible R&I pathways to decarbonisation through social innovation, as a compendium to the priorities for cities.

CHAPTER 8

ECONOMIC IMPLICATIONS OF THE LOW-CARBON TRANSITION

1 Introduction

A well-designed transition towards decarbonisation will represent an unprecedented opportunity and challenge for the competitiveness and well-being of Europeans. The key to success is that decarbonisation is not seen as a single new leitmotif (or recurring theme) in Europe's economic policy, but as one further element to be considered among all the other objectives, including high employment, social inclusion, a (semi-) circular economy and, more generally, the need to promote sustainable production and consumption. In addition to the sectoral-specific research needs highlighted in previous chapters, we discuss here four key general, macro-economic aspects that need to be the focus of R&I efforts to promote European decarbonisation successfully and to ensure economic and social sustainability not only in the EU but also in the rest of the world.

We first **highlight the macro-economic implications of decarbonisation**. In this context, we discuss the critical conditions that need to be put in place to ensure that decarbonisation is not a burden on Europe's business in an already highly competitive global economy, but one of several benefits that an innovation-driven low-carbon transition could bring about. We then discuss the need to **mobilise significant financing capital** to support decarbonisation. As highlighted by the High-Level Expert Group of Sustainable Finance, this will require a deep restructuring of the financing system. We then focus on the **international trade dynamics and implications** arising from decarbonisation. We conclude by highlighting the necessity to **promote innovative and low-carbon business models** to ensure that decarbonisation fully materialises.

Promoting the understanding of these crucial aspects through targeted R&I programmes is absolutely essential to safeguard Europe's industrial place in the global economy and to achieve the global decarbonisation goals. If decarbonisation was a largely European objective only, both the economic and the climate strategies would fail.

2 The macro-economic implications of decarbonisation

Deep decarbonisation, complementing existing economic objectives, can become an unprecedented economic and industrial opportunity for the European economy if it is well managed. It could boost Europe's competitiveness and bring about important co-benefits in terms of jobs, competitiveness and overall well-being. However, this requires that decarbonisation priorities are also priced into international trade practices. The European Commission must avoid a situation in which within Europe, carbon is penalised, and the European economy is flooded by cheap goods from other constituencies that do not put similar restrictions on carbon. This is particularly relevant in the early phases of decarbonisation, when technologies are developed with high levels of investment. Research should also be devoted to the question of how to allow the European economy to advance on decarbonisation without disadvantaging it in economic terms in an open and competitive global economy.

Indeed, irrespective of choices regarding decarbonisation, European countries face difficult economic challenges in the next decades. First, the EU infrastructure, including energy and transport infrastructure, is aging. For instance, average energy infrastructure investments across all sectors of the economy would need to ramp up to EUR 1 000 billion per annum over the period 2040-2050. Second, while EU energy demand will stabilise, EU dependence on foreign energy will increase due to a decrease in domestic fossil-energy production. Third, oil prices are likely to remain volatile. This, and the increased dependence on foreign oil, will make the transport sector more vulnerable. Fourth, the EU building stock will have to be upgraded to reduce the exposure of households and businesses to fluctuations in world fossil-fuel markets. As has already been shown with renewable energy technologies, innovation arising from decarbonisation can generate new industries and investments that can contribute to addressing these challenges.

The major policy challenge facing the EU at present is precisely to design a decarbonisation strategy which reduces emissions but also supports the core political priorities of giving a new boost to jobs, growth and investment while shielding the weaker sections of society. To achieve this, the economic benefits and co-benefits of decarbonisation need to be better understood, as do the policies required to deliver them. This includes the effects that policies and decarbonisation in any one sector or country may have on other sectors or countries, given that the choice of decarbonisation strategies in Europe will affect, and in turn will be affected by, the economic strategies of other countries. It will also include the positive effects, for instance on health, due to the phasing-out of fossil fuel burning. In any transition there will be winners and losers. The EU decarbonisation strategy needs to recognise this, and while generating economic and environmental benefits overall, needs to build in measures to support the weaker sections of society that might be adversely affected.

Europe is well-positioned to address this challenge. Europe's competitiveness almost entirely relies on cognitive capacities, which today must be put to the task of decarbonisation and greatly enhancing resource productivity. Europe has many comparative advantages compared with other regions in the world, for instance in terms of human capital, cultural heritage, media independence, soil fertility and moderate climate conditions. Europe possesses expertise and manufacturing capacity in some of the world's leading technologies in a large number of sectors. However, it strongly depends on the import of raw materials from all corners of the planet, and is challenged by high labour and production costs. Many of these weaknesses could be overcome by promoting innovation, fully exploiting Europe's domestic renewable energy resources, and closing materials loops within a more circular economy.

Europe has a strong track record in the estimation through economic models of the short- and long-term impacts of decarbonisation, and of the different policy choices which can be used to promote this process. However, these models have been quite weak in their ability to capture the wider implications of innovation and of the implementation of new technologies.

In the 1990s, economic models were being improved by implementing endogenous technological change with the purpose of better accounting for phenomena such as learning-by-doing and learning-by-searching or R&D. Partly by lack of real-life representation, this research line lost impetus over the past two decades. Moreover, most of the models have no separate representation of the financial system.

There is a strong need to reduce the large uncertainty around future projections of the implications of decarbonisation. Current economic analyses yield widely diverging results regarding the implications of the transition towards the use of low-carbon energy technologies in terms of economic growth, competitiveness and employment effects or job creation. It is not always clear why different models produce results that cover a broad spectrum of possibilities, that is, whether it is merely a matter of diverging input parameters or whether they originate from different assumptions about the economic structures and relationships that these models embody.

R&I programmes need to design and implement an economic approach that succeeds in developing and deploying the next generation of low-carbon technologies, so as to reap substantial advantages associated with decarbonisation in terms of industrial renewal and competitiveness.

2.1 R&I recommendations

To this end, in the short term (up to 2030), R&I actions should focus on strengthening economic model analyses to ensure informed policymaking. Efforts should be focused in particular on improving the representation of European industrial policy, financing mechanisms and the increased competitiveness that should arise from successful low-carbon innovation and deployment. Research on improving the integrated assessment of climate and economic outcomes deserves renewed attention. Important improvements include the successful representation of the technological developments of the recent past, especially the dramatic cost reductions of some renewables technologies, identifying decarbonisation bottlenecks, designing economically-viable strategies to eliminate harmful fossil-fuel subsidies, performing risk analyses in the financial sector, and estimating the weighted average cost of capital. The costs of PV, for example, have fallen much more in the past several years than even the solar energy optimists hoped for. These dramatic cost reductions should be more adequately accounted for in revised economic models to reflect the continued low-carbon technology advancements due to not only the gaining of experience and fundamental and applied research but also as a result of wider effects such as economies of scale and automation. R&I efforts also need to investigate how employment can be maintained in an open and competitive global economy. For example, the cost reductions in solar technology went hand in hand with a dislocation to other constituencies. If this were to happen across the board, Europe would be stuck in a structural high-unemployment situation. Such R&I efforts need to focus in particular on international trade policies and examine how globally desirable strategies such as decarbonisation could be integrated with rewarding, and not penalising, the early movers.

Economic models are powerful tools, but R&I efforts should be devoted to adapting, refining and expanding them. Specifically, models should be enhanced to reflect some of the quintessential interactions between low-carbon technology innovation on the one hand and financial mechanisms and investment risk-reduction strategies on the other, which currently they broadly do not. At present, one observes shifting patterns for the weighted average cost of capital, with progressively more beneficial financial conditions for renewable energy technologies and less advantageous ones for fossil fuel-based options. The economic and integrated assessment models used to inspect projections for the imminent energy transition — at global, regional, national and local levels — should better account for relative cross-sectoral changes in the cost of capital.

R&I efforts should be devoted to better understanding the role of industrial policy with regards to reconciling and addressing different political and policy goals at the same time. These may include targets regarding not only climate change, but also other environmental concerns such as air pollution and biodiversity conservation, SDGs, communication and digitalisation. Further research should be carried out with regards to the indispensable role public policies and financial assistance mechanisms play and how they can optimally complement efforts from the private sector. It is also recommended to establish a broad R&D cluster around decarbonisation goals that connects energy-mobility challenges and related industrial value chains to the climate sciences. The development of decarbonisation pathways that include the above will allow framing of the prioritisation of R&I actions that enable Europe to lead on climate action while increasing its competitiveness.

