REN21

GLOBAL FUTURES REPORT

RENEWABLES FOR SUSTAINABLE TRANSPORT
BRIDGING PERSPECTIVES

REN21 MEMBERS

GOVERNMENTS

Australia
Austria
Brazil
Denmark
Dominican Republic
Georgia
Germany
India
Republic of Korea
Mexico
Morocco
Norway
Panama
Río Negro Province, Argentina
South Africa
South Australia State, Australia
Spain
United Arab Emirates
United States
Zimbabwe

PRESIDENT

Arthouros Zervos

EXECUTIVE DIRECTOR

Rana Adib

SCIENCE AND ACADEMIA

AEE – Institute for Sustainable Technologies (AEE-INTEC)
Council on Energy, Environment and Water (CEEW)
Fundación Bariloche (FB)
International Institute for Applied Systems Analysis (IIASA)
International Solar Energy Society (ISES)
National Renewable Energy Laboratory (NREL)
National Research University Higher School of Economics Russia (HSE)
South African National Energy Development Institute (SANEDI)
The Energy and Resources Institute (TERI)
University of Technology – Institute for Sustainable Futures (UTS)
World Resources Institute (WRI)

MEMBERS AT LARGE

Michael Eckhart
Rabia Ferroukhi
David Hales
Kirsty Hamilton
Peter Rae

INTER-GOVERNMENTAL ORGANISATIONS

Asia Pacific Energy Research Centre (APERC)
Asian Development Bank (ADB)
ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE)
Electric Power Council of the Commonwealth of Independent States (Executive Committee) (EPC)
European Commission (EC)
Global Environment Facility (GEF)
International Energy Agency (IEA)
International Renewable Energy Agency (IRENA)
Islamic Development Bank (IsDB)
Latin American Energy Organization (OLADE)
Regional Center for Renewable Energy and Energy Efficiency (RCREEE)
United Nations Development Programme (UNDP)
United Nations Environment Programme (UNEP)
United Nations Industrial Development Organization (UNIDO)
World Bank (WB)

INDUSTRY ASSOCIATIONS

Africa Minigrid Developers Association (AMDA)
Alliance for Rural Electrification (ARE)
American Council on Renewable Energy (ACORE)
Asia Pacific Urban Energy Association (APUEA)
Associação Lusófona de Energias Renováveis (ALER)
Chinese Renewable Energy Industries Association (CREIA)
Clean Energy Council (CEC)
Euroheat & Power (EHP)
European Heat Pump Association (EHPA)
European Renewable Energies Federation (EREF)
Global Off-Grid Lighting Association (GOGLA)
Global Solar Council (GSC)
Global Wind Energy Council (GWEC)
Green Hydrogen Organisation (GH_2)
Indian Renewable Energy Federation (IREF)
International Geothermal Association (IGA)
International Hydropower Association (IHA)
International Union of Railways / Union Internationale des Chemins de Fer (UIC)
Long Duration Energy Storage Council (LDES)
Portuguese Renewable Energy Association (APREN)
RE100 / Climate Group (RE100)
RES4Africa Foundation (RES4Africa)
Solar Heat Europe (SHE)
SolarPower Europe (SPE)
Union Internationale des Transports Publics (UITP)
World Bioenergy Association (WBA)
World Wind Energy Association (WWEA)

NON-GOVERNMENTAL ORGANISATIONS

350.org
African Association for Rural Electrification (Club-ER)
Asociación Ivy
CDP
Clean Cooking Alliance (CCA)
Climate Action Network International (CAN-I)
Coalition de Ciudades Capitales de las Americas (CC35)
Collaborative Labeling and Appliance Standards Program (CLASP)
Energy Cities
European Youth Energy Network (EYEN)
Fundación Renovables (FER)
Global Forum on Sustainable Energy (GFSE)
Global Women's Network for the Energy Transition (GWNET)
Greenpeace International
ICLEI – Local Governments for Sustainability
Institute for Sustainable Energy Policies (ISEP)
International Electrotechnical Commission (IEC)
International Institute for Sustainable Development (IISD)
Jeune Volontaires pour l'Environnement (JVE)
Mali Folkecenter (MFC)
Power for All
Power Shift Africa
Renewable Energy and Energy Efficiency Partnership (REEEP)
Renewable Energy Institute (REI)
Renewables Grid Initiative (RGI)
SLOCAT Partnership on Sustainable, Low Carbon Transport (SLOCAT)
Solar Cookers International (SCI)
Solutions for Our Climate (SFOC)
Sustainable Energy Africa (SEA)
Sustainable Energy for All (SEforALL)
The Global 100% Renewable Energy Platform (Global 100%RE)
Women Engage for a Common Future (WECF)
World Council for Renewable Energy (WCRE)
World Future Council (WFC)
World Wide Fund for Nature (WWF)

FOREWORD

The transport sector is a giant when it comes to energy use. It's responsible for 30% of the total final energy consumption. This means nearly a third of all energy we use goes into moving people and goods around. Over the past decade, energy demand in the transport sector has surged by 9%. As our world becomes more connected and mobile, this demand will only continue to grow, making it more urgent to find sustainable energy solutions.

We cannot achieve a decarbonised economy without addressing the transport sector. But there is a significant disconnect between where we are and where we need to be. Currently transport has the lowest share of renewables among all energy-consuming sectors; just 3.9%. This tiny fraction highlights a major gap and a huge opportunity for improvement. To close this gap, we need strategic alignment and a unified approach to boost the use of renewables in transport.

The *Global Futures Report - Renewables for Sustainable Transport, Bridging Perspectives* (GFR) asks forward-looking questions about how to close this gap. The report is unique. Unlike our other reports that focus on the status of renewable energy, the GFR captures the diverse perspectives and current thinking about the future of renewables. It doesn't just present facts; it creates a framework for debate and discussion, shedding light on different viewpoints, blind spots, opportunities, and barriers to progress.

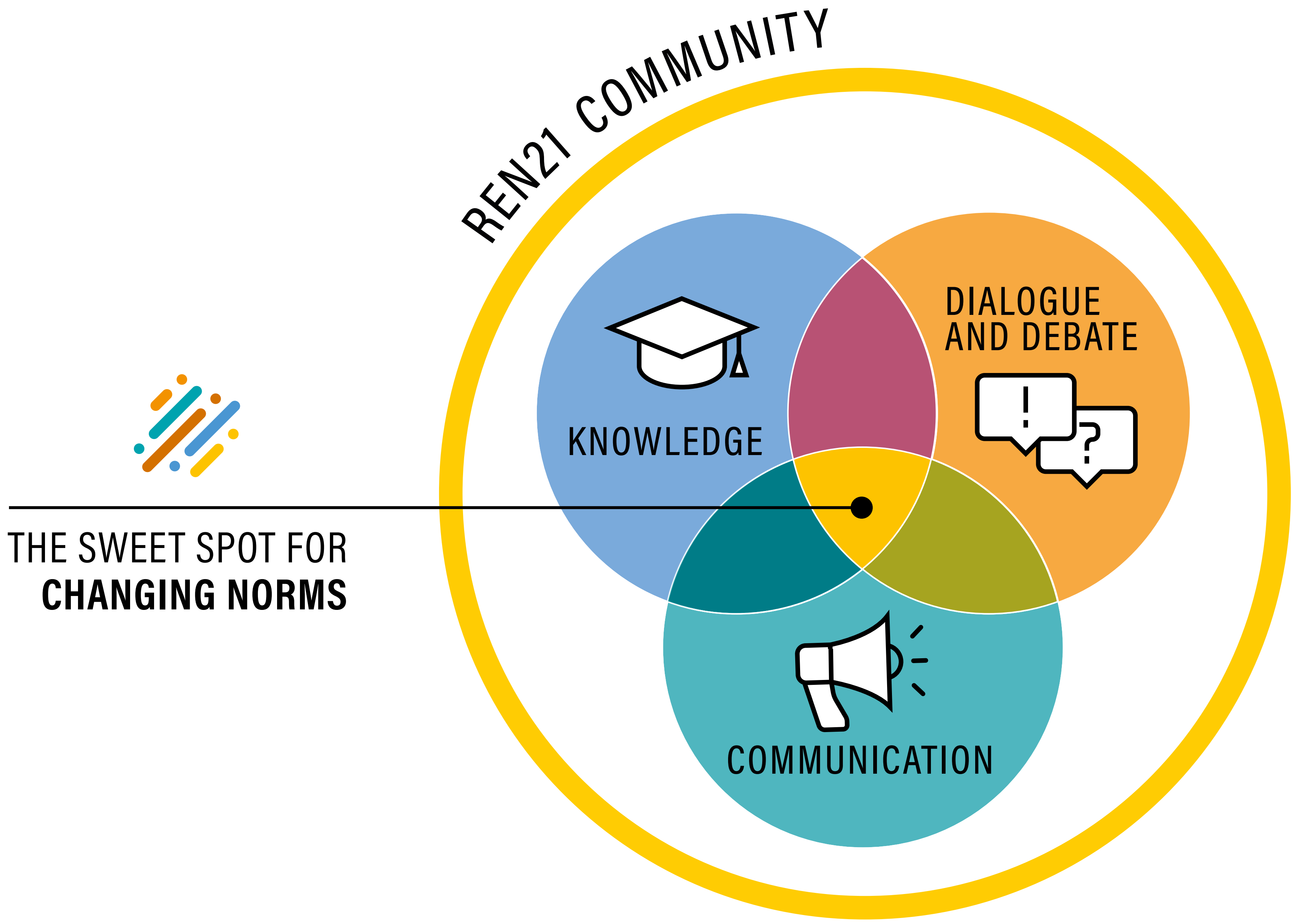
This report is particularly important as it addresses the critical disconnect between the transport and energy sectors. It offers a "toolkit" to foster discussions and inspire strategic actions to bridge this gap.

Renewables for Sustainable Transport, Bridging Perspectives is the result of contributions from many dedicated individuals and organisations. It's a collaborative effort that provides valuable insights and encourages collective action. I hope you find this Futures Report thought provoking. It's not just a report; it's a call to action. Let's use it to ignite discussions, inspire change, and work together towards a future where transport is fueled by renewables, facilitating both equity and addressing climate concerns.

Rana Adib
Executive Director, REN21

REN21 RENEWABLES NOW

RENEWABLE ENERGY POLICY NETWORK
FOR THE 21st CENTURY



REN21 is unique. It is the only global, **multi-stakeholder network** dedicated to renewables.

We create an **enabling environment to support renewable uptake**. Together, we build knowledge, shape dialogue and debate, and communicate this information to strategically drive the deep transformations needed to make renewables the norm.

Shifting to renewables is more than a fuel switch; it requires engaging with market players and society at large. **REN21 works in close cooperation with its community**, providing a platform for all stakeholders to engage and collaborate.

Through these collective efforts, REN21 builds bridges and amplifies positive and sustainable energy solutions. Our goal: enable decision-makers to **make the shift to renewable energy happen – now.**

20 YEARS OF REN21

This year marks two decades since the inception of REN21 – an opportunity to celebrate 20 years of instrumental contributions to the advancement, shaping and understanding of renewable energy worldwide. Established in 2004, REN21 emerged from the collective vision of global pioneers who convened to call for accelerated commitments towards renewable energy adoption. For two decades, REN21 has been pivotal in elevating renewables to the forefront of global agendas for leaders and decision-makers across all stakeholder groups, enabling knowledge exchange, dialogue and debate about the global transition to renewables.

The 20th anniversary celebration of REN21 is also the occasion to highlight REN21's Global Future Report series. Issued periodically, these reports document the current, collective thinking of many experts about a certain aspect of the future of renewables. These reports do not present just one vision of the future, but rather a full and impartial range of visions, based on the collective and contemporary thinking of many. These reports complement REN21's work by providing an objective framework for thinking about a renewable energy future.

20 YEARS OF CROWD-SOURCED, CROWD-OWNED KNOWLEDGE AND DATA

REN21's data and knowledge collection method is unique, drawing upon the organisation's global multi-stakeholder community of experts. Contributors from across the globe are invited to submit data, insights and stories on annual developments in renewable energy technologies, market trends, policies and local perspectives, resulting in a comprehensive and diverse dataset.

REN21 performs rigorous data validation and fact-checking throughout the report's development, ensuring accuracy and reliability. Validation of the data is a collaborative and transparent process conducted through open peer reviews.

ACKNOWLEDGEMENTS

REN21 PROJECT MANAGEMENT AND DATA TEAM

Hong Yang
Jad Baba

Supported by:
Aishwarya Dhar
Hannah E. Murdock
Janne Luise Piper
Sara Strumia
Laura E. Williamson

SPECIAL ADVISORS

Krista Halttunen
Lewis Fulton, University of California, Davis
Zifei Yang, ICCT

AUTHORS

Marion Vieweg, Current Future
Adam Brown, Energy Insights Ltd
Becquerel Institute (Initial design and research)

INTERVIEWEES

Adam Brown (Energy Insights/Independent); Alex Campbell (International Hydropower Association); Alok Jain (Trans-Consult Ltd.); Amit Kumar (The Energy & Resources Institute); Anthony Eggert (ClimateWorks); Bharadwaj Kummamuru (World Bioenergy Association); Bonna Newman (TNO); Bronwen Thornton (Walk21); Cédric Philibert (Independent); Cornie Huizenga (Climate and Environment Services Group); Daniel Bongardt (GIZ); Doug Arent (NREL); Doug Vine (Center for Climate and Energy Solutions); Edwin Bastiaensen (International Motorcycle Manufacturers Association); Elisabeth Windisch (International Transport Forum); Ery Wijaya (Cities Climate Finance Leadership Alliance); Flávia Guerra (United Nations University – Institute for Environment and Human Security [UNU-EHS]); Garima Agrawal (World Resource Institute); Gavin Allwright (International Windship Association); Glynda Bathan-Baterina (Clean Air Asia); Henrik Gudmundsson (CONCITO); Hironao Matsubara (Institute for Sustainable Energy Policies); Indradip Mitra (GIZ); Insan Ridho Chairuasni (PT Transportasi Jakarta); James Leather (ADB, Transport Sector Group); Jonas Stromberg (Scania); Karl Peet (SLOCAT); Kathleen Dematera-Contreras (Clean Air Asia); Keiichi Komoto (Mizuho); Kristie Daniel (HealthBridge, Livable Cities Program); Kristiina Yang (Cities Climate Finance Leadership Alliance); Le Anh Tuan (Hanoi University of Science & Technology); Lewis Fulton (University of California, Davis); Lulu Xue (World Resource Institute); Marc Weiss (Global Urban Development); Mário Alves (International Federation of Pedestrians); Mark Major (SLOCAT); Mika Ohbayashi (Renewable Energy Insitute Japan); Milag San Jose-Ballesteros (C40); Nicholas Wagner (International Renewable Energy Agency); Oliver Lah (Wuppertal Institute for Climate); Patrick Oliva (Orbimob); Pedro Dias (Solar Heat Europe); Philip Turner (UITP); Renato Domith Godinho (Ministry of Foreign Affairs – Brazil); Rik Arends (Smart Freight Center); Roberto S. Capuano Tripp (Metrobus Mexico City); Sam Stewart Mutabazi (Uganda Road Sector Support Initiative); Sheila Watson (FIA Foundation/Global Fuel Economy Initiative); Shri Prakash (TERI); Sophie Punte (Smart Freight Center); Stefan Gsänger (World Wind Energy Association); Sven Teske (Institute for Sustainable Futures); Todd Litman (Victoria Transport Policy Institute); Vijay Nirmal (Cities Climate Finance Leadership Alliance); Wanji Nganga (Shell Foundation); Warren Ondanje (Association for Electric Mobility and Development in Africa); Wei-Shiuen Ng (UN ESCAP); Yossapong Laoonual (Electric Vehicle Association Thailand); Zifei Yang (The International Council on Clean Transportation)

ACKNOWLEDGEMENTS

EDITING
Stefanie Durbin

DESIGN AND LAYOUT
weeks.de Werbeagentur GmbH

PRODUCTION AND COMMUNICATION
REN21 Secretariat, Paris, France

PEER REVIEWS
Abdullah Fahad (International Renewable Energy Agency [IRENA]); Abubakar Musa Magaga (Nigerian Institute of Transport Technology); Adrian Serna Tamez (CALSTART); Alejandra Leon Lavandera (World Bioenergy Association); Ali Shahhoseini, Amin Yahya-Khotbehsara (Qazvin Islamic Azad University); Annika Berlin (UNEP); Avinash Dubedi (WRI India); Bernardo Joel Carrillo Castillo (Independent); Bharadwaj Kummamuru (World Bioenergy Association); Chacrit Sitdhiwej (Thammasat University); Cornie (ATO); Daphne Gross-Jansen (Federal Ministry for Economic Cooperation and Development); Detlef Loy (Loy Energy Consulting); Evaldo Costa (DINÂMIA'CET-Iscte, Centro de Estudos Sobre a Mudança Socioeconómica e o Território, Iscte-Instituto Universitário de Lisboa, 1649-026 Lisboa, Portugal); Hameedullah Zaheb (Kabul University); Hannah E. Murdock (Imperial College London); Joana Portugal-Pereira (Coppe/UFRJ and IST/ULisboa); João Tomaz; Lena Plikat (GIZ); Marlene Mingramm (Internship BMZ); Marvin Stolz (GIZ); Max Schülling (BMWK); Neelofar Karimi, Joshua Rodd (U.S. Department of State); Prof. Dr. Kamil Kaygusuz (Karadeniz Technical University, Department of Chemical & Energy Engineering, Trabzon, Türkiye); Rainer Hinrichs-Rahlwes (European Renewable Energies Federation [EREF]); Ricardo Garcia Coyne (CALSTART/Drive to Zero); Rik Arends (Smart Freight Centre); Soso Mindiashvili (Ministry of Economy and Sustainable Development of Georgia); Sreenivas Chigullapalli (India Climate Collaborative); Stefanie Durbin (n/a); Stefanie Sohm (Kühne Foundation); Suani Coelho (USP); Suraj Kanojia (Junior Energy Advisor); Swasti Raizada (International Institute for Sustainable Development); Yann Briand (IDDRI – Sciences Po); Хузмиев Измаил Каурбекович (Поффессор)

For further details and access to the report, references and endnotes, visit **www.ren21.net/2024-renewables-global-futures-report**

REPORT CITATION
REN21. 2024. *Global Futures Report: Renewables for Sustainable Transport* (Paris: REN21 Secretariat).

ISBN 978-3-948393-16-8

Comments and questions are welcome and can be sent to **gsr@ren21.net**.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF BOXES

LIST OF TABLES

SUPPORTED/FUNDED BY:

Federal Ministry for Economic Affairs and Climate Action

IKI INTERNATIONAL CLIMATE INITIATIVE

THIS PUBLICATION WAS DONE UNDER THE NDC TRANSPORT INITIATIVE ASIA, A PROJECT FINANCED BY THE INTERNATIONAL CLIMATE INITIATIVE (IKI).

NDC TRANSPORT INITIATIVE FOR ASIA

THE NDC TIA IS A JOINT PROGRAM OF SEVEN ORGANISTAIONS:

Agora Verkehrswende

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

icct THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

International Transport Forum

REN21

SLOCAT Partnership on Sustainable, Low Carbon Transport

WORLD RESOURCES INSTITUTE

SUMMARY

REN21's Global Futures Reports provide a framework to debate and discuss possible futures of renewable energy and to identify opportunities, barriers to progress and ways to overcome these. This report focuses on how to scale up renewables in the transport sector rapidly.

Through wide-ranging consultations carried out across the extensive REN21 network, this report seeks to identify "tension points" where views of stakeholders diverge significantly, so as to direct attention to critical areas, and to shape conversations and strategic planning. It intends to be thought-provoking rather than to try to reach definitive conclusions.

Why transport: Transport is a key energy end-use sector, accounting for 30% of total final energy consumption in 2021 and for 20% of total energy-related greenhouse gas (GHG). These proportions are expected to continue to rise in future years as demand for transport grows. However, the renewable energy share of transport is only 4% and is rising slowly.

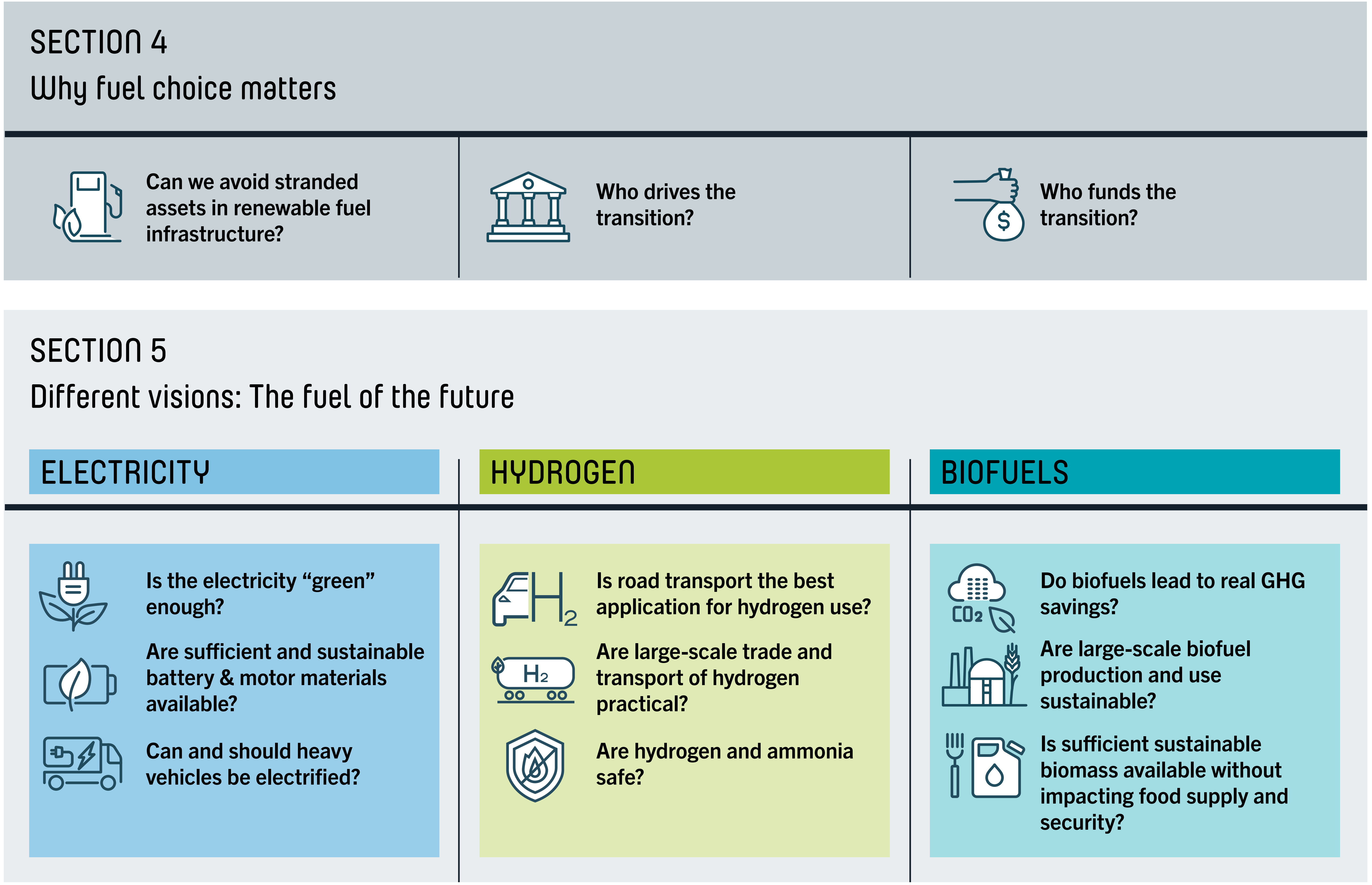
Renewables are only one pillar of action in the sector: There are many options for reducing emissions associated with the transport sector. These are often summarised in terms of the "Avoid-Shift-Improve" (ASI) framework, which involves **avoiding** or reducing the need for motorised transport, **shifting** to less carbon intensive travel modes, and finally **improving** efficiency, vehicle technology and fuels. Each of these components is an important driver for transport emissions. Renewables make a decisive contribution under the "improve" pillar of this framework. Renewable options for transport are the use of renewable electricity, the use of biofuels and of renewables-based hydrogen and its derivatives.

Disagreement centres around the "right" fuel mix: The survey responses and the expert interviews carried out for this report and the analysis of literature showed strong differences in opinion about what the "right" fuel mix will be, with differing views on the advantages, disadvantages and barriers to expansion. There were also some disagreements on a number of important cross-cutting elements. The main "tension points" are summarised in the Figure S1.

Why the fuel mix matters – money and responsibilities are at the heart of disagreements: The cross-cutting issues stem from the fact that a transition to a sustainable global transport system based on renewable fuels will have a significant impact on energy infrastructure at different levels of the supply chain, depending on the type of fuel used. Key questions include:

- Can we implement renewable fuels quickly enough and still avoid stranded assets for renewable fuel infrastructure?
- Who is responsible for steering and enabling the transition?
- Do we have the funds to set up parallel infrastructure for multiple fuels?

Figure S1: Overview of tension points

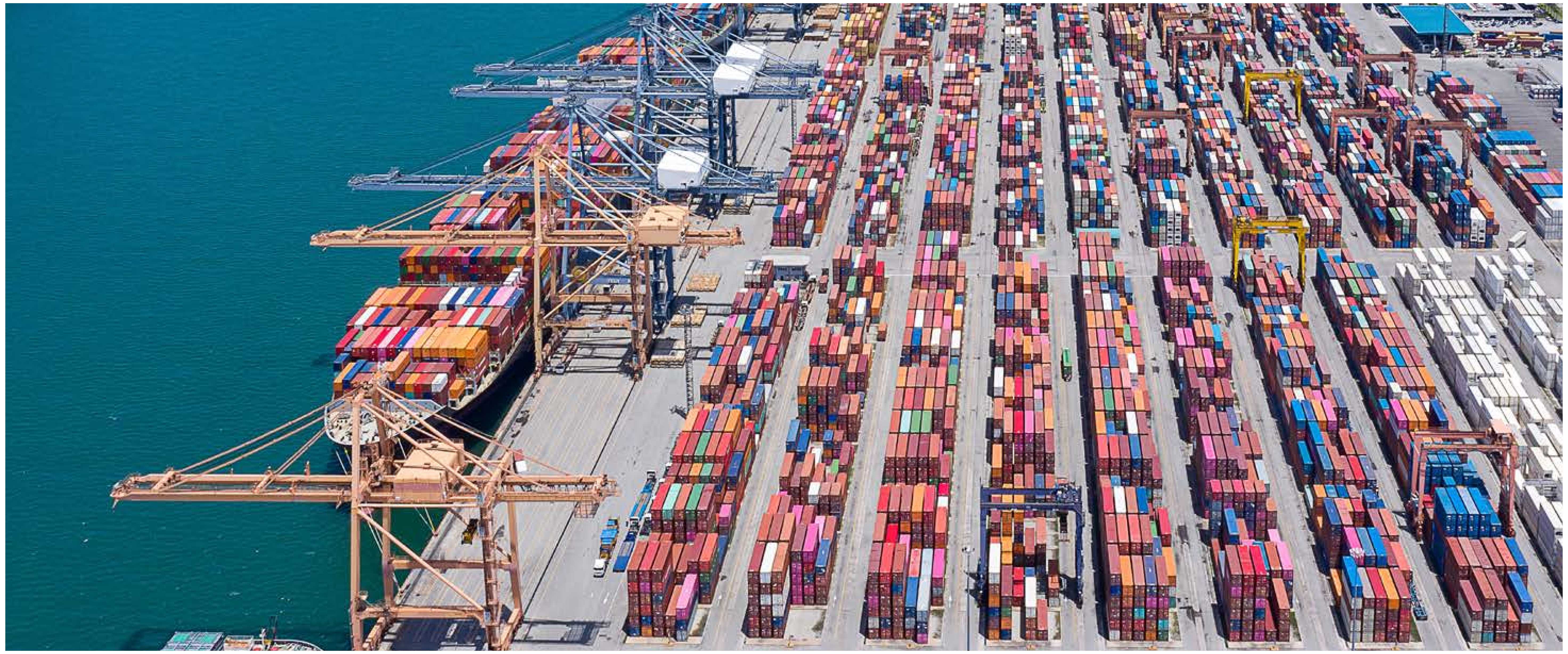


Each fuel has advantages and disadvantages, but views differ on what these are,and whether or how they can be overcome: The need to increasingly electrify transport is generally accepted. However, there is much less agreement about the extent to which this is likely to happen, in which transport segments and the pace that is desirable. The main concerns are around the availability of materials to produce batteries and motors and the GHG intensity of the electricity used. Views also differ on the extent of electrification for heavy vehicles, owing to technical and economic constraints.

There is also general agreement among experts that a dramatic rise in the production and use of sustainably produced hydrogen – produced by the electrolysis of water using renewable electricity or through bioprocesses – is essential to the energy transition, complementing electrification and other measures. There is much less agreement about the role of other low GHG hydrogen and hydrogen use in the transport sector and for which modes and applications it is most appropriate. In particular, views differ on the feasibility of resulting trade and long-distance transport of hydrogen and hydrogen-based fuels under scenarios with high use. Additional concerns arise around the safety of hydrogen and ammonia.

Biofuels are currently used in road transport, but there is growing attention on the potential to use these fuels in the aviation and shipping sectors. The most contentious topic regarding biofuels is the sustainability of their production and use. Sustainability concerns revolve around the actual GHG savings that can be achieved, impacts on biodiversity, air quality and water and on food availability.

Decisions will ultimately be taken locally: This report highlights the issues around each tension point and the different expert views, including some helpful facts and figures. However, this report does not provide conclusions or policy recommendations. We recognise that decisions need to be tailored to fit national and local circumstances and that different solutions will be chosen across the globe. We hope that the arguments, facts and resources provided here will provide food for thought and inform these local debates. We provide a set of guiding questions that can make these debates effective, and help progress towards the sustainable, renewables-based transport system which is an essential part of a sustainable future.



ABOUT THIS REPORT

About REN21's Renewables Global Futures Reports.

REN21's Global Futures Reports[i] provide a framework to debate and discuss the possible futures of renewable energy and to identify opportunities, barriers to progress and ways to overcome these barriers. Each report in the series seeks to capture the current thinking about one aspect of a sustainable energy future through wide-ranging consultations carried out across the extensive REN21 network. This consultation is used to identify "tension points" (where views of stakeholders diverge significantly), direct attention to critical areas, and shape conversations and strategic planning.

The reports are intended to be thought-provoking documents that can be used to stimulate discussion. They do not attempt to reach definitive conclusions or achieve consensus, since different stakeholders are likely to maintain different views. It is also probable that solutions in different regions may differ.

The objectives of the 2024 edition of the Global Futures Report.

In this report we address the question of how to rapidly scale up renewables in the transport sector. The report considers perspectives relating to different transport modes, geographic locations and interest groups and aims to pinpoint areas with significant disagreement about the "right" path forward.

Transport is the second-largest energy end-use sector.[1] Reducing transport greenhouse gas (GHG) emissions is therefore crucial for tackling overall energy sector emissions.

The renewable energy share of transport is currently around only 4% and is rising slowly.[2] To achieve a sustainable energy future, the transition to renewable-based energy sources in transport needs to accelerate rapidly – but there are different views on where to focus.

We are not providing any conclusions or policy recommendations for this report. The objective is to explore different perspectives, to pinpoint areas with significant disagreement and present key facts that can support an evidence-based discussion. The information presented aims to help stakeholders to better understand other positions and support decision-makers to find appropriate solutions for their specific context.

How we did it.

Discussions about the future of transport and its energy and climate implications often happen in specialist "bubbles" that inhibit cross-cutting debate. To break down these barriers, this report is based on a wide-ranging consultation with a cross section of experts. The experts have different interests, including those specialising in overall transport systems and those focussing on social and economic issues, as well as technology and fuel experts, energy economists, and energy and climate modellers and planners. They have also provided different regional perspectives (→ *see Box 1*). We have carefully considered all the views we have heard and taken into account other published views and opinions.

The report is organised as follows:

CHAPTER 1:

The need for transport decarbonisation outlines the links between transport and global emissions, energy use in transport and the development of renewables in the sector.

CHAPTER 2:

Options for reducing transport emissions: The role of renewables looks at approaches to reducing emissions, related to renewables as well as others, and at various scenarios for a possible future of transport compatible with 1.5 degrees Celsius (°C).

CHAPTER 3:

Tension points: Where experts disagree explains how we arrived at the key questions of divergence that are discussed in chapters 4 and 5.

CHAPTER 4:

Why fuel choice matters discusses different views on whether and how decisions on fuel choice need to be taken today and outlines different views on who drives the transformation and who should pay for it.

CHAPTER 5:

Different visions: The fuel of the future provides contrasting expert views on key questions related to the use of each of the renewable fuels available for transport and aims to provide key facts related to the arguments used most commonly as a basis for further debate and discussion.