Another crucial short-run R&I priority is to assess, compare and project successful ways to remove environmentally harmful subsidies without disproportionately affecting vulnerable and less well-off households. Environmentally damaging subsidies, especially those to fossil fuels, inflict damage on both the economy and environment. The economy suffers from the costs of financing these subsidies, while the environmental harms from the activities being subsidised are increased. Significant macro-economic gains, as well as environmental improvement, can be realised through the removal of these subsidies, which should nevertheless be carried out in such a way as to protect more vulnerable members of society. However, each country will need to develop targeted strategies to address fossil fuel subsidies removal.

In the medium term, R&I efforts should be devoted to the thorough assessment of the impacts of decarbonisation on labour, competitiveness and quality of life, including understanding uncertainty. This will allow the design of sound strategies to manage transitional costs. New low-carbon technologies will provide many new job opportunities as they are deployed, but there will also inevitably be job losses in those sectors that fail to adapt to a low-carbon future, especially in the fossil fuel industry. The new jobs will in many cases require different skills to the jobs they replace. More understanding is required of the gains in 'new employment' and the losses in 'old jobs', and their relative sizes, to establish the technical and socio-economic skills needed to assist the energy transition and climate change control efforts.

Furthermore, multi-disciplinary research at the intersection of the natural and social sciences in the field of energy and climate change should be funded. In this respect, special focus should be devoted to enhancing the insights that economic analysis can give into the European competitive advantage in low-carbon technologies and industries. It should be much more researched how this advantage can be both fostered, and how energy-economy-environment models or other quantitative integrated assessment methods can create greater insight in the issues associated with transitioning from high-carbon to low-carbon economic activity. Much progress still needs to be made with regards to reflecting European industrial policy and competitiveness appropriately in these models.

3 Financing decarbonisation

Achieving the EU's energy and climate targets will require a huge redirection of investments away from fossil-based and towards zero-carbon technologies. Overall, Europe is relatively well placed to address this challenge, as Europe's banks, insurance companies, institutional investors and stock exchanges have been significant players in the evolution of green (and sustainable) finance over the past 25 years, and particularly in the last five years. Achieving the EU's energy and climate targets, while keeping and raising the level of employment and prosperity, will require large-scale investments across the European economy, estimated at around EUR 170 billion a year up to 2025. However, the transition will only work if hurdles to long-term, physical investments (infrastructure, low-carbon transportation, electricity storage, etc.) are reduced and the permanent pressure on the corporate and financial sectors to deliver short-term results is attenuated.

The EU will be able to deliver a 'just transition' only through swift and substantial action to harness and redirect both public and private investments towards large-scale, low-carbon and zero-carbon projects. This will radically shift the EU economy away from high-carbon, resource-intensive and polluting sectors in favour of low-carbon economies. It will also secure net benefits and co-benefits for workers and communities, including better lifestyles, secure employment, increased productivity and global competitiveness. In this context, the public sector has a critical role in ensuring the right alignment of financial policies and tax policies, as well as in giving sufficient predictability on the overall policy framework so that investors can make the projections that are necessary to invest long-term capital.

The EU need to engage in the re-design of the current financial system to support the transition towards a decarbonisation economy and, more broadly, a sustainable economy, as proposed by the High-Level Expert Group on Sustainable Finance. This restructuring entails, in particular, reducing the financial decision-making short-termism that is particularly embedded in many segments of the capital markets. In stock and bond markets, a range of short-term investors create undue short-term volatility and pressure for short-term results to the detriment of long-term orientations. Investment horizons that are shorter than the horizon generating the underlying economic return should be penalised. For example, whereas in corporations, returns on investment relevant for decarbonisation and environmental issues materialise over years, there is a range of investors including high-frequency traders, day traders, hedge funds and short-term stock traders that seek to extract returns over days and weeks, if not even over minutes and seconds (high-frequency trading). Such strategies of short-term value extraction are a massive detriment to the long-term investment needed for decarbonisation. Mobilising investment capital for the low-carbon carbon transition needs to be a long-term commitment, setting in place a stable system which focuses on the long-term consequences of financial practices and does not disrupt them by short-term value extraction.

Specifically, the financial system needs to be in tune with a model of economic development that will necessarily be more capital-intensive. In this respect, entire sectors and industries will need to shift their paradigms of economic production by breaking out of carbon-intensive capital and technologies. In practical terms, this entails switching away from financing the throughput of energy and materials and committing large sums of upfront capital to long-lasting assets. This puts prime importance on capital, and specifically on its cost, time horizon and quality.

A non-trivial aspect of this massive transformational change is the need for investments in innovation — be it in technologies, business models or services. Innovation is inherently a highly uncertain endeavour. Rather than focusing mainly on near-term profits, the investment sector should take into consideration strategic fundamentals in investment decisions. In particular, for the private sector to be willing to commit substantial capital, investments for the low-carbon transition will need to earn a standard risk-reflective return. A further challenge arises from the fact that, being relatively new, low-carbon investments are subject to considerable technological- and policy-induced fluctuations that impact cash-flow and profitability calculations (e.g. feed-in tariffs, subsidies for renewables). Such technological and policy-shocks are a major concern for private investors, especially when it comes to investment in rather illiquid assets such as infrastructure.

The role of public capital will be particularly crucial for infrastructure development, while private capital should play a leading role with respect to funding technologies. In this respect, as highlighted elsewhere in this report, a useful instrument is the creation of public-private partnerships targeted at supporting the early, more uncertain phases of R&I. Conversely, appropriate financing mechanisms should promote the influx of private capital during later stages of technological development.

This is the time for action — the benefits of a sustainable financial system are sizeable and they now need to be seized. Through sustainable finance, the EU will be able to reap the full spectrum of co-benefits associated with decarbonisation. At home, Europe's financial institutions will become more resilient, Europe's businesses will access better priced and more patient capital, and they will be able develop the products, skills and innovations that are increasingly needed to deliver a healthy financial sector, and promote growth and employment. European citizens will see their sustainability values expressed in their financial choices, and their needs met. Abroad, first-mover advantage will grant a position of leadership to the EU, which has the opportunity to act as a champion of international policy reform for low-carbon and sustainable finance.

European financiers will be able to serve global markets seeking unprecedented flows of sustainable finance. They will provide the platform for exports of sustainable financial services to the numerous countries now looking for capital and expertise to deliver decarbonisation and more generally the SDGs. Importantly, the EU leadership role will be paramount to ensure that financial and trade flows into the EU consider sustainability appropriately and do not undermine fair competition that would hurt European employment.

Designing a comprehensive strategy to finance sustainable and inclusive growth should be one of the key targets of R&I actions in the next decades. Fundamentally, it is important to recognise that the misalignment of today's financial system is by no means an immutable situation. Such misalignment is simply the consequence of the evolution over decades of financing economic development and technological change focused on carbon-intensive energy. However, a comprehensive approach towards restructuring will be able to deliver a long-term solution and to change the way in which the duties of financial institutions, their governance, risk management and supervision are delivered.

By 2050, R&I programmes should support the full restructuring of the financial system towards sustainability and implementation of sound strategies to fund fully the decarbonisation transition.

3.1 R&I recommendations

In the short term, a first R&I requirement is the generation of high-quality data and information that can be used to inform decision-making. This includes the definition and implementation of harmonised metrics, data quality requirements, availability and access guidelines, but also the development of a taxonomy for sustainable financing. It also points to the need to understand how to improve disclosure rules and procedures. The EU should also engage in experimentation with respect to new, forward-looking disclosure rules concerning sustainability-related financial risks. This will require trial and error by companies, as well as capacity building and promotion of best practice by all the key institutions involved, governments included. A successful example in this respect is that of the Task Force on Climate-related Financial Disclosures (TCFD), the first industry-led framework with the potential to become a 'new normal' of climate disclosure. Momentum behind the guidelines is growing fast, with more than 230 companies representing a combined market capitalisation of over EUR 5.1 trillion having voiced their support for the TCFD recommendations.

A second important short-term R&I focus should promote the understanding of the barriers which hinder the flow of finance towards decarbonisation efforts, low-carbon technologies and low-carbon business models. First, it is crucial to expand our knowledge regarding the specific geographical, technological and business-model areas where investments are needed most. In this respect, it will be particularly important to devise ways to redirect capital flows towards remote regions to promote mitigation while making them economically viable. Second, research will also have to be put into the barriers to large-scale finance flowing into these areas, and how these barriers may be removed.