CHAPTER 6:

Developing your local vision does not provide any conclusions or assessment, but is rather a set of guiding questions that can be used to stimulate discussion and debate and enable development of better communication between communities involved at a national and regional level. After all, decisions will need to be made locally based on specific local circumstances, not at a global level.

i Previous versions can be found on https://www.ren21.net/reports/global-futures-report/.

BOX 1 CONSULTATION WITH THE EXPERTS

In total, 134 experts were consulted on their views on the topic of transport decarbonisation. A wide-ranging group of 76 experts were asked to complete a written survey designed to collect opinions on the future of transport, its links to energy and climate change, and the role of renewable energy options in a sustainable transport energy future. An additional group of 57 experts provided their opinions via a series of structured interviews which allowed more detailed discussions.

Of all the consultees, 36% described themselves as energy specialists, 29% as transport specialists and 26% as specialists in both domains. A total of 8% had other areas of expertise. Of the 82% of consultees who provided their gender, 73% were male and 26% were female. The research and academic community made up 35% of consultees, nongovernmental organisations (NGOs) comprised 23%, 22% were from intergovernmental and international organisations, and 17% were from private industry (→ *see Figure 1*).

The surveys and discussions have provided insights into experts' current thinking on the main issues affecting the future of transport and its implications for energy and the climate, and on the prospects for rapidly increasing the renewable energy share within the transport sector.

Figure 1: Affiliation of survey respondents (number of participants)

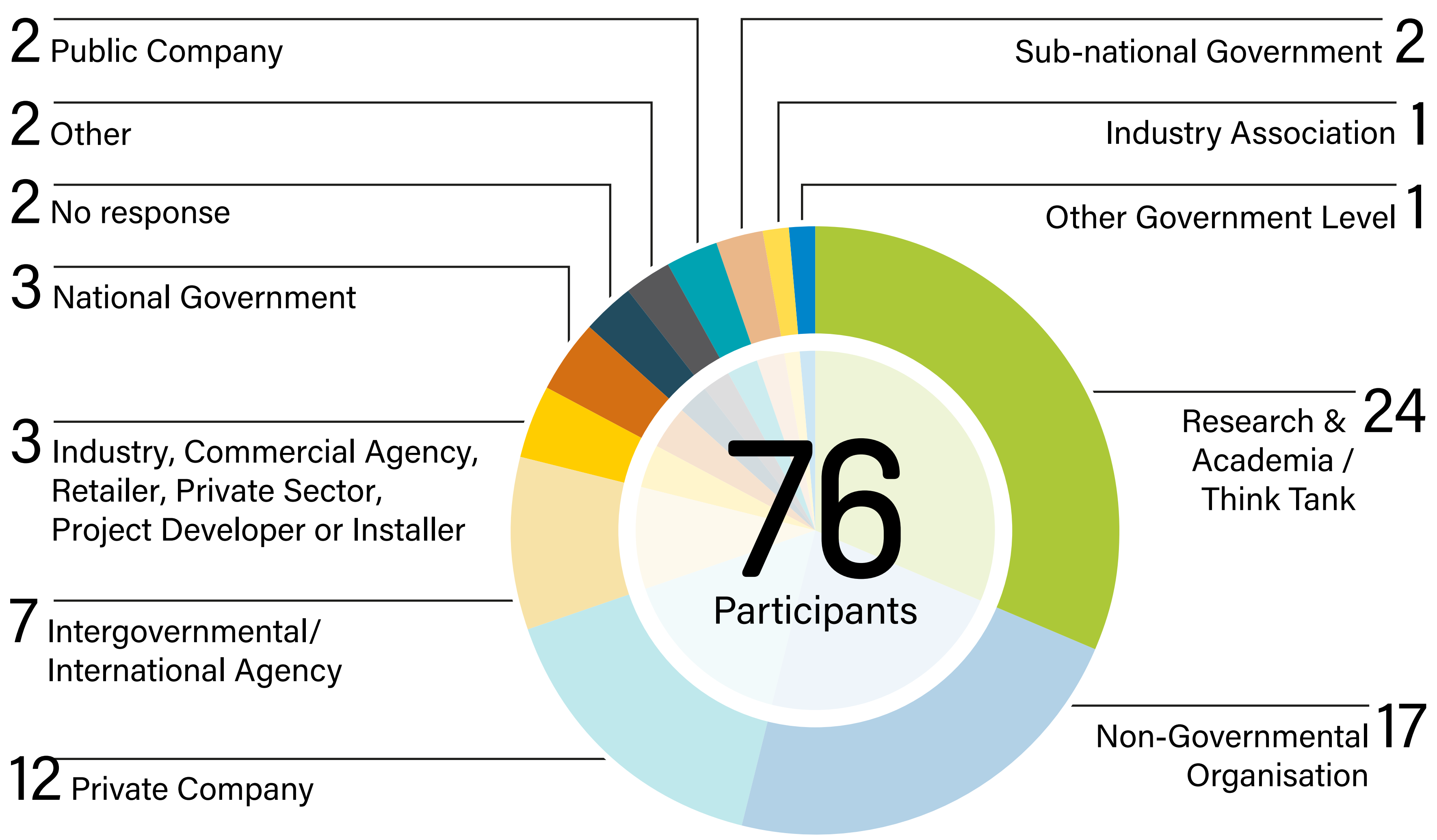
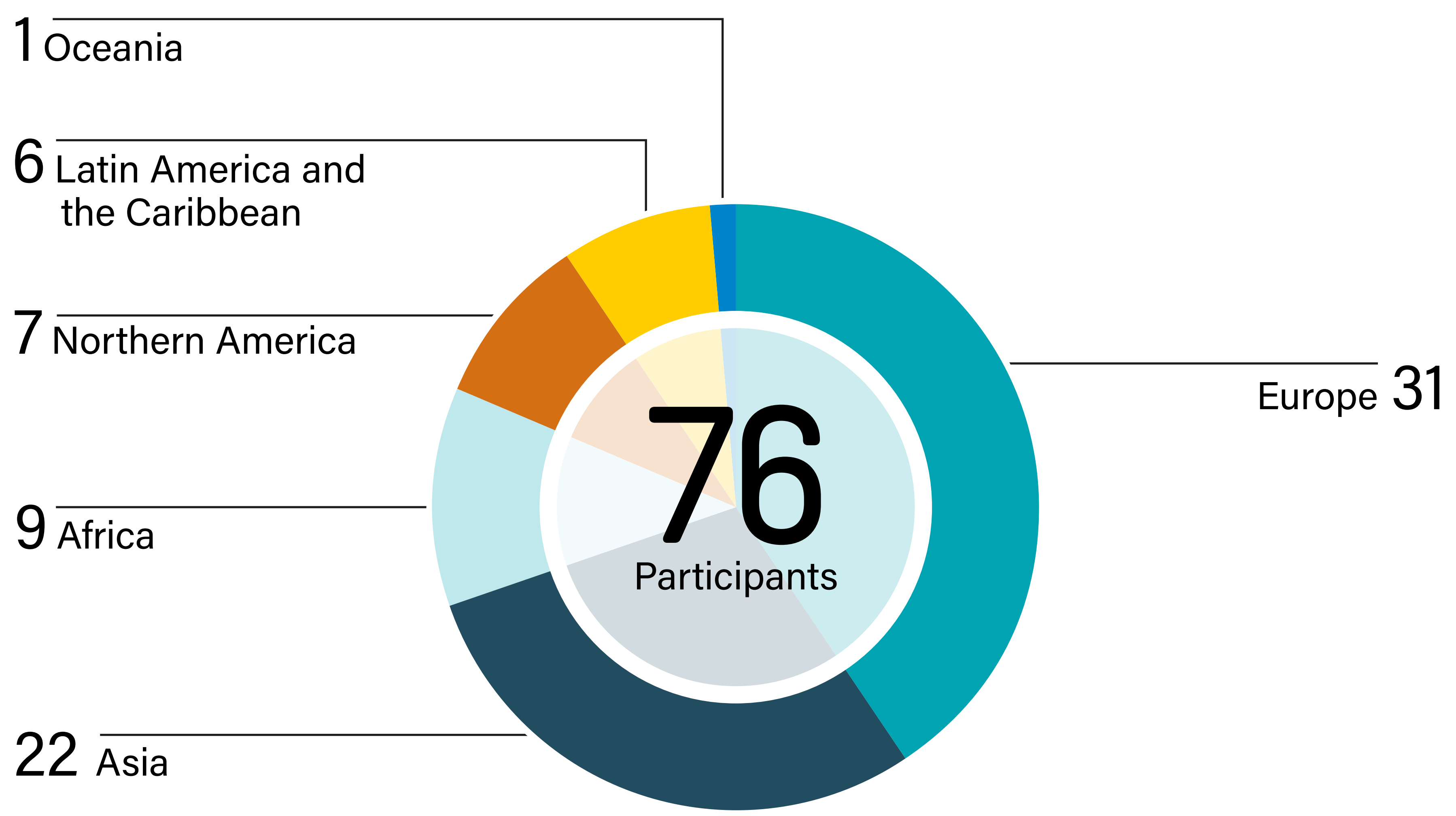


Figure 2: Participants by region (%)



1. THE NEED FOR TRANSPORT DECARBONISATION

The world is already experiencing the **devastating effects of climate change on human societies and economies**. A rapid and fundamental shift is required to move away from fossil fuels to meet the goals of the Paris Climate Agreement.[3] Unless deep reductions in greenhouse gas (GHG) emissions occur immediately, global warming will exceed tolerable limits during the 21st century.[4] The Global Stocktake conducted in 2023 under the United Nations Framework Convention on Climate Change (UNFCCC) also calls on countries to contribute to the global effort and specifically asks for accelerated action to reduce emissions from road transport.[5]

Transport is a **key energy demand sector**, accounting for 26% of total final energy consumption in 2022 and for 24% of total energy related GHG emissions.[6] Transport energy demand rose from 102 exajoules (EJ) in 2010 to 122 EJ in 2019 before falling to 105 EJ (due to the Covid-19 crisis) in 2020. Demand picked up again in 2021 and bounced back to almost 2017 levels in 2022 at 118 EJ as travel and trade picked up again after restrictions were removed.

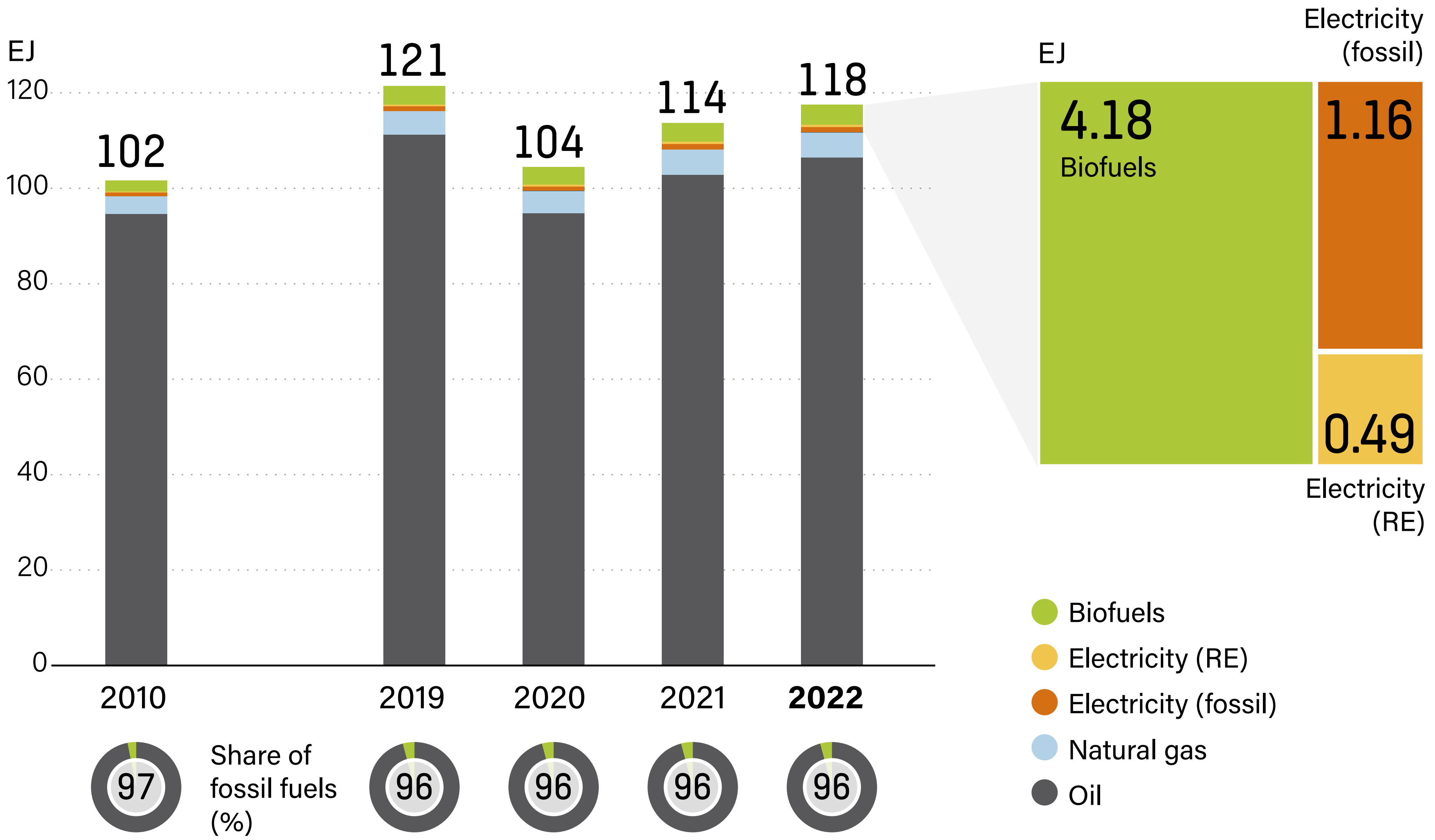
GHG emissions from transport grew at an annual average rate of nearly 1.8% from 2010 to 2019 (continuing a longer-term trend), faster than any other end-use sector, before being slowed by the Covid-19-related reduction in transport demand (→ *see Figure 4*).[7] However, after the severe drop in GHG emissions from transport during the pandemic in 2020, the sector's emissions rebounded in 2021 and 2022.[8] Emission from transport is expected to continue to rise in future years as demand for transport grows. Rapid reductions in transport emissions are therefore an essential part of the transition to a sustainable energy system.

Transport energy demand is predominantly provided by oil-based fuels (90.5%) and natural gas (5.5%). The remainder is from biofuels (3.6%) and electricity (1.4%), of which an increasing share, 29.6% in 2022, comes from renewable sources (→ *see Figure 3*).[9] In terms of regional demand, Asia was the largest transport fuel user in 2021 (34% of total consumption), followed by North America (27%) and Europe (16%).[10]

Currently transport has the lowest share of renewables among the four demand sectors,[i] despite renewables' benefits such as enhanced energy security, opportunities for the creation of local supply chains and reduced pollution. In 2022, renewables accounted for only 4% of the sector's total energy consumption, made up of 3.6% biofuels and 0.4% renewable electricity.[11]

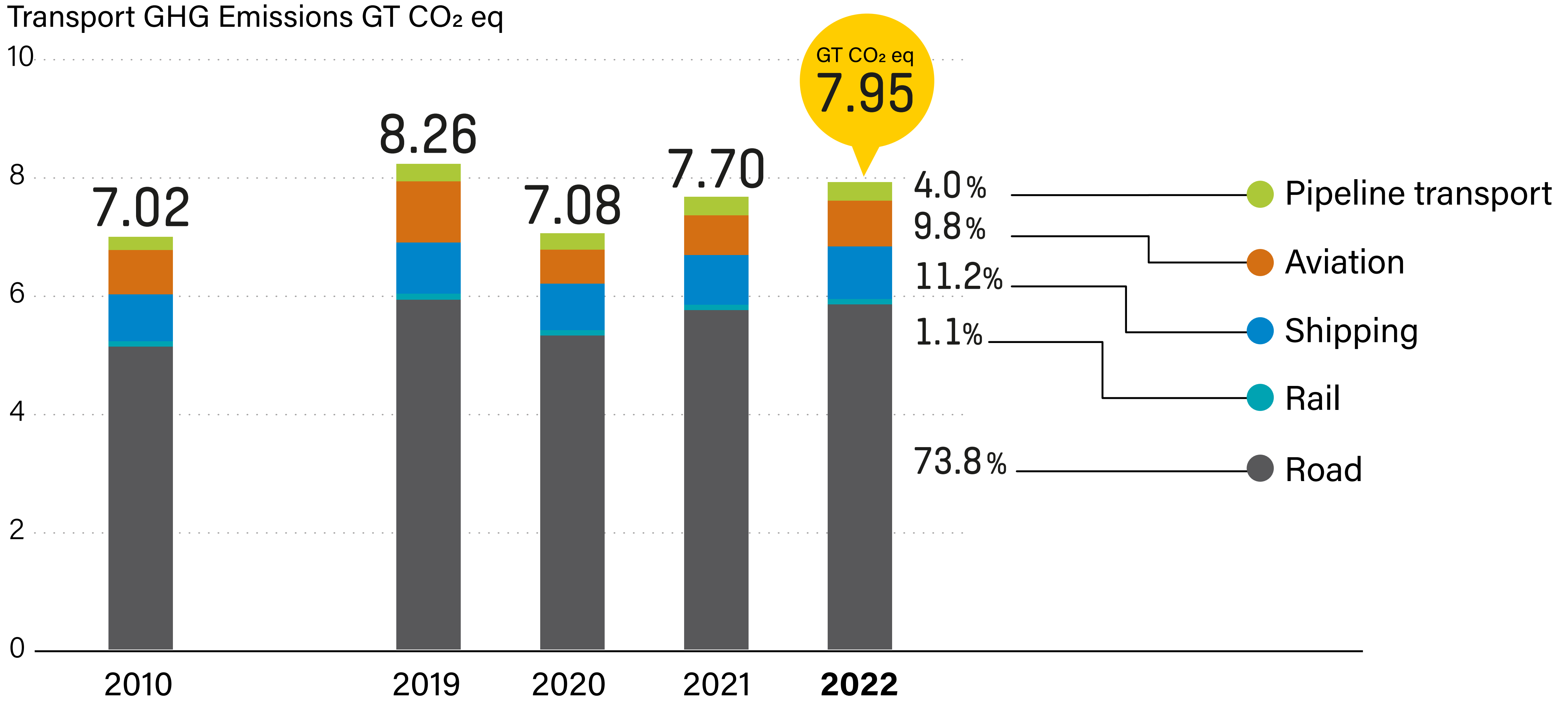
i Transport, industry, buildings and agriculture.

Figure 3: Global transport energy demand by fuel type, 2010-2022



Source: IEA. See endnote 9

Figure 4: GHG emissions from transport, 2010-2022



Source: IEA. See endnote 7

Biofuels are used as a substitute for gasoline and diesel fuels, principally in road transport. Currently biofuels use in other sectors is very small, although their potential in the aviation and marine sectors is considered to be significant. Biofuel use is largely driven by policy, particularly blending mandates, because in most countries it is not cost competitive compared to its fossil fuel counterparts (→ *see Box 3: The role of fossil fuel subsidies*). In addition, most conventionally produced biofuels cannot be used alone in existing motors without adjustments, although 100% biofuel vehicles exist, often as flexible-fuel vehicles that can run on pure biofuel as well as blends.

Electricity is primarily used in the light vehicle and rail sectors. While rail transport is largely electrified, the use of electricity in road transport is still small. Despite the exponential growth over the past years, overall electric vehicle (EV) stock is still small across all vehicle categories. The share of renewables in electricity is driven by steadily increasing renewable electricity generation.

Hydrogen is not widely used in transport owing to technical challenges and high costs (see Chapter 4.1 and Chapter 5.2 for detailed discussions).

2. OPTIONS FOR REDUCING TRANSPORT EMISSIONS: THE ROLE OF RENEWABLES

2.1 TRANSPORT DECARBONISATION OPTIONS

Many options are available for reducing emissions associated with the transport sector. These are often summarised in terms of the Avoid-Shift-Improve (ASI) model (→ *see Figure 5*).[12] This approach aims to provide a framework to transition to a sustainable transport system. Applying this approach can reduce the climate impact of transport and contribute to improved access to mobility, reduced congestion and air pollution, and the provision of safe transport.

A key aspect of this framework is that it focuses on the mobility needs of people and goods as well as on the actual vehicles and infrastructure.[13]

The ASI system represents a complex matrix of complementary approaches across the different transport subsectors and considers the structure of local transport systems. Reducing energy demand as much as possible through avoid and shift measures as well as vehicle efficiency improvements will make it easier to replace significant shares of energy used with renewable alternatives. This is an important element of the Improve track, which seeks to replace GHG-intensive fuel systems with those that have lower GHG impacts.

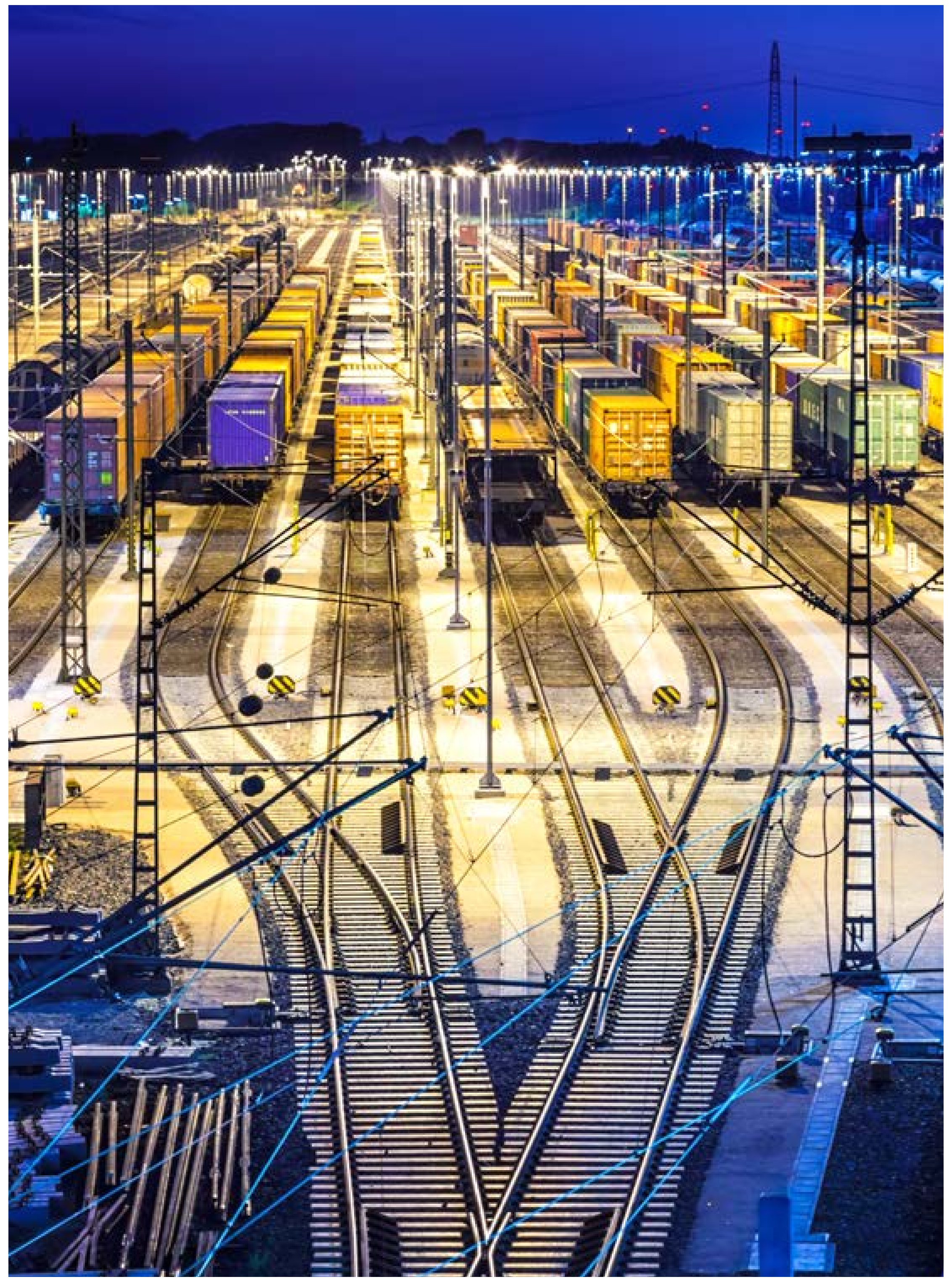
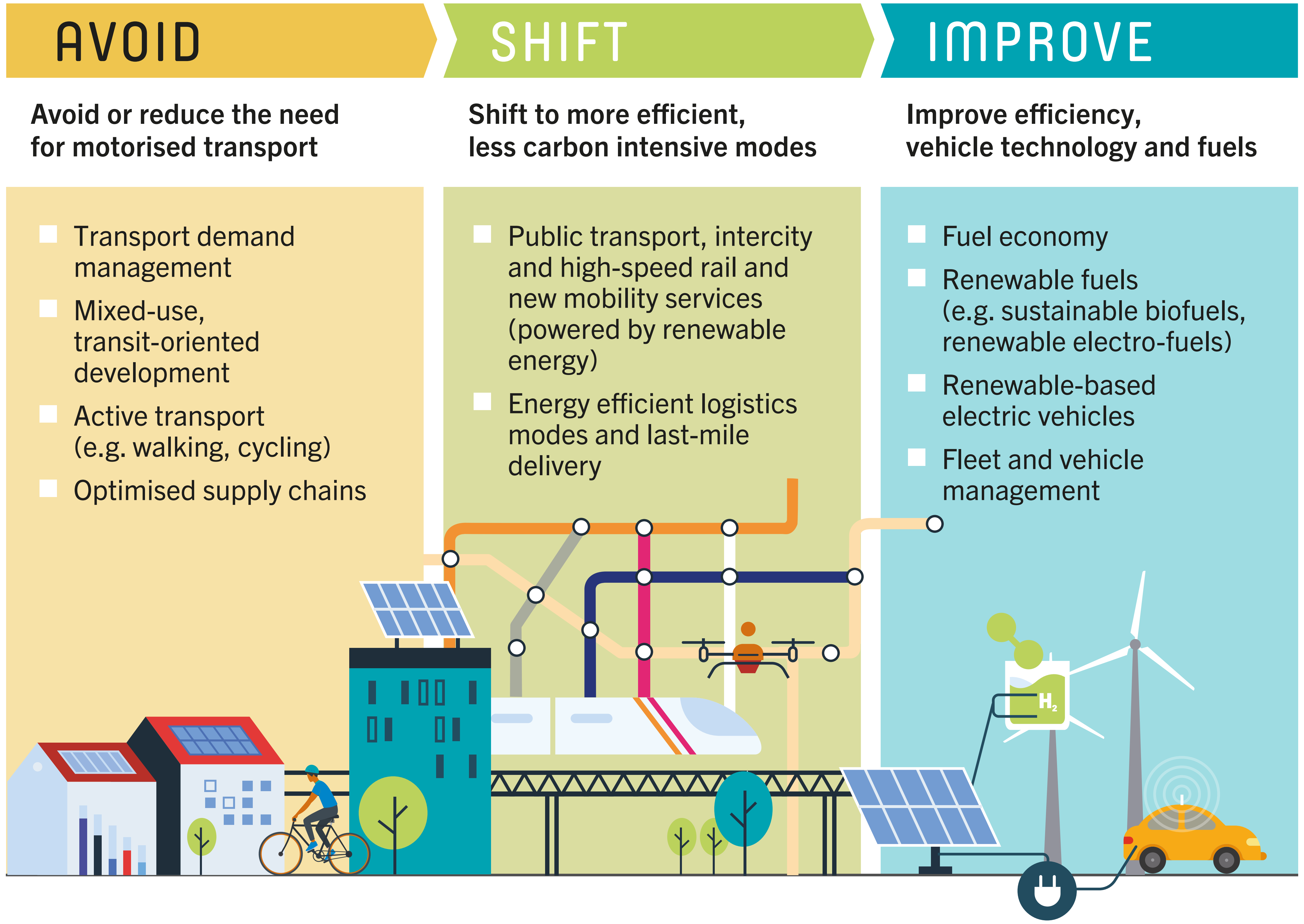


Figure 5: Avoid-Shift-Improve framework in the transport sector



Source: REN21. See Endnote 11

While policies and targets often focus on Improve measures, some estimates have shown that Avoid and Shift components could contribute to 40% to 60% of decarbonisation targets. Implementing these measures, along with improved energy efficiency for vehicles, is essential to be able to achieve deep decarbonisation of the sector, as they help reduce overall energy demand. Avoid and Shift measures can also have additional benefits for sustainable development, such as reducing congestion, increasing safety and providing more equitable access to mobility, which Improve measures usually do not address.[14]

> *“Let’s not forget that it is not just about electrification, it is also about having less congestion, less pollution, having inclusive transport, having safe transport.”*
>
> **Oliver Lah**, Wuppertal Institute

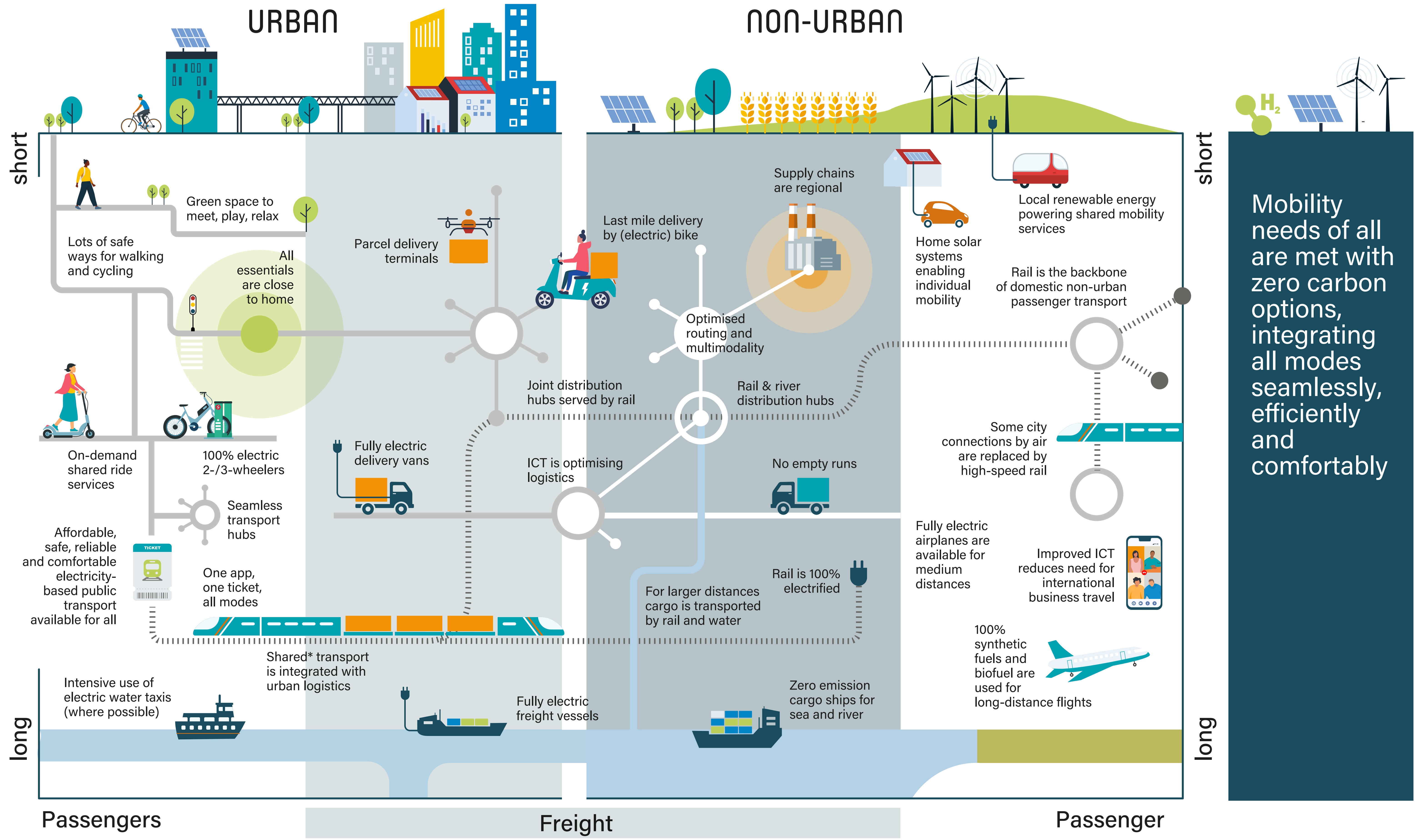
BOX 2 THE TRANSPORT VS. THE ENERGY VIEW ON TRANSPORT SECTOR DECARBONISATION

While the ASI approach outlined above addresses all elements required for decarbonisation, we find that transport experts and energy actors have a different focus in discussions. The two examples below illustrate the difference in perspective from the transport and the energy sector.