Furthermore, R&I efforts in the short-term should be devoted to the design and implementation of a coherent and predictable policy and regulatory framework promoting the restructuring of the financial sector and the alignment of funding with long-term climate targets. This is absolutely crucial to allow financiers to allocate savings to low-carbon technologies and business models with confidence, thus ensuring that the private sector plays the major role in closing the decarbonisation investment gap. Optimal strategies and policy instruments to overcome the short-termism in stock and bond markets should be studied. Practical solutions should be developed to limit the role and influence of short-term traders and investors in stock and bond markets that create undue volatility and hamper long-term investments. Crucially, R&I needs to identify how such policy instruments can be coupled with an even stronger orientation towards mobilising investment to address the long-term needs of the real economy, not only in terms of climate mitigation but also with respect to other priorities such as employment, education and savings.

In the short term, R&I investments should also be focused on the development of forward looking economic models that include the financial sector alongside energy and climate. Such models will be instrumental in improving the simulation of the financial needs for the low-carbon transition. They will also allow the identification of practical solutions to ensure that financial decision-making can anticipate the shifts that will arise from transformational sustainability, and capture future opportunities while minimising their related risks. Importantly, such models should have a sectoral, regional and national dimension.

In the medium term, R&I efforts should allow modification of the behavioural barriers of investors and financiers which give rise to financial market myopia. Such myopia draws investments away from long-term value creation and undermines the financing of deep decarbonisation. It hampers investments in real assets that are amortised over many years and the development of technologies and business models that will drive the transition to sustainable development. On the one hand, the long-term horizon of end-beneficiaries (such as pension funds, household savers and sovereign wealth funds) is currently not reflected by financial intermediaries (due, for instance, to principal-agent issues and misaligned performance metrics and incentives). On the other hand, the needs of businesses for enduring capital are undermined by an excessive focus on short-term price performance, particularly on listed equity and bond markets.

In the long-term, R&I efforts should ensure the identification and implementation of financial instruments which move capital at scale. This entails ensuring that long-term considerations on low-carbon investments are included in investment strategies, risk management, asset allocation, governance and stewardship. Practical examples in this respect include promoting and incentivising the adoption of double bottom-line (considering the conventional bottom line related to fiscal performance as well as social impact) or even triple bottom-line (adding environmental impact as a third bottom line) accounting. A clear R&I priority in this respect should be to understand better which instruments can be put in place to ensure that capital markets respond to policy and other signals (such as technological change, physical disruption and social expectations), thereby anticipating change in the real economy and allocating capital faster and more efficiently.

4 International trade dynamics and implications

Over the past few decades, a rapid and complete global integration of trade and finance has led to an increasing geographical disconnect between the production of goods and their consumption and use. The delocalisation of production and the associated transportation of raw materials, intermediate and finished goods have increased around the globe, with a clear impact on global CO_2 emissions, as well as on environmental risks of all kinds. This process has accelerated significantly as China, Eastern Europe and other emerging markets integrated into the global economy and attracted global production across the whole range of industrial as well as agricultural goods. From 1997 to 2007, for example, global emissions grew by 2.8 % per year but global emissions from trade of goods grew by 4.6 %. In 2007, about 7 Gt of CO_2 emissions arose from global trade of goods alone (Andrew et al., 2013).

Trade provides important economic opportunities for both exporters and importers, but is also associated with significant environmental and climate costs, with indirect social costs (unemployment, premature deaths, social security expenses), and decline of entire regions. Delocalisation and shifts in production and transportation patterns have for a long time been considered as economically efficient, based on measured costs of capital and labour input. At the same time, many export-oriented economies have a high level of carbon intensity. This is for instance the case of China, from which the manufacture of exports is a substantial source of CO_2 emissions. It makes no climate sense for manufacturing to move from CO_2-efficient to CO_2-intensive economies. In addition, industry relocation and de-industrialisation has high social costs, triggering unemployment and internal and external migration. Deindustrialisation is not an inevitable result of decarbonisation. Indeed, many industrial and manufacturing sectors in the EU are decarbonising and yet have a massive trade surplus. Even in some energy-intensive sectors such as chemicals, the EU is a global leader.

The magnitude and bilateral flows of carbon emissions associated with the production and consumption of traded goods have important implications but remain uncertain. Initial estimates suggest that combined international trade in carbon (as fossil fuels and also due to the production of traded goods) increased from 12.3 $GtCO_2$ (55 % of global emissions) in 1997 to 17.6 $GtCO_2$ (60 %) in 2007 (growing at 3.7 % year). Within this, trade in fossil fuels was larger (10.8 $GtCO_2$ in 2007) than trade in embodied carbon (6.9 $GtCO_2$), but the latter grew faster (4.6 % year compared with 3.1 % year for fuels) (Andrew et al. 2013). Yet, these estimates are strongly influenced by methodological considerations regarding how to account for emissions in traded goods. The increasing interdependence of countries via international trade has important implications for both energy security and climate policy, and is worthy of further study. Furthermore, the environmental impact of trade goes beyond the CO_2 problem alone. For instance, recent findings suggest that about 22 % of premature deaths related to $PM_{2.5}$ pollution (762 400 deaths) were associated with goods and services produced in one region for consumption in another (Zhang et al., 2017).

Only a few studies exist on the effectiveness of environmental and trade policy levers to counterbalance the impact of trade-related emissions. A shift to a decarbonised world can certainly be expected to change trade patterns as the costs of carbon emissions become increasingly incorporated into the prices of goods and services, and is likely to go hand-in-hand with greater congruence of production and consumption of goods, with positive impacts on local employment and regional development. In light of this, it is paramount to explore how trade decisions can be optimised, taking into account external costs, that is, how to ensure that sustainability considerations and goals are reflected in trade patterns. This is particularly important now that the cost of environmental externalities has risen. Research is required into policy measures which could address this issue, such as border tax adjustments. **The literature assessing the impact of environmental and climate policies on competitiveness, industry relocation and carbon leakage[29] has come to contradictory results.** There is still too much uncertainty as to whether more stringent climate policy simply leads to relocation of industrial production to countries with laxer environmental standards, and to an associated increase in emission in those countries which (partly) offset the reduction of emissions the policies should have brought about. Theoretical analysis and simulation models suggest that the issue or relocation and carbon leakage is a potentially relevant one, while empirical analyses of sectoral and firm dynamics have not found strong support for either the pollution haven hypothesis or carbon leakage. The extent to which this is related to unrealistic assumptions in models on the one hand, and to empirical choices and the inability to compare actual developments with a proper counterfactual on the other, is not clear.

By 2050, R&I programmes need to support the decarbonisation of trade-flows.

4.1 R&I recommendations

In the short term, R&I actions need to understand and provide quantitative assessment as regards the relation between greenhouse gas emissions and trade. Clearly, the first gap to be addressed is that of measurement. Computing embedded emissions is a complicated process with large uncertainties. Several efforts should be carried out to fill the gap. Research that develops consolidated methodologies and maintains open-source databases of trade-related emissions, their past dynamics and their future projections should be encouraged. Countries and companies should be required to report consumption-based emissions on a regular basis, following clear reporting rules. Finally, international cooperation should be deployed to develop international standards, in cooperation with the UNFCCC (which currently tracks emissions where they are produced). This could also clarify the role of trade-related emissions in international climate negotiations. Furthermore, methods and approaches to quantify climate and environmental costs of delocalisation need to be developed, with a specific focus on key sectors such as agriculture. Strategies and approaches to reduce the emission intensity of highly polluting imports need to be designed and evaluated. Finally, the impact of embedding environmental considerations into global trade dynamics on the welfare of European consumers, on their employment and on the competitiveness of European industries will have to be fully understood.

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[29] Carbon leakage is measured as the increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries. It is expressed as a percentage, and can be greater or less than 100 %.

R&I actions in the short-term should focus on understanding what strategies and policies are effective in lowering the emission intensity of highly polluting imports. The focus should be on super-polluting industries and sectors, for which mitigation could provide a win-win solution to decrease consumption and production emissions simultaneously. For instance, emissions embodied in Chinese exports are primarily the result of China's coal-based energy mix and the very high emissions intensity in a few provinces and industry sectors. The effectiveness of trade-related policies will depend on several criteria (legal, economic, etc.). Recent modelling work has devised a list of priorities for policy tools, which include technology lists, supply chain procurement, carbon-intensive material charges, infrastructure improvement, product location at scale and retailer product choice. These policy levers are believed to be effective in reducing imported CO_2 emissions, and at the same time be acceptable to citizens in the sense that they would not raise the prices of goods by too much.