The Council for Decarbonising Transport in Asia envisions a future zero-carbon transport system (→ *see Figure 6*)[15]. The focus is on the modes used and their connections, ensuring seamless and efficient mobility for all needs. Another focus is on the vehicles used. Fuels play only a minor role and are assumed to be fully renewable, in many cases without specifying the type of fuel.

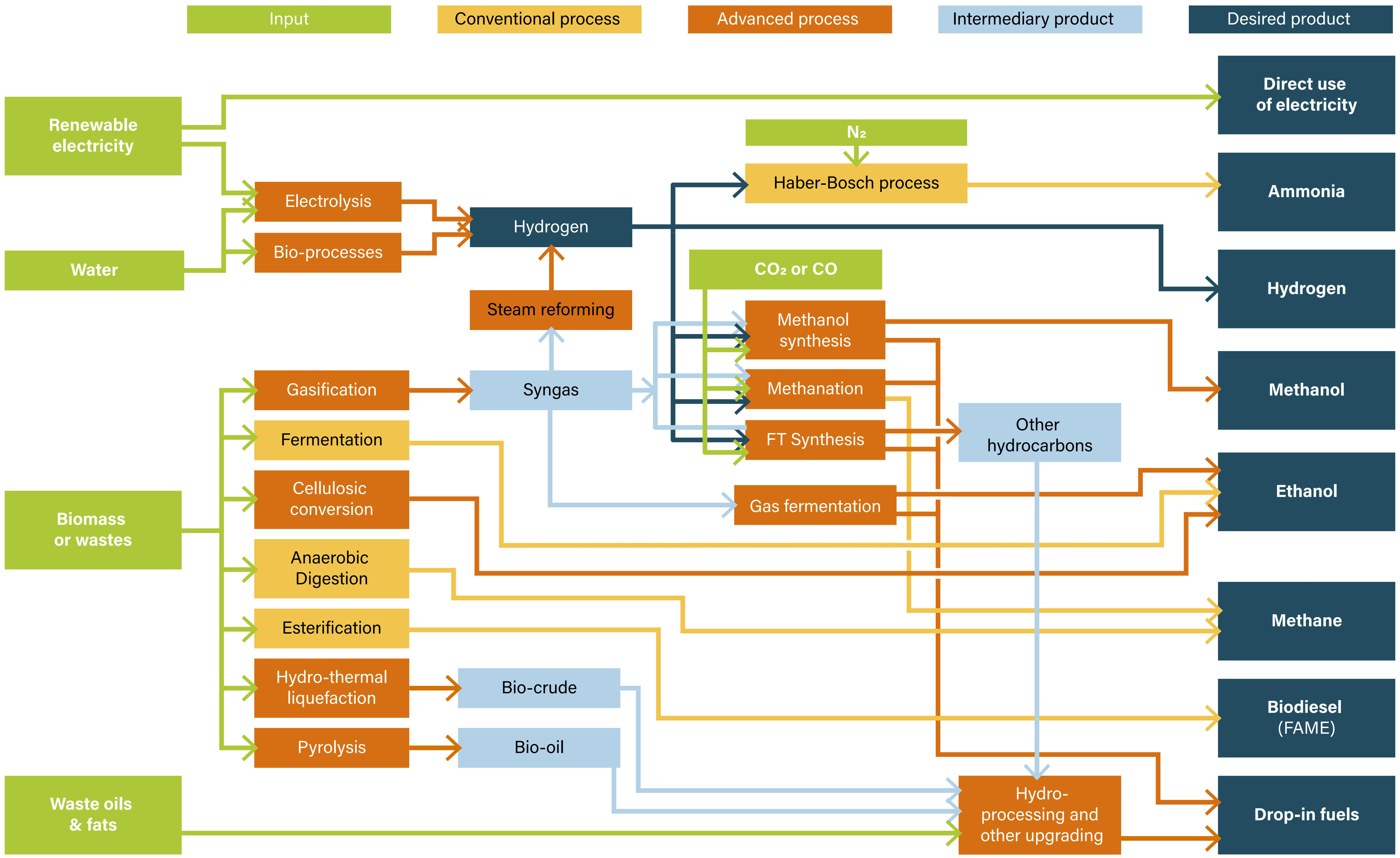
From the energy perspective, transport modes are largely irrelevant and even vehicles are only of moderate interest. The focus is on feedstocks used and technologies for transforming feedstocks into usable fuels (→ *see Figure 7*)[16].

Figure 6: Vision for a decarbonised transport sector



Source: Council for Decarbonising Transport in Asia. See endnote 15.

Figure 7: Renewable energy pathways for transport

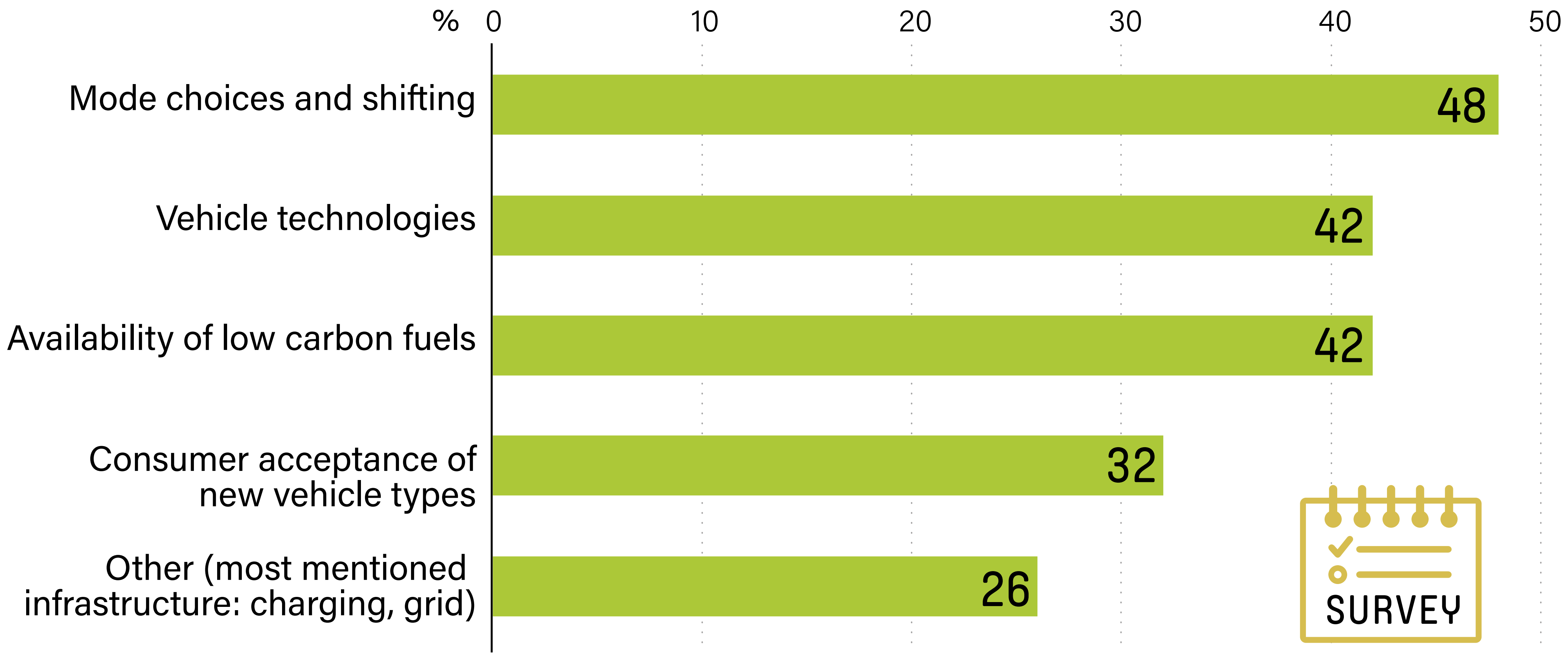


Notes: Processes specified as “conventional” are already fully commercially operational, while those specified as “advanced” are at various stages of development; carbon dioxide (CO_2) or carbon monoxide (CO) for further processing of hydrogen to different e-fuels can be from direct air capture (DAC), from industrial or power sector sources based on chemical processes (e.g. cement, steel) or fossil fuel burning, or from point sources in combination with burning of biomass (so-called biogenic CO_2). Other processes exist that convert biomass to hydrogen which we have not included in the graph for simplification as none of these are being discussed at large scale and all are in early development stages. N_2 = nitrogen.

Source: Adapted from REN21. See endnote 16.

> *“The key difference is that in Asia, urban density is relatively higher than many other regions. At the same time, things are moving very quickly. Urbanisation is complemented by motorisation and rapid population growth and economic development, making transport planning a bigger challenge. Thus, we need different measures and tailored pathways, taking into consideration the availability of informal transport, for example, which will influence mode shift and travel behaviour.”*
>
> **Wei-Shiuen Ng**, former ITF

Figure 8: Survey – What do you think is the biggest challenge for decarbonising the transport sector in the country for which you are providing information?



> *Every single policy that we come up with, the shifts we try to make, is a losing proposition for someone, and almost always someone powerful, like the fossil fuel industry. Humans are not very good at accepting that. If we fail, it will be because we haven't managed those winners-losers trade-offs.*
>
> **Lewis Fulton**, UC Davis

Almost half of the experts that participated in the survey see the largest challenge in shifting to more efficient modes, emphasising that renewables are only one part of the puzzle. A large number agree that vehicle technologies and the availability of fuels are big challenges. Others see infrastructure – especially for charging and to stabilise power grids – cost and renewable electricity supply as the biggest challenges in their respective context.

2.2 SCENARIOS FOR A LOW-CARBON TRANSPORT SYSTEM: DIFFERENT PERSPECTIVES ON FUTURE MOBILITY

Routes toward a low GHG future have been modelled in many energy and emission scenarios that include detailed projections for the transport sector. We are comparing the results of these modelling exercises to provide context and to help identify differences of views on how a future transport system could look in addition to the views expressed by the experts interviewed.

The analysis below focuses on reviewed scenarios that look at how a Net Zero Emission (NZE) or equivalent 1.5 degrees Celsius (°C) scenario might be delivered by 2050. The main scenarios considered provide consistent detail on several criteria, which allows the scenario results to be compared. Only one scenario is a transport-only scenario. All others look at economy-wide emissions, and the role of transport decarbonisation in those scenarios depends on assumptions for other sectors, especially regarding carbon removals. The scenarios are briefly described in Annex 1.

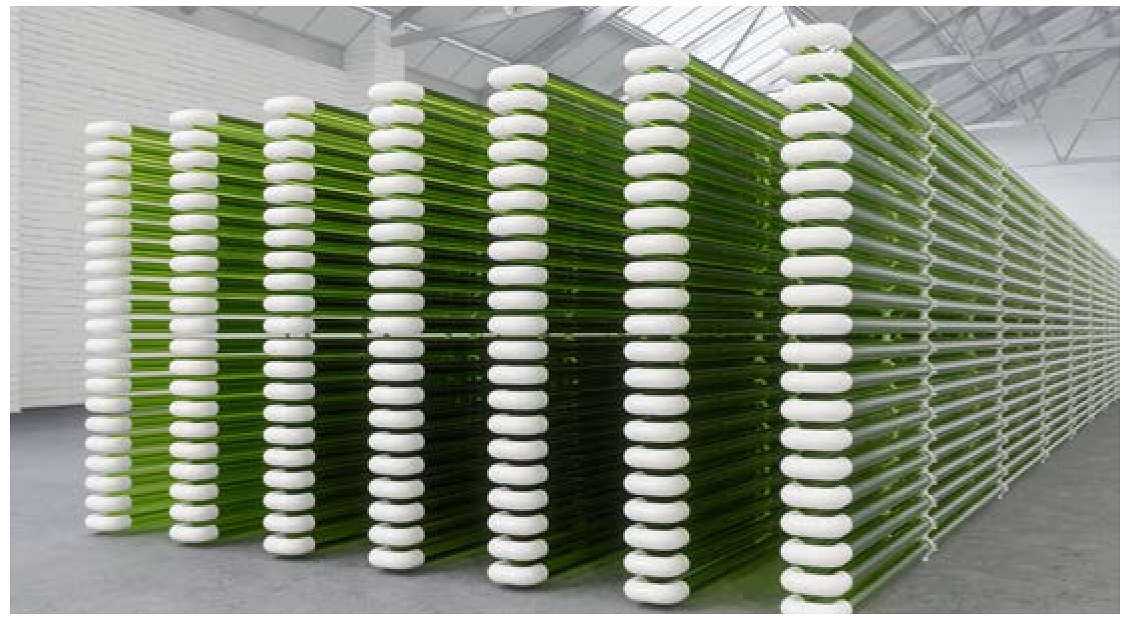
The three scenarios of the Intergovernmental Panel on Climate Change (IPCC) illustrate mitigation pathways (IMPs): IPCC IMP-LD, IMP SP and IMP-REN. One focuses on lowering demand (IMP-LD), one on high renewables penetration (IMP-REN) and one on achieving both Sustainable Development Goals and climate policies (IMP-SP).[17] In addition, it includes three energy scenario exercises (the International Energy Agency [IEA] NZE Scenario, the International Renewable Energy Agency [IRENA] 1.5°C[i] and Bloomberg's Net Zero Scenario) and three transport scenarios (the Transformative Urban Mobility Initiative [TUMI] Transport Outlook 1.5°, the ITF High Ambition scenario and the International Council on Clean Transportation [ICCT] Ambitious yet Feasible scenario) that are in line with the 1.5°C global warming limit (→ *see Figure 9*).[18] The IEA and IRENA updated their original scenarios in 2023. We include both the original and the updated scenarios in this analysis, as this also highlights the evolving thinking about how future transport systems will take shape.

While all scenarios show a clear reduction in GHG emissions, energy consumption and penetration of low-carbon fuels, the comparison shows:

- **GHG emissions:** The level of emissions from transport in 2050 varies considerably across different scenarios.
- **Energy consumption:** There is no agreement on the magnitude of future energy consumption in the transport sector.
- **Fuel mix:** There is no agreement on the fuel mix of the future.

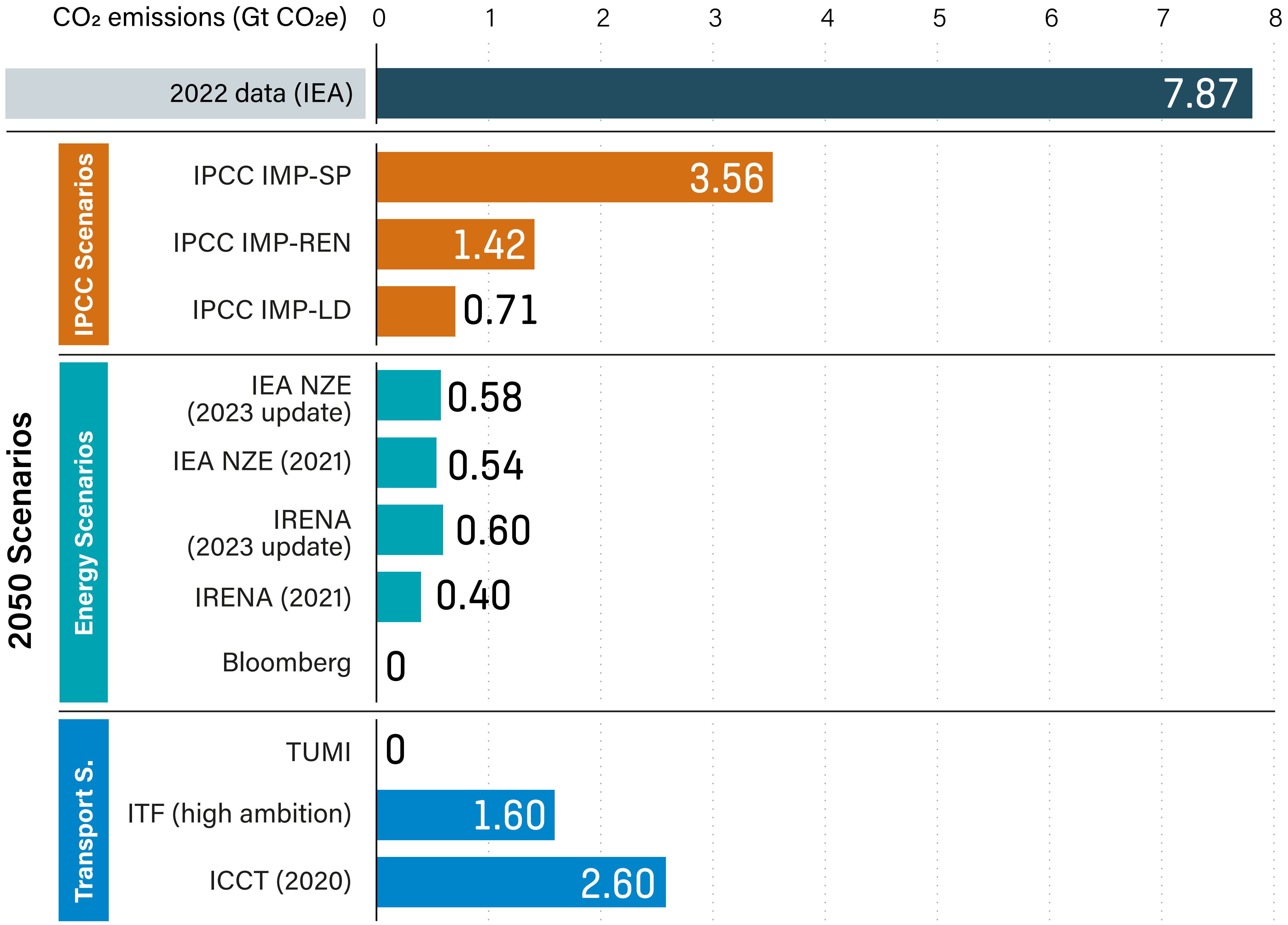
In the analysis of the different scenarios, we again find the different focus described in **Box 2** above: mode vs. fuels. While all scenarios show GHG emission projections, the detail provided on underlying assumptions is very different.

Scenarios developed in the transport community often do not provide details on energy-related aspects of the modelling. ITF, for example, focuses on transport demand projections and mode choice in different transport segments. The transition to cleaner fuels is often summarised using the term "zero emission vehicles" (ZEVs) without specifying individual fuel types. This limits the opportunity to directly compare scenarios. Energy modelling exercises, such as those conducted by the IEA or IRENA, provide detailed information on energy consumption and fuel types.



i Both the IEA and IRENA updated their scenarios in 2023, and we show values from the old and new scenarios to illustrate their changing outlook.

Figure 9: Comparison of key results across selected 1.5°C compatible scenarios: Remaining GHG emissions in 2050



Source: Based on REN21 analysis of data in studied scenarios, see endnotes 17 and 18.

GHG emissions: The level of emissions in the transport sector compatible with NZE/1.5°C depends on assumptions about the actions in other sectors and, to a large extent, on the ability to remove carbon from the atmosphere.[i] Cross-sectoral energy scenarios seem more optimistic about achieving low emissions in the transport sector than sector-specific scenarios. The exception is the TUMI scenarios, which achieve zero emissions in the sector.

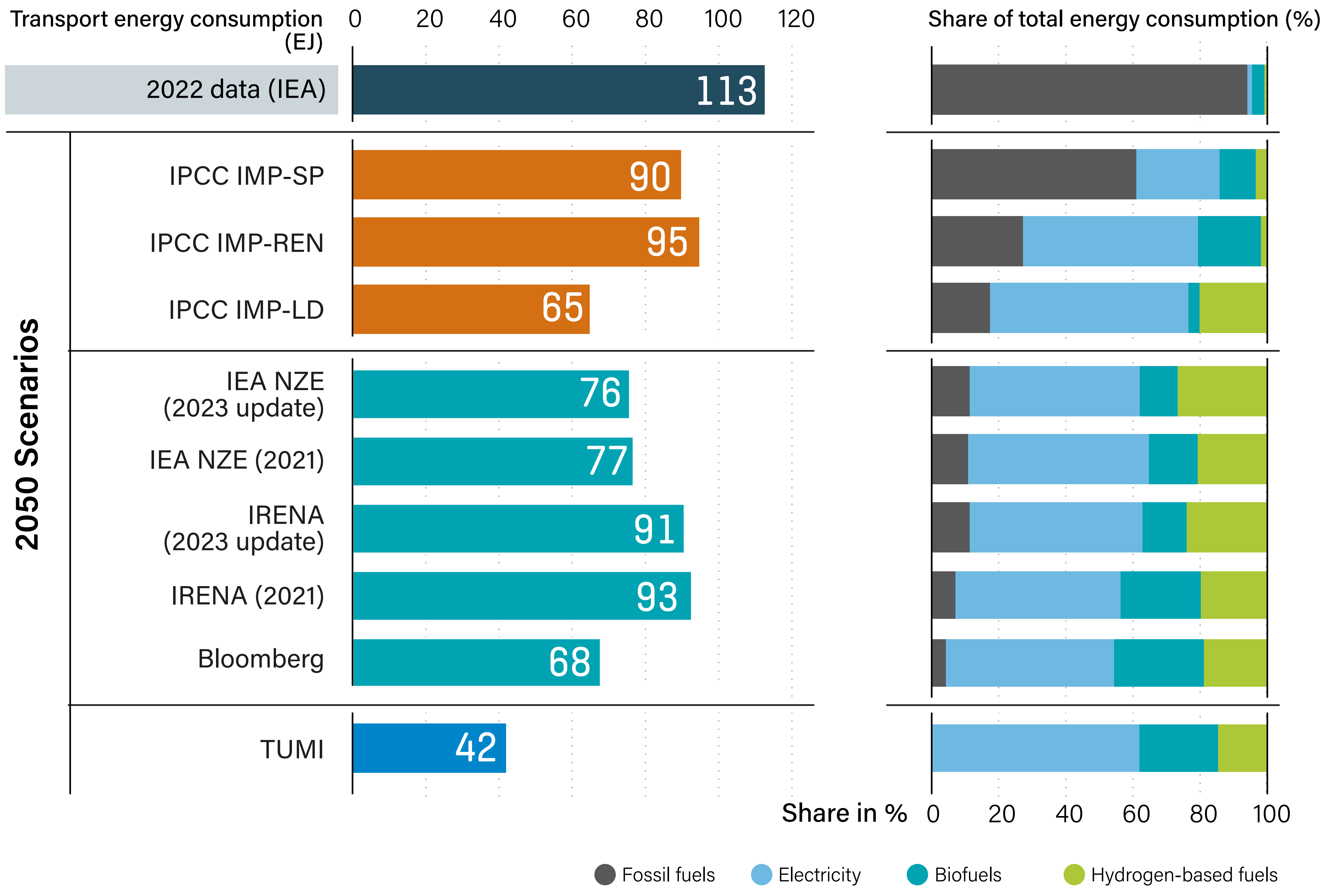
Energy consumption: The differences in energy consumption across scenarios are the result of different assumptions about the implementation of ASI vehicle efficiency measures. The more efficient the transport system and its vehicles, the less energy will be required. If we assume the same amount of renewable transport energy can be realistically produced at a given time, lower total energy demand will increase the share. However, these activities are not the focus of this analysis.

Fuel mix: The scenario comparison shows some clear differences in the importance of different types of fuel, depending on the assumptions made (→ *see Figure 10*). The IPCC illustrative pathways in particular show that similar climate results can be achieved with very different fuel mixes. The other scenarios seem to agree that large parts of transport need to be electrified by 2050, with shares between 50% and 62%, but vary most in the reliance on biofuels (between 15% and 27%) and hydrogen-based fuels (15% to 21%).

So, the key question for renewable energy is: what is the right mix of fuels? To answer this, several further questions arise that are implicitly or explicitly included in the scenario assumptions. We will discuss these in Chapter 5.

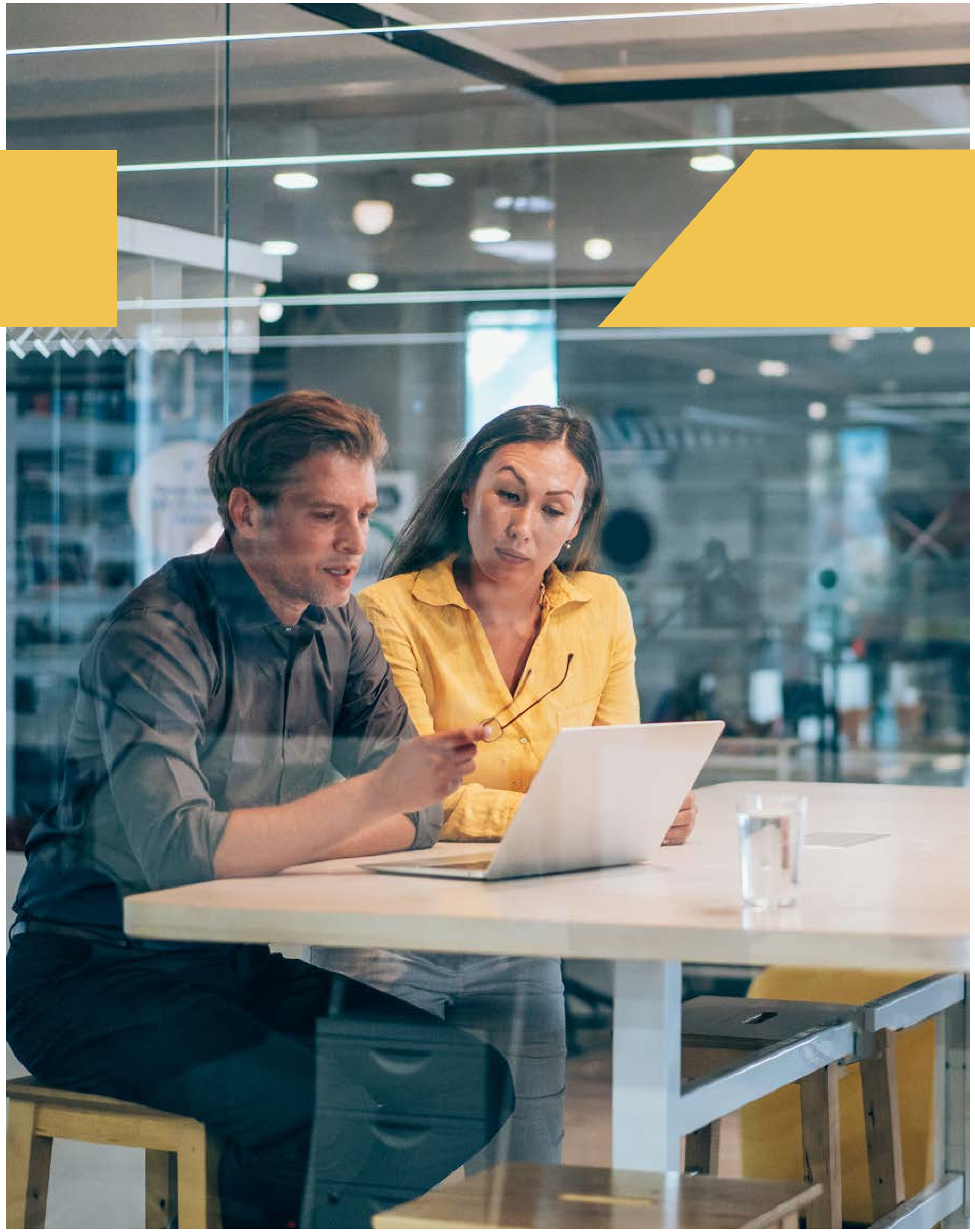
i Carbon dioxide removal (CDR) refers to a cluster of technologies, practices and approaches that remove and sequester carbon dioxide from the atmosphere and durably store the carbon in geological, terrestrial or ocean reservoirs, or in products. The feasibility of such removals is subject to intense debate, which is outside the scope of this report.

Figure 10: Comparison of key results across selected 1.5°C compatible scenarios: Energy use in 2050



Note: Hydrogen-based fuels include the direct use of hydrogen as well as all gaseous and liquid fuels produced from hydrogen, such as methane, ammonia and synthetic fuels.

Sources: Based on REN21 analysis of data in studied scenarios, see endnote 18



3. TENSION POINTS: WHERE EXPERTS DISAGREE

Based on the survey responses and the expert interviews, we realised that there is no converging vision of how renewable energy will play out in the transport sector over the next decades. We therefore decided to support the ongoing discussions by highlighting the areas of divergence – tension points – and provide an overview of the arguments used to support those different opinions.

This is not to say that there is no agreement at all, but for the purpose of advancing the discussion, this report focuses on the questions about which there seems to be the most tension and the different visions for how the future will and should unfold.

Expert input as well as the analysis of low-carbon pathways (→ *see Chapter 2, Section 2*) indicated that the largest disagreements are around what the "right" fuel mix will be for the future low-carbon transport system, but there were also some disagreements on cross-cutting elements. We have broken these down into key questions that summarise where opinions vary and gathered arguments frequently made on both sides of the spectrum. We also provide our assessment of how large the disagreement is within the expert community.

Additionally, we provide some key facts, figures and analysis relevant to the arguments put forward. They do not represent expert opinion but will help guide an evidence-based discussion around the key areas where there are significantly differing views.

Figure 11: Overview of tension points

SECTION 4

Why fuel choice matters

- Can we avoid stranded assets in renewable fuel infrastructure?
- Who drives the transition?
- Who funds the transition?

SECTION 5

Different visions: the fuel of the future

ELECTRICITY	vs HYDROGEN	vs BIOFUELS
Is the electricity “green” enough?	Is road transport the best application for hydrogen use?	Do biofuels lead to real GHG savings?
Will sufficient and sustainable battery and motor materials be available?	Is large-scale trade and transport of hydrogen practicable?	Are large-scale biofuel production and use sustainable?
Can and should heavy-duty trucks be electrified?	Are hydrogen and ammonia safe?	Is sufficient sustainable biomass available without impacting on food supply and security?

However, the pros and cons for supporting different fuels are based on differences in underlying assumptions and views on how systems and technology will develop. **Figure 11** provides an overview of the questions that shape views and preferences for one fuel type vs. another. In addition, there are different views on several cross-cutting topics.

WHAT WE DO:

- The following chapters will provide an **overview of the different arguments** for each of those questions, as well as feedback and opinions from our respondents and other experts.
- This report aims to **stimulate discussion**, which in most cases will need to be held at the national or even local level. The arguments can help ensure that all important aspects are taken into consideration in decisionmaking. The guiding questions in Chapter 6 aim to support this.
- The **analysis and facts** related to key arguments, including historic developments and possible future scenarios, aim to provide a solid information basis that can support local discussion.

WHAT WE DON’T DO:

- We **do not provide our take on what the right answer is** to each of the identified questions, based on the expert inputs. Unlike other Global Futures Reports, we do not focus on identifying converging views, but instead focus on where there is the most need for additional debate.
- We **do not provide recommendations** about what the right policies are going forward.

4. WHY FUEL CHOICE MATTERS

We have shown that views vary on the relative importance of the different renewable fuels available for transport decarbonisation. But why is that important? Is a decision required, or is it something that will crystallise with time and market forces? Here, experts express views at both ends of the scale.

The transition to a sustainable global transport system based on renewable fuels will have a significant impact on energy infrastructure at different levels of the supply chain, depending on the type of fuel used.[i] **Figure 12** illustrates the infrastructure and vehicle requirements for the different fuels across the supply chain.

In the transport sector, experts often focus on vehicles and the associated charging and refuelling infrastructure. In the energy sector, discussion focuses mainly on generation and production capacity for renewable fuels and the availability of raw materials. Other elements of the supply chain, such as transport and storage of feedstocks, intermediates and fuels, expansion of existing infrastructure, new infrastructure and new technologies are less often part of the overall discussion (→ *Chapter 5.3*).

Experts agree that in principle, biofuels and drop-in fuels (based on biomass or hydrogen) do not require any changes to the existing infrastructure other than an increase in production capacity. This makes it easy for the transport sector, as investment needed for replacing existing infrastructure is minimal and no real change is required for distribution infrastructure, vehicle manufacturers or vehicle owners. Nevertheless, the investment required to provide the required amount biofuels is substantial, apart from other concerns related to biofuel production, which are discussed in Chapter 5.3.