Another important area of concern for R&I actions should be the agricultural sector, for which a detailed assessment of trade-related carbon and other greenhouse gas emissions should be performed. This requires understanding of where agricultural goods are produced and where they are shipped. In this context, a crucial concern should be that of quantifying whether farmers, who are low in the global value chain, are able to get good prices for their products, and whether profits associated with the trade of agricultural goods are reaped by those higher up the value chain (i.e. supermarkets, etc.). There are a number of indirect measures which pertain to trade, including sustainable trade and government procurement programmes, circular economy programmes and mandatory sustainability reporting, whose effectiveness in reducing the carbon content of trade needs to be assessed. Overall, more research should be devoted to rethinking the mix between global and local to reduce trade-related carbon emissions. In this respect, low-carbon business models discussed below could play a crucial role.

In the longer run, R&I efforts should be focused on identifying demand-side and supply-side policy levels to reduce trade-related environmental costs and capitalise on trade-related co-benefits. In this respect, a key component will be the development of approaches to embed carbon emissions considerations in trade measures and to promote the harmonisation of carbon related standards and measures internationally. The understanding of the solution space is currently very limited and would need to be drastically improved before legislating policies. On the demand side, many policy levers exist, ranging from behavioural ones (e.g. information disclosure, labels, nudges) to regulatory tools (standards, mandates). Citizens' knowledge of the impacts of trade is limited, despite the wide-ranging consequences on health, environment, employment, etc. The potential for better-informed decision making is large, but more tests — possibly conducted via randomised control trials — are needed. Regulatory schemes are better understood. Nonetheless adequate knowledge is lacking about their distributional impacts and economic consequences. On the supply side, measures — most notably border tax adjustment — exist, but their use is contentious and can lead to a race to the bottom, especially in the current political situation. Nonetheless, other measures exist.

Another target of longer-term R&I programmes should be to favour the establishment of academic fora which promote the design and

harmonisation of standards and environmental policies across countries. Indeed, simply focusing on domestic interventions alone cannot resolve the issues. R&I actions should promote the debate regarding the extent to which trade measures in respect of greenhouse gas emissions be successfully embedded in the international debate about trade more generally. They should support the achievement of multilateral environmental agreements that can contribute to decreasing the wedge between production-based and consumption-based CO_2 emissions. This debate is complex because a part of why production is delocalised and trade plays such an important role is linked to the fact that some countries have laxer environmental policies and standards than others. However, other aspects also play a crucial role. For instance, labour costs are much higher in developed countries than in developing countries. A possible way to partly reduce this imbalance would be to support the improvement of working conditions, labour standards and benefits in low-income and developing countries. This clearly could have immense impact on competition and comparative advantages.

5 Innovative and low-carbon business models

At present, innovative business models represent a small share of the market and are followed and implemented mainly by niche companies. Business models describe how companies create, deliver and capture value. Deep decarbonisation of the European economy requires that all economic activities develop innovative low-carbon business models which will allow them to deliver products and services with low- or zero-carbon content and processes. This is currently hindered by the presence of institutional, behavioural and regulatory barriers. Such barriers will need to be overcome to promote an adequate acceleration of the development and deployment of low-carbon business models.

There is great potential for innovative, low-carbon business models in all sectors of the European economy. There are many successful examples of innovative and low-carbon business models, including those centred around production of low-carbon products, promoting conservation and recycling, or focusing on servitisation (i.e. the selling of services, rather than products). Low-carbon business models also include processes compatible with the circular economy concept. Innovative, low-carbon business models have emerged in several areas and industries (see Box 1).

The emergence of innovative business models is often brought about by, and at the same time reflects, deep societal and attitudinal changes. This is exemplified for instance by the transport sector, which has seen an increase in business models centred around mobility-as-a-service, e-hailing, peer-to-peer car rental and car-pooling 2.0. The proliferation of these modes of alternative, lower-carbon mobility clearly reflects the fact that car ownership has become less attractive for younger generations. At the same time, these types of services are favoured and supported by the proliferation of ICT technologies, which allow faster and better market coordination and matching. Similarly, the emergence of low-carbon logistics business models is a direct result of increases in online shopping, which has changed consumer behaviour and increased the demand for home deliveries.

Not all new business models are low-carbon. For instance, the current business model for mobile phones leads to much resource inefficiency, with (carbon- and material-intensive) hardware (i.e. the cell phones) being offered for free as part of a subscription plan, leading to a high rate of turnover in hardware, with a fast rate of introduction by producers of new models. This increases resource intensity and negative social impacts (i.e. conditions of workers in mines, disposal of electronic materials, etc.). In personal transport, companies such as Uber and Lyft offer convenience by enabling travellers to contract trips via an app. While these mobility business models have the potential to reduce carbon emissions per passenger kilometre by increasing vehicle occupancy and decreasing the number of vehicles on the roads, they are also likely to increase the overall demand for transport because they are cheap and can conveniently be booked via an app. Similarly, business models based on block-chain technologies (hyper-ledger and smart contracts) could potentially prove instrumental in decarbonisation (promoting traceability of sustainable materials and low-carbon transactions, peer-to-peer distributed energy grids). However, the impacts of these business models on energy consumption and carbon emissions are not yet fully understood and could potentially be very high.

In the long term, R&I actions should support the development and diffusion of low-carbon business models.

Box 1: Examples of low-carbon business models

Logistics: Examples of low-carbon logistics businesses include those focusing on (lower-carbon) last-mile deliveries. Typically, a consolidation centre coordinates the final part of the distribution with other logistics firms, eliminating the need for individual trips to each shop. This increases vehicle loading factors and it is very interesting for local authorities as it can contribute to reduced congestion and emissions in and around commercial centres. Furthermore, last-mile deliveries logistics services can be provided via very low-carbon freight modes (i.e. walking, cycling).

Energy: The integration of ICT into the energy system enables energy service companies (ESCOs) to offer contracts for energy supply, energy performance, heating (comfort contracting), integrated energy and facility management. Also in this case, customers are provided with a service (lighting, heating, cooling, power) and it is in the best interest of the supplier to implement the most cost-efficient measures as higher energy consumption results in lower profits. A successful example is that of the 'pay-per-lux' model, emerging from a collaborative project between architect Thomas Rau and Philips. The innovative business model came about due to the specific demand for a service, rather a product. The architect turned to Phillips, asking to be provided with a light plan for one of his new buildings. In response, Philips created a minimalist plan for lighting services which relies as much as possible on the building's natural sunlight and on very efficient LED lighting combined with a sensor and controller system that dims or brightens the space, as needed. This intelligent lighting system is based on Phillips retaining ownership and control of the product, and the customer paying for a maintenance and service plan.

Smart cities: The potential for innovative, low-carbon business models is high in cities. For instance, designing cities to enable the flourishing of local farms can reduce food miles. Examples of such businesses include a GrowUp Box, by

GrowUp Urban Farms, that has developed 14-m^2 aquaponics containers where tilapia and vegetables are farmed and sold to local restaurants. Other approaches include Sky Greens, a system to grow more food by using vertical structures or orchards on roofs such as the Brooklyn Grange or the Deu Horta Na Telha in São Paulo.

Industry: The use of artificial intelligence and robotics will increase productivity in industry by steering product and process innovation. This, in combination with low-carbon energy infrastructure, will reduce the carbon intensity of manufactured goods. Businesses conducting carbon accounting audits and those assessing the resilience of firms regarding the risks associated with the negative impacts of climate change are also emerging. The impact of 3D printing to reduce carbon emissions depends on the type of product. While it is more efficient to mass produce cheap items, 3D printing could play a role in high-cost low-demand goods such as complex engineering parts. This could decrease the need for storage space and transportation.

Low-carbon products: Examples of business models revolving round a low-carbon product are Tesla products and other smaller examples such as LifeStraw, which uses carbon-offset systems to distribute and finance easy-to-use equipment that removes waterborne bacteria and parasites. Finally, examples of business models favouring conservation are H&M and M&S 'bring your old clothes' campaigns.

5.1 R&I Recommendations

In the short-run, R&I actions should be focused on understanding what are the most cost-efficient innovative low-carbon business models, and what potential emission reductions can be expected from their widespread diffusion. Innovative and low-carbon business models are nowhere near being mainstream. They are very heterogeneous in characteristics and impacts across the different sectors. There are only few (and rarely comparable) analyses aimed at understanding successes or failures. Overall, there is a lack of clear and systematic understanding on how business models are facilitated (or impeded) by the interaction with the other sources of low-carbon profitability. Such knowledge should be developed. To this end, data collection and data analytics are crucial. For instance, a sort of repository for case studies could be devised containing a collection of systematic reviews and results. This would then become a key resource for much-needed evidence-based business decisions and policy making.