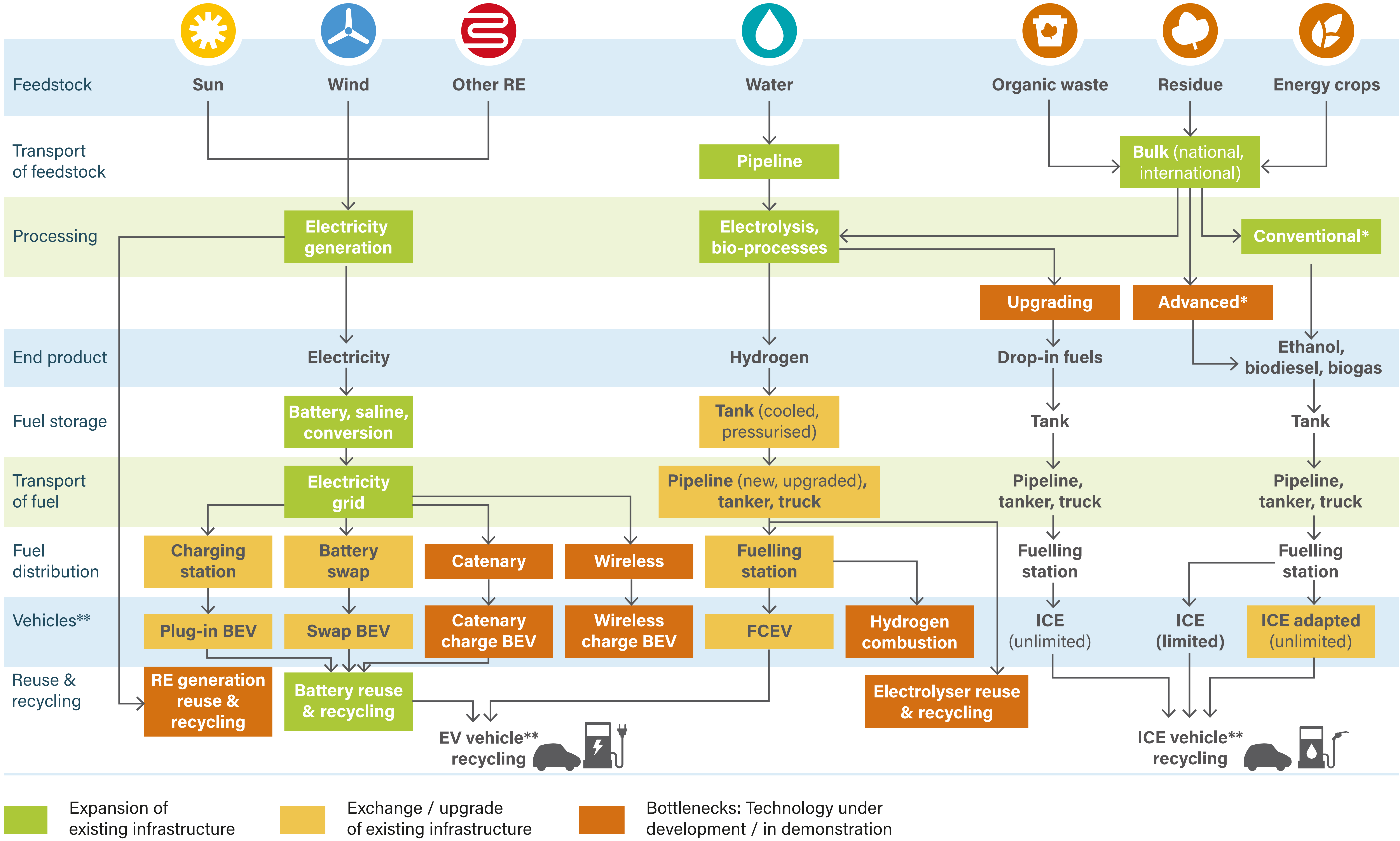
However, there is less agreement among experts on possible constraints on biofuel supply, as discussed further in Chapter 5. With potential limits to supply, some additional fuel may be needed to decarbonise the sector. This will require significant additions and changes to infrastructure and vehicles, leading to a set of questions:

- Can we implement renewable fuels quickly enough and still avoid stranded assets for renewable fuel infrastructure?
- Who is responsible for steering and enabling the transition?
- Do we have the funds to set up parallel infrastructure for multiple fuels?

The following sections outline expert responses to these questions and why, in some views, the choice of fuel matters. However, not all experts have a clear view, and it is obvious that the situation is complex and will increase in complexity with new renewable fuels.

i It will also depend on the amount of energy needed, which will depend on efforts to reduce energy demand from the sector through avoid, shift and vehicle efficiency measures, which are not the focus of this report and therefore are not discussed in detail here.

Figure 12: Fuel supply chain and infrastructure requirements



* → *See Figure 7* on the distinction between advanced and conventional processes

** "Vehicles" in this graph refers to all types of vehicles, incl. planes, ships, cars, trucks, etc.

Notes: RE = renewable energy; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle; ICE = internal combustion engine; catenary = overhead electricity lines for charging during driving. RE generation reuse & recycling refers to the reuse and recycling of old wind turbine elements, photovoltaic (PV) panels and any other equipment used in RE generation.

Source: REN21.

4.1 CAN WE AVOID STRANDED ASSETS IN RENEWABLE FUEL INFRASTRUCTURE?

RENEWABLE FUEL PRODUCTION CAPACITY

Experts agree that a key element in the assessment of risk for stranded production capacity is whether the product has sufficient demand to make it financially viable even if the transport sector develops in a different way than expected today. Demand from other sectors is also a critical question to consider because high demand can lead to competition for certain fuels across sectors, making them more or less attractive for transport in the long term.

There is broad agreement that production capacity for all types of renewable fuels needs to be expanded rapidly to achieve the required GHG emission reductions from the sector. Experts also agree that the speed needed to get there is unprecedented. In the past, the rollout of new energy sources to current scale took more than 30 years,[19] while we only have around 25 years to achieve carbon neutrality in line with the Paris Agreement. The IEA estimates that currently announced projects for hydrogen electrolysers and liquid biofuel production are not sufficient to meet the demand in its Net Zero Scenario, and very few of these have yet reached a final investment decision.[20]

Investment decisions[i] for production installations depend on the specific local combination of demand for the end product, the availability of energy sources and feedstocks, distribution options and available technologies, and their resulting economic viability.[21] These factors can also be influenced by policy frameworks that can help or hinder the achievement of economic viability (→ *see also Box 4*). The situation varies strongly between the different fuel options available for transport and across countries. Especially where renewable energy production is not currently financially viable, many experts are of the view that governments need to set framework conditions that ensure overall profitability, often including incentive schemes or tax breaks that impact countries' budgets.

In some cases, this will require financial incentives or direct investment by governments. **With limited public budgets, the question is where these funds are best spent in the long term and if uncertainty about future fuel preferences can lead to stranded assets in the future.**

WILL ALL RE PRODUCTION CAPACITY BE ECONOMICALLY VIABLE?

Medium agreement PRO

PRO

Non-transport sectors will generate sufficient demand for renewable fuels to make building new RE infrastructure viable.

CON

Some fuels will not be economically competitive even in the longrun, so building up infrastructure could result in stranded assets as markets go for other fuels.

> *Modernity is mastering complexity. While most decisionmakers are still looking for (simplistic) monolithic solutions, progress will come from our ability to engineer and operate sophisticated, complex solutions, suited to geographical contexts.*
>
> **Patrick Oliva**, Transport Expert

> *Investment decisions are long-lived and the risks of stranded assets high, so fixed infrastructure should be assessed with a long-term logic.*
>
> **IRENA**, *Geopolitics of the Energy Transformation*, 2022

i We are only looking at energy system-related elements here, although there are of course many more aspects influencing decisions, such as political stability, availability of skilled workers and geopolitical considerations.

BOX 3 THE ROLE OF FOSSIL FUEL SUBSIDIES

Competitiveness with fossil fuel alternatives is a key element determining the financial viability of renewable fuel production. Particularly where new production technologies need to be developed towards market readiness, governments often step in to support nascent industries. However, industries are expected to become competitive at some point, which largely depends on their price (assuming they offer the same functionality).

Subsidies provide a comparative advantage for fossil fuels in many countries. Governments provide support in various forms, from support for exploration to caps on end-user prices. The Global Subsidies Initiative estimates that public financial flows to fossil fuels in G20 countries reached USD 1.4 (United States dollars) trillion in 2022, which is twice the pre-Covid spending. While much of this was for consumer price support, around USD 440 billion was driving investment in new fossil fuel production.[22] The International Monetary Fund (IMF) estimates that total fossil fuel subsidies amounted to USD 7 trillion in 2022, equivalent to nearly 7.1% of global gross domestic product (GDP), with explicit subsidies increasing from USD 0.5 trillion in 2020 to USD 1.3 trillion in 2022.[23]

The comparative disadvantage this poses for renewable alternatives can be countered by also providing subsidies to renewable fuels or by removing existing fossil fuel subsidies to level the playing field.

Renewable electricity[i] generation is already cheaper than fossil fuels in many parts of the world (→ *Figure 27*),[24] and investments have outpaced fossil fuel generation capacity for the last decade (→ *Figure 18*). With increasing electricity demand and the need to increasingly replace fossil fuel-based infrastructure, investments in renewable electricity generation are largely financially viable and there is little danger of stranded assets. Adding transport demand can make renewable electricity production even more attractive, especially if electrification in transport is directly coupled with renewables. It can also make grid expansion into formerly unattractive areas, mini-grids and off-grid solutions more viable through increased demand. Limitations arise mainly from grid infrastructure and the need to balance variable renewables with demand.

Hydrogen is already used in many sectors, and demand in traditional uses in industry and refining has been growing at a slow pace.[25] However, with production currently almost fully based on fossil fuels,[26] the demand for hydrogen produced with renewable energy will increase steadily, as governments, companies and supply chains aim to decarbonise. Additional demand can be expected from new applications, including hydrogen-based direct reduction in steel production, industrial energy use, electricity storage and transport. However, owing to the properties of hydrogen, transport and storage are technically more challenging than the handling of fossil fuels today.[27] The viability of investments will therefore largely depend on the available distribution infrastructure and on cost developments of hydrogen compared to fossil fuel alternatives. At current hydrogen prices, a FCEV in the United States was found to have a total cost of ownership of up to 40% above a comparable EV, with the extra expense mostly driven by fuel cost.[28]

Drop-in fuels are very specifically tailored to the needs of vehicles and certain types of engines. While they can also be used in other applications – much as diesel is used for power generation in some regions today – the main use is likely to be in transport applications, especially those where alternatives such as direct use of electricity or hydrogen is not technically feasible. While this limits the demand to some extent, there remains a clear and growing demand from the transport sector. Competitiveness will depend on the availability of cheap feedstocks and technological developments.

Biofuels are already well established, at least for conventional production processes. Similar to drop-in fuels, demand is likely to be mostly from the transport sector and has been mostly driven by policies, such as blending mandates.[29] Sustainability concerns have driven the development of advanced production technologies based on organic residues and waste rather than dedicated crops. Demand for advanced biofuels will increase as overall biofuel demand increases and policy further regulates sustainability. Many advanced production processes, except fatty acid methyl ester (FAME) and hydrotreated vegetable oils (HVO)/hydroprocessed esters and fatty acids (HEFA) biodiesel, are still under development, although some are close to market readiness. Key risks relate to the continuous availability of high-quality feedstock and the development of technologies to full commercial scale.[30]

Overall, the risk of stranded assets in production capacity seems low to medium for all renewable fuels from an energy demand perspective. Risks remain related to feedstock availability and technology maturity for advanced biofuels and drop-in fuels. The viability of green hydrogen production will rely on the availability of wholesale distribution infrastructure, such as adapted pipelines and shipping capacity. This will highly depend on local circumstances, so siting is crucial for new investments. Demand for conventional biofuels could be limited by sustainability concerns and blending limits, while demand for advanced biofuels will be determined by policy and cost developments as technologies mature (→ *see Figure 13*).

i Note that renewable electricity generation is not completely GHG emissions free. Emissions occur in the manufacturing and construction of generation capacity. However, emissions savings during operation far outweigh these emissions, resulting in very low emission factors on a lifecycle basis.

Figure 13: Risk of stranded assets for new infrastructure investments

	FUEL PRODUCTION			FUEL DISTRIBUTION TO VEHICLES	
	Demand from other sectors	Risk	Challenges	Risk	Challenges
Electricity	●●●		Grid integration		Range Charging time
Renewable hydrogen (electrolysis) H_2	●●●		Cost Distribution infrastructure		Cost Safety
Drop-in fuels	●○○		Technology maturity Feedstock availability	Use of existing infrastructure	
Advanced biofuels	●●○		Technology maturity Feedstock availability	Use of existing infrastructure	
Conventional biofuels	●●○		Sustainability concerns Blending limits	Use of existing infrastructure	

Source: REN21.

DISTRIBUTION INFRASTRUCTURE

With growing sales of BEVs over the last years (→ *see Table 1*), the incentive for private sector investment is clearly increasing but in most markets is not yet sufficient to enable the required rollout of charging infrastructure. This is even more the case for FCEVs, which have seen a much lower uptake, except in China, the Republic of Korea and the United States.[31] To resolve this "chicken or egg" situation and drive the transformation, experts broadly agree that governments need to guide the transport system and incentivise investment accordingly.

However, **views differ on whether we need to decide now on the fuel of choice for road transport and concentrate investment efforts accordingly or if parallel efforts are needed to speed up the transition.**

ARE FUEL CHOICE DECISIONS NEEDED NOW?

PRO

Decisions must be taken now and investments based on a clear vision.

Making choices now will maximise overall GHG effects and minimise overall economic cost.

No Agreement

CON

Policy should be technology neutral and the market will decide on the most practical and affordable solution.

> *Transport planners must decide now on the sustainable transport systems they want in the future.*
>
> **ITF**, *Transport Outlook*, 2023

> *Technology neutrality will give the choice to citizens to assess which technology will best answer their needs, in terms of practicality and affordability.*
>
> **FuelsEurope**, *Genuine technology neutrality in transport benefits 2050 climate targets*, 2024

ITF, for example, clearly advocates a "decide and provide" approach to infrastructure provision. This approach aims to make a conscious decision on the desired future transport system and then design infrastructure accordingly. This is a paradigm shift from the existing approach to "predict and provide", where infrastructure decisions are based on the projection of demand based on past demand trends.[32] ITF argues that there will be significant competition for renewable fuels between sectors and that policy makers must prioritise use in applications where cost and technology barriers make direct electrification unfeasible.[33]

Others argue that the full spectrum of low-carbon technologies will be required, and technology-neutral regulation must ensure fair competition between technologies. Customers and markets then decide on the solutions that fit best in their specific context.[34]

While biofuels and drop-in fuels may have a slightly higher investment risk for production capacity, they require no additional investment in distribution infrastructure at the wholesale or end-user level, as existing infrastructure can be utilised. This is different for the use of electricity and hydrogen in transport.

BEVs and FCEVs need specific charging and refuelling infrastructure. With the exception of Tesla, which rolled out its fast-charging network to promote vehicle sales, automakers have been reluctant to invest heavily in such infrastructure without clear demand, policy signals or government support. On the other hand, end users are not likely to buy a BEV or FCEV if they are not sure that they can refuel their vehicle on longer trips.

> *Even in the scenario where well-intended policies make fossil fuel vehicles difficult to own, economic reality suggests that policy measures will make fossil fuel vehicles more expensive. While fossil fuel vehicles might become more expensive to own, they would not just disappear overnight because in some places, the infrastructure or lack thereof would only allow fossil fuel vehicles to be the feasible choice.*
>
> **Alok Jain**, Trans-Consult Ltd.

For BEVs, home charging is predominant today, with the majority of chargers privately owned either at home or at the workplace.[35] Additional options are needed for car owners that do not have the opportunity to charge at home to achieve a higher adoption of EVs. Charging requirements differ for busses and trucks, where overnight charging at depots needs to be complemented by public "mid-shift" fast-charging infrastructure and for commercially used two- and threewheelers.[36] Governments are increasingly shifting their focus to supporting charging infrastructure, expanding efforts to also address the challenges for other road transport segments and alternative charging solutions, such as battery swapping.[37]

For FCEVs, public fuelling infrastructure is key. Hydrogen refuelling stations are at the moment almost exclusively located in Asia, Europe and North America.[38] While a lot of these stations have received some support from governments, some are also driven by private companies, especially those focusing on specific use cases, such as heavy-duty trucks or at ports.[39] However, hydrogen stations have already experienced closures, for example in Denmark, where demand from the existing 136 FCEVs was not sufficient to ensure profitability.[40] This illustrates the high risk for this infrastructure unless it is clearly coupled with policy incentives for FCEVs and for hydrogen production to bring down prices for end customers.

4.2 WHO DRIVES THE TRANSITION?

ENERGY VS. TRANSPORT ACTORS

The choice of fuels not only determines the necessary infrastructure. It also influences who is responsible for acting to enhance renewable fuel use in transport (→ *see Figure 14*).

As described above, production capacity for all renewable fuels needs to be ramped up quickly. This is mostly in the domain of energy ministries, often supported by ministries and agencies that are responsible for industry and economic development.

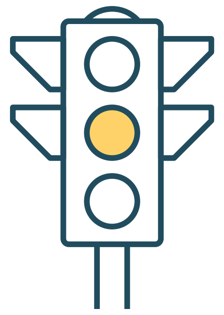
For already well-established fuels, such as biofuels, this largely remains undisputed. This is not as clear for renewable electricity and hydrogen use in transport, and **views differ on which sector should take the lead in driving developments – the energy or the transport sector.**

WHICH SECTOR SHOULD TAKE THE LEAD?