Research needs to understand the role played by the regulatory framework, energy prices and labour costs in the success and failure of innovative, low-carbon business models. Another main source of complexity in business model innovation is due to the uncertainty of associated behaviour and impacts on the environment, the economy and society (the three sustainability dimensions). It is key to identify in which environments low-carbon business models thrive, and in which they fail. Furthermore, firms need to be supported in identifying value flows and exchanges, thus promoting opportunities for business model innovations and de-risking experimentation. Importantly, the potential of business models for developing countries needs to be understood. Indeed, low-carbon business models targeted for the social and institutional frameworks of developing and fast-developing countries will have a very high marginal impact on decarbonisation, given that emissions are projected to increase significantly in those countries in the years to come.

R&I actions should support the development of economic and climate models which can capture the dynamics associated with innovative, low-carbon business models. Such models will help in demonstrating the impact of new business models. For instance, the outcomes of high levels of penetration of connected and autonomous vehicles in the transport sector are still not well understood. While there will be energy consumption efficiencies due to new vehicle designs and more efficient driving, there could be rebound effects via modal shifts from public transport to smaller vehicles. Research is needed to ascertain the rebound effects of those new business models and innovative technologies.

R&I efforts should be devoted to the education of the workforce to promote the proliferation of low-carbon business models and strategies. Workforce education is a crucial component in ensuring the uptake of low-carbon business models. Specifically, this can be achieved by developing educational models focused on nurturing a general low-carbon entrepreneurial spirit, while raising awareness and clarifying the relevance of climate change targets. While it will be crucial to target the highest levels of management within those organisations, deep decarbonisation will be possible only if the whole workforce within businesses understands the importance of a low-carbon economy and contributes to a low-carbon production process, and if the awareness level of customers increases. Overall, entrepreneurs should be trained to focus on early customer discovery and validation, which will ensure that customers' perceptions, awareness and attitudes towards lower-carbon businesses are incorporated in business strategies and models. Indeed, developing an innovative business model is an iterative process of putting into practice, learning and adapting or developing. Finally, low-carbon, innovative and successful business models often arise from the presence of strong leadership on the side of the firm, or the active consumer, as discussed in the chapter on social innovation.

6 Summary of recommendations on the economic implications of the decarbonisation transition

This chapter discusses four general cross-cutting issues which will play a crucial role in the decarbonisation of the European economies and which need to be the focus of R&I efforts. **First, decarbonisation will have important macro-economic implications. Second, decarbonisation will require the mobilisation of significant financing capital. Third, decarbonisation will be impacted by — and will impact — international trade dynamics. Fourth, innovative and low-carbon business models** need to be promoted to successfully promote the transition. Overall, this chapter puts forward some key R&I needs to ensure that considerations regarding these important aspects are factored into decision- and policymaking.

First, **in the short-run, R&I actions should strengthen the data collection, monitoring and modelling ability of the European Union**, to promote a full and detailed understanding of the macro-economic implications of decarbonisation. This includes data collection, which will enable the quantification of the economic implications of decarbonisation. It also entails investing to economic models, which should be enhanced to study financial flows and investments but also to address key research questions related with international trade dynamics or the key role of low-carbon business models.

In the medium-run, R&I actions should finance the assessment of the macro-economic implications of decarbonisation and the design of strategies to address the key barriers hindering this process. This implies understanding the impact that decarbonisation can have on trade and the competitiveness of different industrial sectors, and how to overcome the barriers linked with the deployment of zero-carbon technologies and their associated investment needs. It also requires research to identify the appropriate policy mix to reduce embedded emissions, to promote low-carbon business models and to ensure that transitional costs of decarbonisation are mitigated through appropriate social policy measures.

In the long-run, R&I actions should be devoted to monitoring progress with respect to decarbonisation targets, as well as to the establishment of stable partnerships for decarbonisation. This includes the promotion of interdisciplinary research, but also research on the effectiveness of policy instruments and measures and the ability to respect targets. It also includes R&I actions targeting the full restructuring of the financial system, the design of effective strategies to move capital at scale, cooperation around the harmonisation of trade standards and, more generally, the sharing of information and experience regarding successful low-carbon business models.

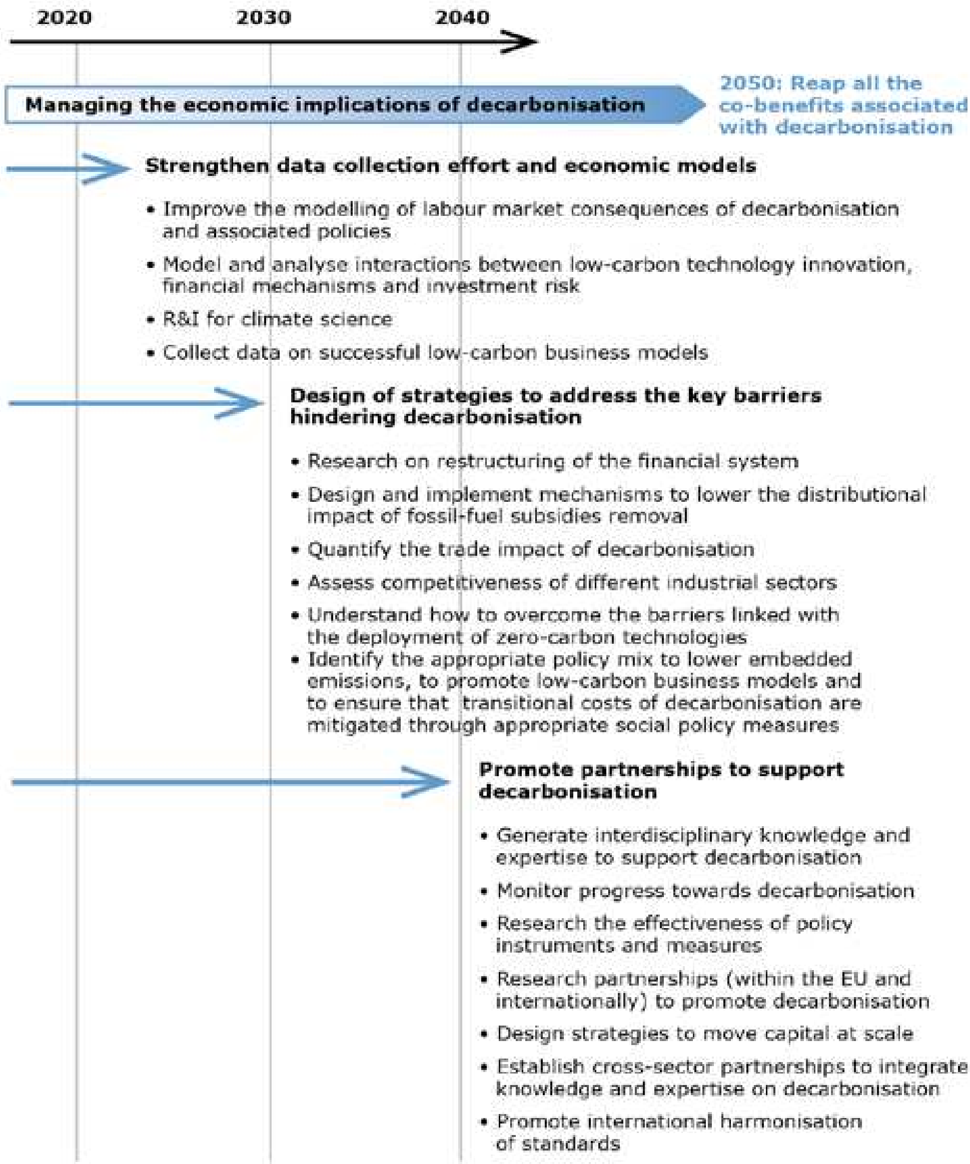

Figure 21: Possible pathways in R&I on the economic implications of the transition.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

The recently published IPCC 'Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways' (IPCC, 2018) provides an exhaustive assessment of the modelling work that may help to estimate the residual CO_2 budget consistent with the Paris Agreement goals. Notwithstanding the uncertainties related to the absolute amounts, what emerges from this literature assessment is that emissions should peak as soon as possible and decrease very rapidly, including those of short-lived GHGs and in particular of methane, if we wish to minimise the uncertain potential impact of negative emissions. The scientific literature shows that the rate of decarbonisation, i.e. the higher or lower speed at which emissions are reduced, has an impact on the probability of achieving a lower or higher final temperature stabilisation. But the most important message of this IPCC Special Report is that there is a sizeable difference of impacts between 1.5 °C and 2.0 °C, and that above 1.5 °C there is the risk of triggering some non-linear effects. The costs of keeping the planet at 1.5 °C are higher, but these are outweighed by the avoided impacts and co-benefits. Climate action ambition must therefore step up.

As argued in the introduction, the EU has to maintain and increase its leadership in research and innovation for developing zero-carbon solutions towards a sustainable planet, so as to maintain its leadership in climate action. Research and innovation investments are the best way to address the decarbonisation challenge while also ensuring European industrial and economic leadership.

As 'sectoral' chapters of this report already contain a concluding section where recommendations for addressing the research and innovation dimensions are presented, this final section focuses on the system-level, cross-cutting dimensions of the decarbonisation challenge.

Before discussing these dimensions, it is worth listing again the guiding key principles that were proposed in the introduction to develop a EU strategy for research and innovation in the zero-carbon domain and to summarise some of the evidence presented in earlier chapters with respect to each principle.

Engage in a race to the top in innovation for decarbonisation, searching for new alternatives.

A good example comes from the European Battery Alliance, launched in October 2017 by the European Commission. This industrial initiative has the goal of re-establishing a competitive battery industrial sector in Europe, which is considered essential, in particular to support the transformation of the European car manufacturing sector towards electromobility. This initiative contains several action areas, as well as a research and innovation component. While among the actions we can find support for the development of cell manufacturing, including that based on current Li-ion technologies, an important debate took place for the definition of the priorities of a dedicated Horizon 2020 call on batteries, where we can find the following statement: *"[…]*

it is the complete electric batteries value chain and life-cycle that has to be considered, from access to raw material, over innovative advanced materials and nanotechnologies to modelling, production, recycling, second life, life cycle and environmental assessment and skills." It is very questionable whether incremental progress on Li-ion technology, for which Asian manufacturers cover about 90 % of world production, is worth pursuing in the EU, using resources that could be better used for breakthrough developments in new directions. The value chain approach proposed by the call is very appropriate, as it is here that competitiveness can be generated.

Give priority to zero-carbon solutions that have the potential to be developed and deployed within the 2050 timeframe.
Europe has a very small remaining carbon budget to to stay within the Paris Agreement goals. This calls for focusing public research and innovation funding on solutions that eliminate emissions without creating further lock-in of lower emissions. The development and deployment timeframe of new zero-carbon technology is an issue (it cannot be longer than 20 years from today), and it is also connected with its critical size and modularity. Low-carbon technologies may be necessary in a limited number of cases for a limited time when difficult transition issues need to be addressed. This is the case, for instance, in the transport sector, where residual funding for incremental improvement of today's technologies should be limited to aviation and shipping, where zero-carbon solutions still look far from being marketable. However, in all sectors, research should first look at how to reduce demand, and not only at replacing today's fossil fuel-based technologies with cleaner ones.

Explore and develop portfolios of zero-carbon technologies, promoting diversification, and reducing the risk of too early and risky choices.
Smart diversification makes economies stronger and more resistant to crises and market fluctuations. Europe has the capacities, in terms of scientific and technological competence, engineering skills and financial robustness, to develop technology portfolios and decide on which priorities to invest.

Emphasise system-level innovation, promoting sector coupling, so that the individual elements of decarbonisation fit together in a coherent whole.
The interplay between zero-carbon energy generation and the electrification of industry, mobility, heating, and of other services is very evident, and has been broadly outlined across the report, highlighting the enabling role of digital technologies for system-level management. Fossil fuels created a system that can only be replaced by another one, and not by individual technologies.

Focus investments in the high added-value segments of value chains.
Photovoltaic technology was developed in Europe, but the substantial drop in unit costs driven by technological development and market volume resulted in the move of the PV industry to Asia, where costs of mass manufacturing are lower. It has been claimed that the decline of the European PV industry was due to feed-in tariff schemes. This analysis is superficial, in that PV is today cost-competitive almost everywhere thanks to the unit costreduction triggered by the feed-in tariff schemes. Furthermore, higher added-value segments of the PV value chain — such as plant engineering, production of inverters and ancillary equipment, financing, etc. — are still providing value in Europe. What this does teach us, however, is that demand side policies can be successful drivers of accelerated deployment of innovative technologies but should be supplemented

by a strong R&I policy so as to achieve a competitive edge in production as well.

These five principles have to be complemented by a sixth one:

Engage in smart international cooperation for zero-carbon innovation. Value chains have increasingly become international, across various complex technological domains. International cooperation should not therefore only be limited to the research phase, but should also develop at higher TRLs until market penetration. This may generate important win-win situations, particularly, as in the previous point, if the segments of value chains where Europe may excel have high added value. It is important to speak up about this evident issue in times when 'EU first!' slogans are emerging, and in discussion about the new research and innovation framework programme, Horizon Europe.

1 The system-level dimension of the decarbonisation challenge

As stated above, only a system-level approach to decarbonisation can be appropriate, and this has to be reflected in research and innovation priority-setting.

An example of the system-level dimension, building on the conclusions of Chapter 2, is that a fully decarbonised power system at EU level is possible, even with today's technology. However, considering that the decarbonisation of other sectors – namely transport, industry, and (partially) residential heating – strongly relies on their electrification, the demand for electric **energy is expected to grow substantially in the coming years. Energy efficiency in all sectors, and particularly in industry, is therefore the necessary starting point.** However, as shown in Chapter 4, although profitable low-carbon solutions are available, these are not yet deployed at their potential scale. It is necessary to invest in short-term research to investigate why, and test possible actions for removing existing barriers that limit their diffusion.

Chapter 2 also concluded that the decarbonised power system will require **smart grids and systems capable of integrating baseline production** (from hydro, biomass and nuclear, and in the transition period from natural gas) **with variable wind and solar energy**. These systems will need to integrate electric energy storage and the utilisation of excess wind-solar energy for the generation of hydrogen or the production of synthetic fuels (providing that non-fossil sources of carbon, e.g. from industrial fermentations, are available).

The **inter-sectoral dimension** is therefore of outstanding importance. For instance, batteries of electric cars connected for recharge should be capable of contributing to peak grid demands, while the **bioeconomy** – with its management of organic feedstock and residues – should provide ways for making the circular economy a true means of mitigation.

The complexity of the future energy system can only be managed through its **pervasive digitalisation and smartness**. This will require substantial developments from research and innovation in the medium term. Within the same timescale, **large-scale demonstrators** of hydrogen and synthetic fuels production from excess renewable energy – through processes that can be easily switched on and off – have to be realised close to the point of use by clusters of energy-intensive industries.

Partnerships with industries will be required to boost carbon-neutral innovation at all stages, in particular for those industries with process-based emissions. This will lead to changes in feedstock (e.g. bio-refineries and green chemistry) and alternative materials (e.g. using engineered wood instead of cement and steel in construction). Partnerships with industries are also needed to develop the radical breakthroughs needed to fully decarbonise some 'difficult' transport means, such as aviation, shipping and heavy-duty road transport.

As illustrated in Chapter 5, the **multi-purpose agriculture-forestry bioeconomy of tomorrow** will not only have to contribute to this intersectoral effort, but also guarantee the role of **soils as carbon sinks** and the concurrent deep reduction of other greenhouse gas emissions.

Cities (see Chapter 6), with their peri-urban industrial locations and agricultural areas, constitute the ideal integrating **laboratory for the future energy system**. Here – beyond the deployment of zero-carbon technological solutions – spatial planning, integrated urban mobility plans, urban regulations and social innovation will provide the necessary push and pull dimensions for helping the decarbonisation transition to succeed, including by acting on individual and social habits. In this respect, **mission-oriented research and innovation** programmes co-designed with the main city actors may be the most successful.

All the above aspects, in particular with regard to system-level issues, have always to take into account the various dimensions addressed in Chapters 7 and 8 of this report, i.e. the aspects of **social innovation, finance, trade, new business models, and policies needed to promote the development and the diffusion of zero-carbon innovation**.

Finally, it is necessary to accompany and facilitate the implementation of the Paris Agreement through adequate support to the first-class **climate change science** that the European scientific community has developed over the last few decades. The success of the EU greenhouse gas emission reduction strategy is also linked to the five-year update of the nationally determined contributions that the Paris Agreement links to science. Therefore, it is of utmost importance that key knowledge gaps in climate change science are adequately supported by future programmes, not only in relation to the **biogeophysical aspects**, but also the **economic** ones and the research on **policy design**. The importance given to the Earth system and economic **modelling dimensions** – where Europe has leading roles – has to be continued. So too does looking into the future to support decision-making. In this regard, the achievement in the long-term of a **seamless and reliable weather-to-climate prediction system** that can allow quantification of risks and provide climate services to end-users is of primary relevance.

The above high-level summary of this report is also presented in a time-based graphic format at the end of this chapter (Figure 22): an updated version from what was presented one year ago in the Interim Recommendations of this High-Level Panel in 2017. This proposal aims to provide a major input to the strategic programming of the **forthcoming Horizon Europe**, by providing priorities to organise the 35 % of climate-related investments that are expected in the period 2021-2027, which should be complemented by national programmes and by even bigger private investments.

2 Horizon Europe

2.1 Climate mainstreaming in Horizon Europe

The mainstreaming of climate action in EU Framework Programmes, with its 35 % target, has to be substantial and not simply a formality. Climate change is the major global physical risk caused by human activities that can be halted by human decisions and actions. **Actions are urgent and necessary, they are not an option.** The risk of exceeding the Paris Agreement targets and falling into a warming runaway situation is too high and must be avoided by all means. The carbon budget that is estimated by the IPCC as safe for staying 'well below 2 °C' as requested by the Paris Agreement provides the upper limit of acceptable emissions. In research and innovation, all programmes have to contribute to solutions, while programmes that have the potential to generate higher GHG emissions have to be discontinued. The EU Treaties provide a very good basis for this line of action. However, it is necessary to embed the climate dimension more deeply, in the application of the 'integration principle' (Art. 11 TFEU), and of the 'precautionary principle' (Art. 191 TFEU). Such climate dimensions can only be assessed through complex projections, and not by simpler tests as is the case with most environmental pollutants. In turn, this should affect the use of the new 'innovation principle' that is currently being proposed. It is precisely for these reasons that the forthcoming Horizon Europe, particularly all programmes under Pillar II dedicated to Global Challenges, must explicitly address climate change and recognise the constraint of achieving carbon neutrality by 2050. Within this broader framework, the contribution to decarbonisation should be a guiding principle for the strategic planning that will design and operationalise the Horizon Europe activities. It is at this planning stage that the coherence with the 35 % target will need to be checked.

2.2 Mission-oriented activities

A mission-oriented approach is needed for those complex societal challenges which require solutions within the medium term (5 to 15 years) that cannot simply be achieved by relying on independent developments driven by market conditions or by current innovation trends. Missions, currently being debated in the design phase of Horizon Europe, allow the achievement of difficult goals in a focused way. Particularly for challenges with a profound cross-sectoral dimension that requires the contribution of different stakeholders, and where public engagement is of high importance.

This Panel formulates three proposals for missions in our recommendations, which are synthesised in Figure 22:

- A mission that could be called '**the Internet of Electricity**', meaning the transformation of the power system based on renewables, integrating storage, transmission, dispatchment, and through smartness and digitalisation. This is a fundamental step towards the full integration and decarbonisation of the energy system;

- A mission on **European soils as carbon sinks**, addressing the need for structural and management changes capable of making EU agriculture, forestry and land use contribute to the overall carbon neutrality of the continent, as needed by 2050;

- A mission on **climate-neutral, 'circular' and liveable cities** (including energy, mobility, waste, construction, urban planning, etc.), that may well be formulated as the one presented in a recent paper of Mariana Mazzucato (Mazzucato, 2018) and entitled '**100 carbon-neutral cities by 2030**'.

2.3 Partnerships

PPPs are very relevant means to drive a critical mass of investments in some fields of industrial development where it is essential to bring to maturity new complex processes, and to generate breakthroughs that may become the basis for further competitive research by individual players outside the partnership agreement. For the decarbonisation challenge, the role of public investments is also to correct market failure, level the playing field, and then leave market competition to follow on. The HLP is therefore of the opinion that PPPs may be necessary for limited periods of time, for instance the first 10 years of development of zero-carbon solutions for industries showing process-based emissions (steel, chemistry and cement). PPPs should have the goal not only of developing the basis for a portfolio of alternative carbon-neutral processes, but, in possible solutions with intrinsic difficulties or complexities, to also develop alternatives capable of replacing the functions of today's products.

Partnerships for decarbonisation of this kind have to be designed based on the decarbonisation constraints and on the commitments of the Paris Agreement, with the goal of exploring all possibilities for arriving at carbon neutrality. Their long-term horizon has to go very much beyond incumbents' short-term plans – through visionary research and innovation programmes.

2.4 Transition Super-Labs

The urgency and the complexity of the challenge however requires a further 'instrument', here defined as a real-life laboratory where systemic innovation for the transition to a fully decarbonised economy is tested at scale in locations where particularly difficult transition efforts will be required. There is compelling evidence that rapid decarbonisation of advanced industrialised societies can only be achieved through systemic solutions. In other words, the transformation of whole entities – such as non-sustainable business complexes, mining regions and polluted metropolitan areas – is required, not just the replacement of wasteful components by more efficient ones. In theory, based on big data and simulation modelling, such transformations can be straightforwardly identified and devised. For instance, cost-benefit analysis and operations research deliver optimal concepts for multimodal transport systems or for sector coupling that maximises CO_2 reduction without hampering performance and competitiveness.

However, these concepts often fall apart when theory collides with technical, environmental and socioeconomic realities: critical bottlenecks have been overlooked; cultural resistance has been underrated; ecological trade-offs have been ignored; and so forth. What ultimately matters is the truth on the ground, where targets, timetables and measures have to be matched. This is the challenge of the **mission-driven integration** of innovative elements and steps.

Research and innovation will constitute the core of the intelligence needed to be deployed at large territorial scale, making use of other sources of European or national funds. The HLP therefore proposes to establish a small number of '**Transition Super-Labs**' (see Figure 23), where rapid decarbonisation is conceptualised, implemented, monitored and revised in line with the insights gained on the transformational behaviour of the complex system in question. These are flagship demonstrators where research, business, administration and civil society co-produce integrated solutions.

Super-Labs would be realised in critical locations where the transition can be particularly difficult – such as coal-mining areas, territories characterised by high density of energy intensive industries, cities with very energy inefficient building stock, etc.

Candidate demonstrators are:

- mining-industrial complexes that need to be transformed quickly without destroying their value-creation potential;
- conventional agricultural regions that are suitable for conversion into climate-neutral/negative bioeconomies and can also become havens for biodiversity and sustainable tourism;
- metropolitan areas where novel concepts of mobility, construction and operation can be combined, most notably by making use of the powerful tools provided by digitalisation and artificial intelligence.

Mission-driven integration should be funded from a portfolio of sources – merging European, national, regional and private funds - for 5-10 years under the supervision of Horizon Europe. The Climate-KIC of the European Institute of Innovation and Technology (EIT) (or a new KIC within the EIT) can be the nucleation element for broad territorial alliances among academia, research centres, industry, public administrations, and other stakeholders.

2.5 Climate science

The focus on the 'solution space' in relation to climate change should accompany the maintenance of **a strong European programme on climate change science**, in particular **to reinforce the IPCC process**, and through its reports to feed the Paris Agreement process. The 5-year cycle of the Global Stocktakes has to be informed by science, and very robust and high-evidence statements in IPCC reports will be of outmost importance for raising ambition and achieving the Paris Agreement goals. In the coming years, the more the available carbon budget for remaining within the maximum warming targets is used, the more it will be necessary to have highly reliable modelling and simulation tools available to support decision-making at all levels.

The new possibilities offered by artificial intelligence and machine learning will allow new developments in tracking, attributing, and forecasting a number of climate phenomena and events. However, this will not replace the need to fill a number of knowledge gaps in climate processes, in order to increase modelling capabilities. A lot still needs to be done to be able to forecast and quantify the impacts of climate change, the triggering of non-linear responses, the occurrence of extremes and of low-probability high-consequence events.

Focused attention on the areas of the planet where climate is changing more rapidly with high potential consequences for biodiversity loss, such as the Arctic, has to be continued and extended to other areas of high risk, such as the oceans, tropical areas, and Antarctica.

In terms of mitigation, integrated assessment models are still limited and have to evolve, because they are increasingly used to support informed decision-making. They need in particular to be able to consider the effects of lifestyle and behavoiural changes, and other non-economic factors.

A stable policy environment will be a key framework condition to ensure that this huge innovation challenge is successfully addressed. For this reason, research on policy design and policy evaluation will be an important component of the future European R&I endeavour.

In addition, economic research on adaptation should lead to a more complete consideration of the costs of adaptation and of the costs of non-action.

2.6 Outreach and education

The Herculean research and innovation efforts that have been briefly depicted for preparing the full decarbonisation of EU economies and societies by or around 2050 have then to be reflected in a **revision of school and university curricula** of all grades, that incorporate climate change knowledge within the ordinary basic body of knowledge in science, engineering, economics, political science, geography and even history teaching. It is therefore recommended that the development of school and university teaching materials and relevant outreach programmes that are also addressed to citizens more generally should be a contractual obligation of Horizon Europe projects in the climate change domain. The understanding of the mechanisms and underlying challenges of anthropogenic climate change cannot remain restricted to few insiders.

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The role of publicly funded research and innovation is of paramount importance for the success of the decarbonisation strategy of the EU. As extensively argued here, **climate change is the result of the biggest market failure of our times**, a 'tragedy of the commons' that can only be corrected through the intervention of governments and by steering zero-carbon innovation through very large public R&I investments. Such R&I programmes will have the double effect of providing new incentives associated with deep decarbonisation for the many incumbents currently benefiting from the fossil fuel economy, and of promoting **a new generation of brave and visionary actors to lead this challenging transition**.

Time is short, and efforts must be adequate to the challenge, which is immense.

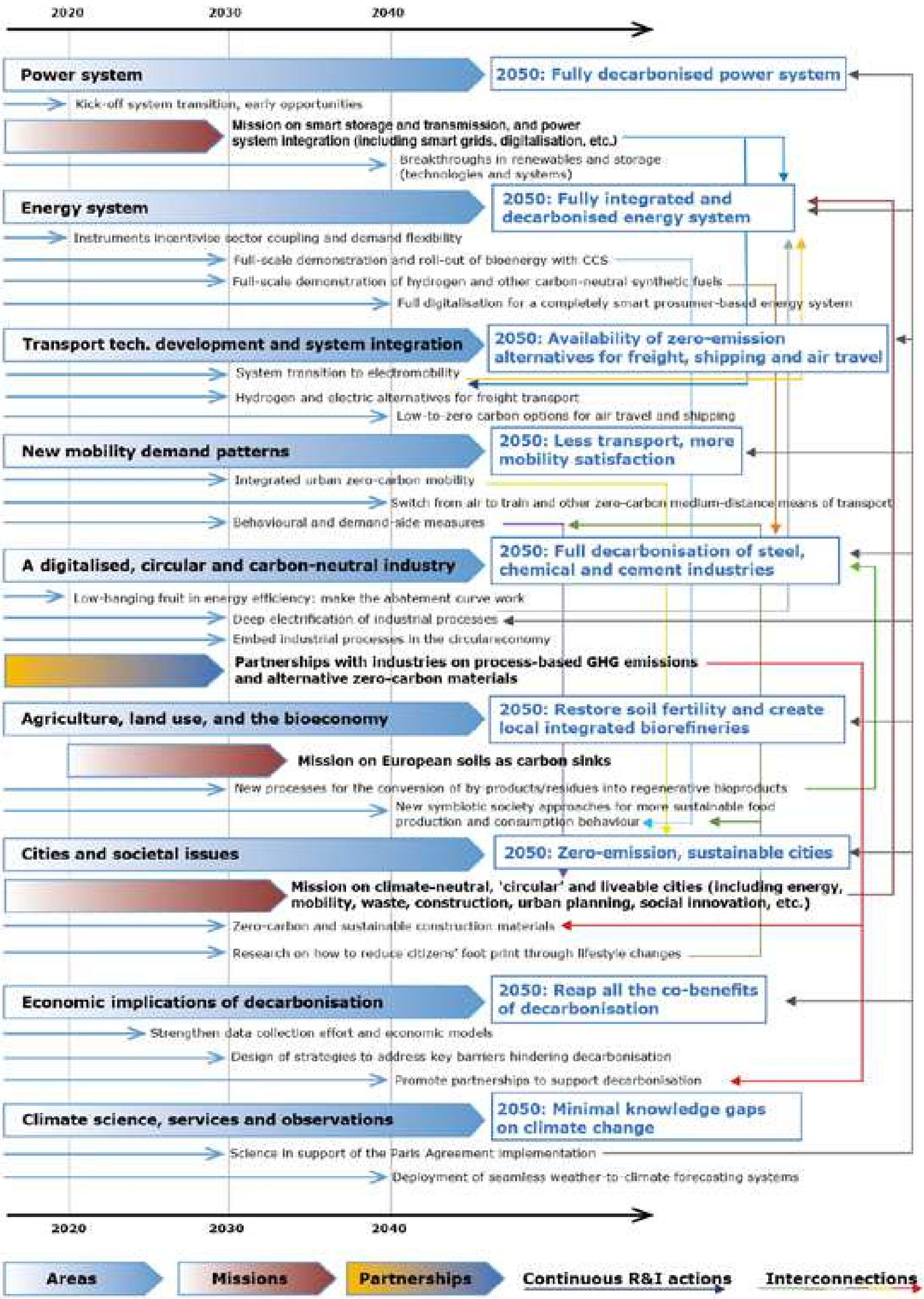

Figure 22: Proposed priority research and innovation actions for supporting the decarbonisation process in different areas in the timeframe 2018-2040, in order to achieve the 2050 goals indicated in the boxes. Red arrows represent Horizon Europe mission-oriented actions; yellow-brown arrows represent Horizon Europe public-private partnerships. All linear arrows are intended as roadmaps that produce various outputs throughout their timeframe until their end-date, when the activity should be completed and deployed in society. Many of the proposed actions are interrelated, and their results contribute to different 2050 goals.

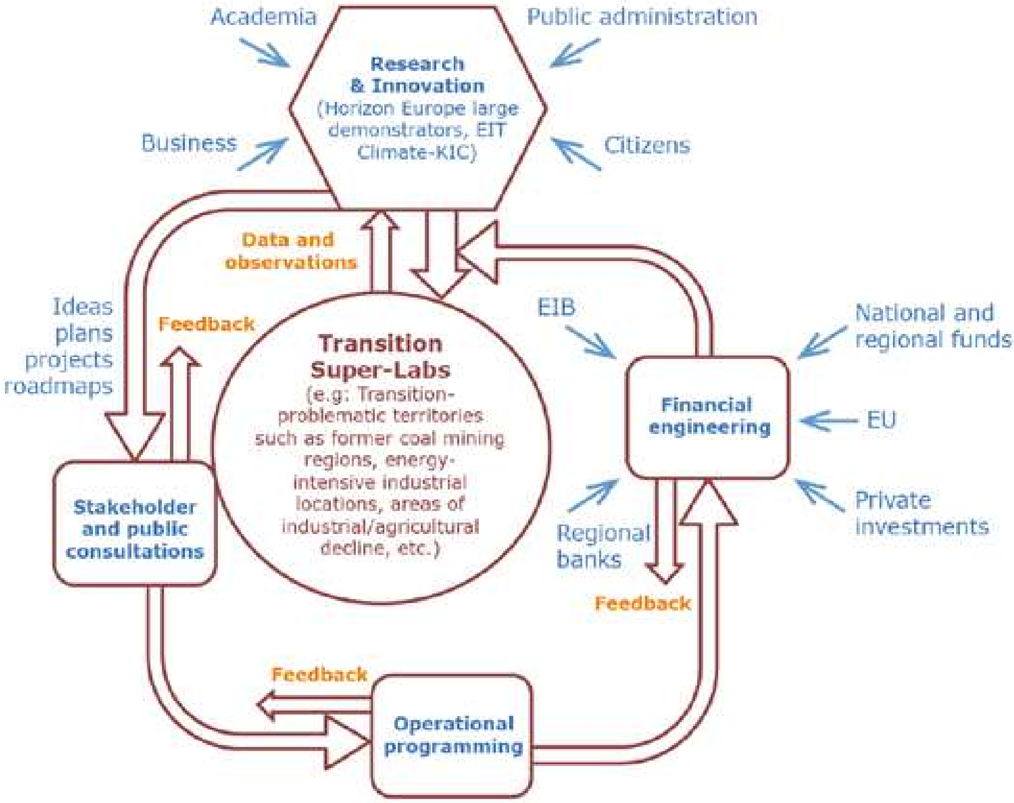

Figure 23: Conceptual representation of Transition Super-Labs: large territorial initiatives for fostering the transition to a zero-carbon economy in particularly vulnerable areas.

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Which strategy to adopt in research and innovation in order to speed-up and foster mitigation policies in the EU that respond to the goals of the Paris Agreement, while growing the competitiveness of the EU economy? To reply to this question, the nine Members of the High-Level Panel on Decarbonisation have designed a straightforward strategy, which implies that the design of future programmes of Horizon Europe – the new EU Framework Programme for Research and Innovation 2021-2027 – and of similar national programmes in the EU - have to massively invest in a wide portfolio of zero-carbon solutions, in particular for addressing the most difficult aspects of decarbonisation where alternatives to fossil-fuels are still far from the marketplace.

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