ENERGY ACTORS

The energy sector is traditionally responsible for fuel distribution and should also take the lead for new fuels.

Limited Agreement



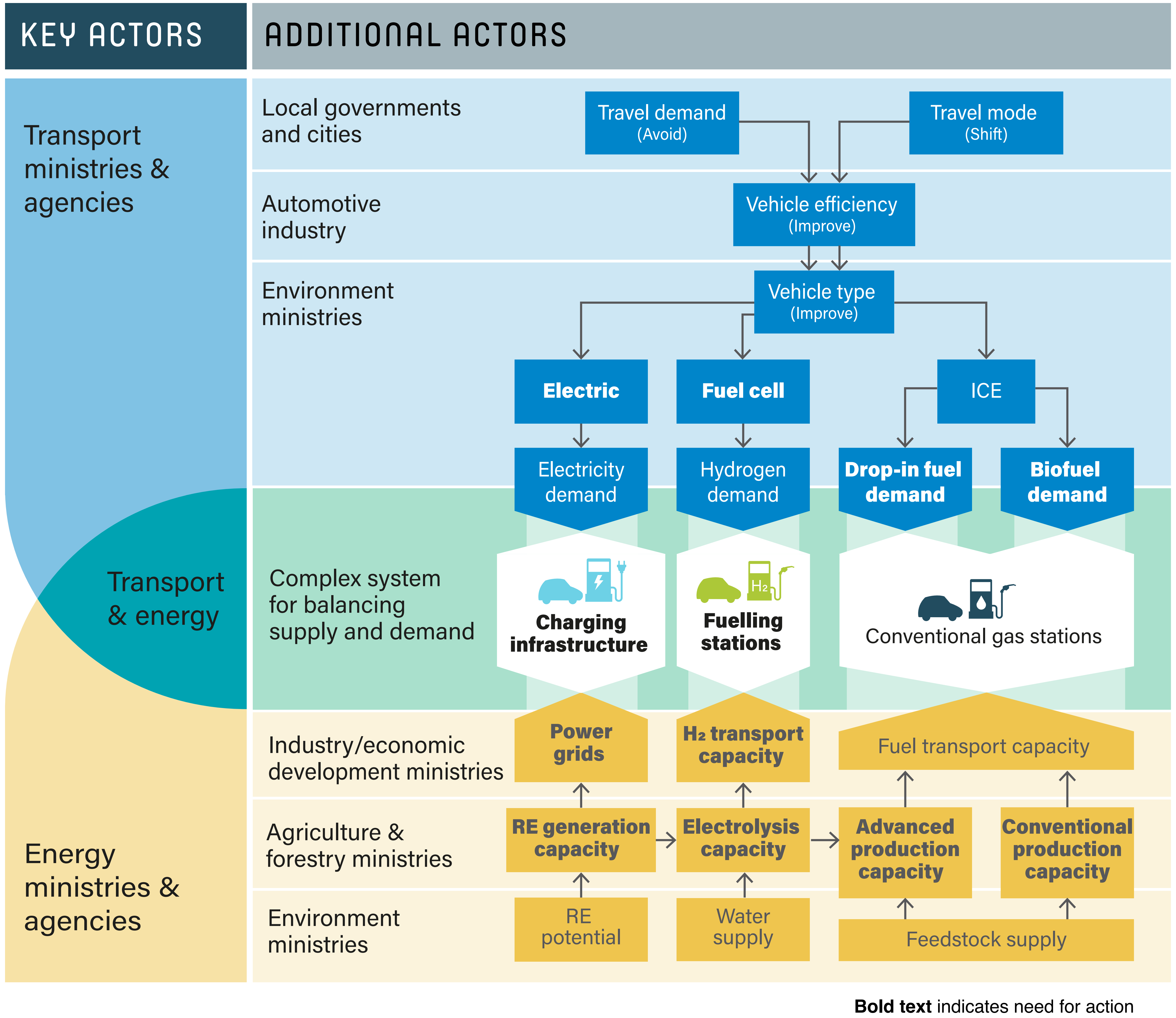
TRANSPORT ACTORS

Especially where new fuels require new vehicle technologies, the transport sector needs to take the lead.

> *In order for e-mobility to work, we need cheap electricity.*
>
> **Warren Ondanje**, Association for Electric Mobility and Development in Africa

> *In the climate agenda, there is a sense that transport solutions will come from technology. What the research suggests is that we need both social (changes in travel behaviour and choices) and technological solutions – which makes it more complicated than other sectors like energy. However, the social solutions can be deployed more rapidly than most of the technological options with more immediate impact.*
>
> **Bronwen Thornton**, Walk21

Figure 14: Responsibilities in the transport-energy nexus



Note: H_2 = hydrogen.
Source: REN21

For **biofuels** and **drop-in fuels**, the role of transport ministries is largely limited to ensuring that there is demand, for example through setting blending mandates or other incentives. Otherwise, supply chain infrastructure is mostly set up and there is little coordination across sectors required. This limits the responsibility of the transport sector drastically and makes it an attractive choice for transport decision-makers. However, some form of coordination can also be beneficial here; otherwise, there is a risk of mandates not being achieved. There are examples of biofuel mandates that have been reduced or suspended because not enough biofuel was available in the country. China, for example, did not meet its 10% ethanol blending target for 2020 and reduced its mandate to 4%.

For renewable **electricity** and **hydrogen** use in transport, the situation is very different. Here, a complex supply chain system needs to be developed – in many cases, from scratch – which requires a minimum level of coordination across sectors. While the expansion of production capacity for renewable electricity and hydrogen may not solely depend on the demand from the transport sector, the placing and type of wholesale distribution infrastructure may already be influenced by where demand is expected. Retail infrastructure for charging and refuelling must go hand in hand with expanded production and growing demand from BEVs and FCEVs.

Electricity and hydrogen as fuels for transport each have their own additional challenges that need to be tackled. Power grids need to be upgraded to be able to cater to vehicle charging needs. Ideally, this includes utilising the opportunities offered through vehicle batteries in balancing the grid through vehicle-to-grid technologies. Hydrogen requires safety standards and sufficient wholesale infrastructure for transport and storage. All of these challenges require close collaboration between the transport and energy sector authorities.

Experts broadly agree that incentives, policies and government support should be coordinated in a way that ensures that vehicle types, wholesale and retail distribution infrastructure, and production capacity are developing at a similar pace. Otherwise, the transition will not be fast enough, investors along the supply chain may end up with stranded assets and government spending will have been ineffective. However, there is less agreement on who should take the lead in driving these developments and ensuring that all actors are aligned.

Of course, all these efforts need to be seen in the context of other efforts in the transport sector that aim to reduce travel demand, move to more efficient – or, where possible, non-motorised – modes of transport and to improve the overall efficiency of vehicles. These efforts are traditionally under the responsibility of transport ministries and often local administrations.

A good example of well-coordinated action across the sectors is the construction of the Ethio-Djibouti Railway in Ethiopia, which opened in 2018. The planning of the fully electrified 760-kilometre (km) line connecting the two countries was conducted in parallel with works on new hydroelectric plants and grid extension, enabling benefits for the country's development needs as well as the new rail connection.[41]

> *"One key approach we need to adopt right now is to enable radical collaboration. We need more collaboration between sectors, including public and private sectors. Adequate public and private stakeholder engagement is required to invest in the right kind of transport infrastructure with governments leading the transition to net zero carbon."*
>
> **Wei-Shiuen Ng**, former ITF

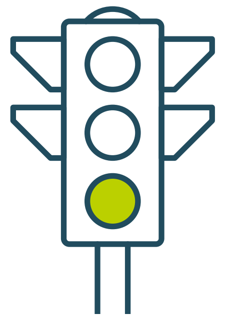
NATIONAL VS. LOCAL ACTORS

It is not only unclear whether decisions that impact fuel choices in transport need to be driven by the energy or the transport sector. It is also unclear at which level these decisions need to be made. Particularly in the transport sector, many responsibilities lie at a local or regional level, as choices depend very much on specific local circumstances.

Here also, **experts express different views on where the main responsibility to drive the transition is – more at the national or at the local level.**

WHO HAS THE MAIN RESPONSIBILITY TO DRIVE THE TRANSITION?

Medium agreement NATIONAL



NATIONAL ACTORS

Energy policy is mostly decided at the national level.

National level policies and regulations first need to enable local action.

LOCAL ACTORS

In many countries important transport planning decisions are made at the local level where the specific circumstances are known best.

> *In some developing countries, national governments are not a major transport player – but they should be. The decisions then are made at the provincial level and local levels. We can do a lot of things at the local level - not necessarily for transport but for planning in general. If we want walking and cycling at the local level, we need land use planning. Building new communities, for example, requires urban planning that optimises transport demand.*
>
> **Kristie Daniel**, HealthBridge – Livable Cities Program

> *Municipal governors are often restricted by state/national governments and have limited access to revenue and other resources to implement policy.*
>
> **Flaviá Guerra**, United Nations University – Institute for Environment and Human Security (UNU-EHS)

4.3 WHO FUNDS THE TRANSITION?

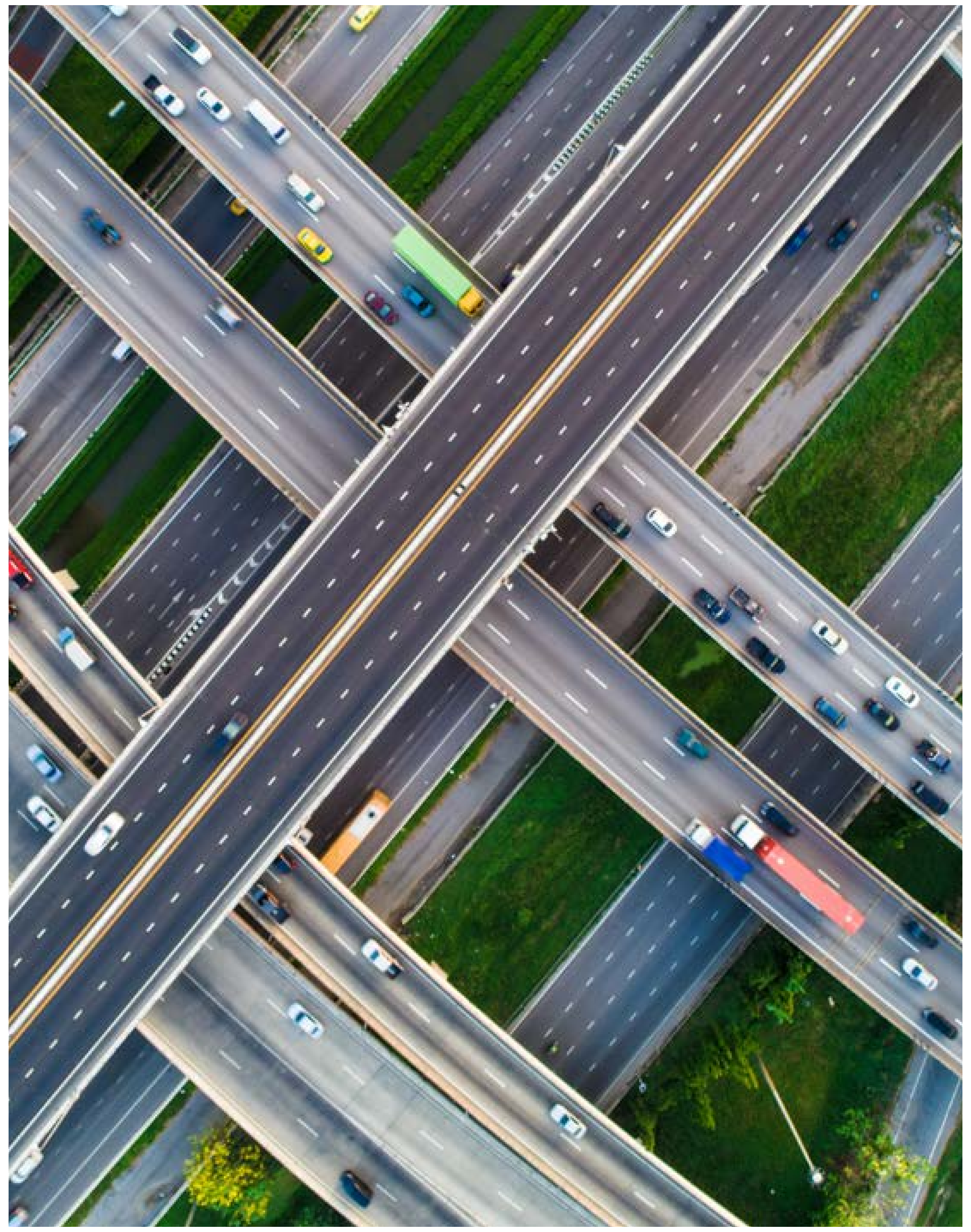
As outlined above, substantial investment is needed to enable the switch to renewable energy in the transport sector for production of fuels as well as distribution infrastructure. These investment needs will vary depending on local circumstances and fuel choices.

While key transport infrastructure is typically funded from public budgets, investments in fuel production and distribution are usually from the private sector. However, the public sector regularly provides incentives to ensure a sufficient and affordable energy supply.[42]

The business case for investments in renewable transport fuel production varies strongly across the different options and locations. Renewable electricity generation is already the cheapest option in many countries,[43] so financial government support and investment are limited in many regions, except where power generation is state-owned.

The production of hydrogen from renewable electricity, hydrogen-based fuels and advanced biofuels is currently still more expensive than their fossil fuel alternatives. To make them commercially attractive, experts agree that either a clear and stable demand is required, for example through mandates, or through government support,[i] such as subsidies. Mitigating the risks outlined above can also increase the attractiveness of investment for the private sector at relatively low direct budgetary costs to governments.[44] But overall, there is broad agreement that governments need to support new renewable fuels while they are not yet competitive.

A crucial question is whether these required investments are in fact additional to current spending, or if they can replace other, more carbon-intensive investments. In the transport sector, this needs to be seen in the context of the ASI approach. Investments in renewable fuels related to vehicles and infrastructure are likely to be additional if no meaningful measures to avoid and shift transport are implemented. Under a balanced approach, investment needs for road infrastructure could also be repurposed to enable the transition (→ *see Box 4*).[45]



i We focus on financial support here, but for successful rollout further factors play a role, such as the predictability and stability of the policy environment, technology development and availability, and the price of feedstocks.

BOX 4 OVERALL TRANSPORT SECTOR INVESTMENT NEEDS UNDER DIFFERENT SCENARIOS

ITF estimates investment for sustainable transport could be lower than under the business-as-usual scenario. Total capital investment needs for core infrastructure for road, rail, airports and ports are in fact 5% lower in their ambitious policy scenario compared to the current ambition scenario.

Savings come from measures that address transport demand and the shift to more efficient modes, which finally reduce the need for road infrastructure. Investments in public transport infrastructure, policies that support the move to transport modes with higher occupancy or load factors, and more compact cities could potentially save governments from spending USD 4 trillion globally on road maintenance and investment (excluding investment in adaptation).

There are regional differences in the overall level of required investment and in potential savings under the ambitious scenario. Sub-Saharan Africa, the Middle East and North Africa (MENA) region, and Latin America and the Caribbean have the largest investment needs and could also benefit most from investing in a sustainable transport system.

Source: See endnote 55.

VEHICLES

As outlined above, there is little need to invest in new vehicles for the use of conventional biofuels and drop-in fuels. This is not the case for other renewable fuels, such as electricity and hydrogen. Consumers need to shift from their well-known vehicles to a new technology, which – at least at the moment – still comes at additional cost.

Views differ on whether governments should provide incentives for new technology vehicles.

WHO SHOULD FUND NEW VEHICLES?

Limited Agreement

PUBLIC

Public support is needed to make new technology vehicles cost competitive.

PRIVATE

Not all governments have the funds to provide financial support for vehicles.

Financial support for new vehicles mostly benefits higher income households and the automotive industry.

> *"Policy choices need to be regulatory and also financial to support a just transition. For instance, the phase out of fossil fuel subsidies must go hand-in-hand with increased financial incentives for sustainable alternatives in line with the SDGs. This ensures that no one is left behind, especially poor and vulnerable communities."*
>
> **Flaviá Guerra**, United Nations University – Institute for Environment and Human Security (UNU-EHS)

> *"Financing is the main challenge. African leaders have high-priority goals that are competing with climate goals. They might prioritise other pieces they're trying to solve over climate change mitigation. This will be the biggest obstacle."*
>
> **Wanji Nganga**, Investment Expert

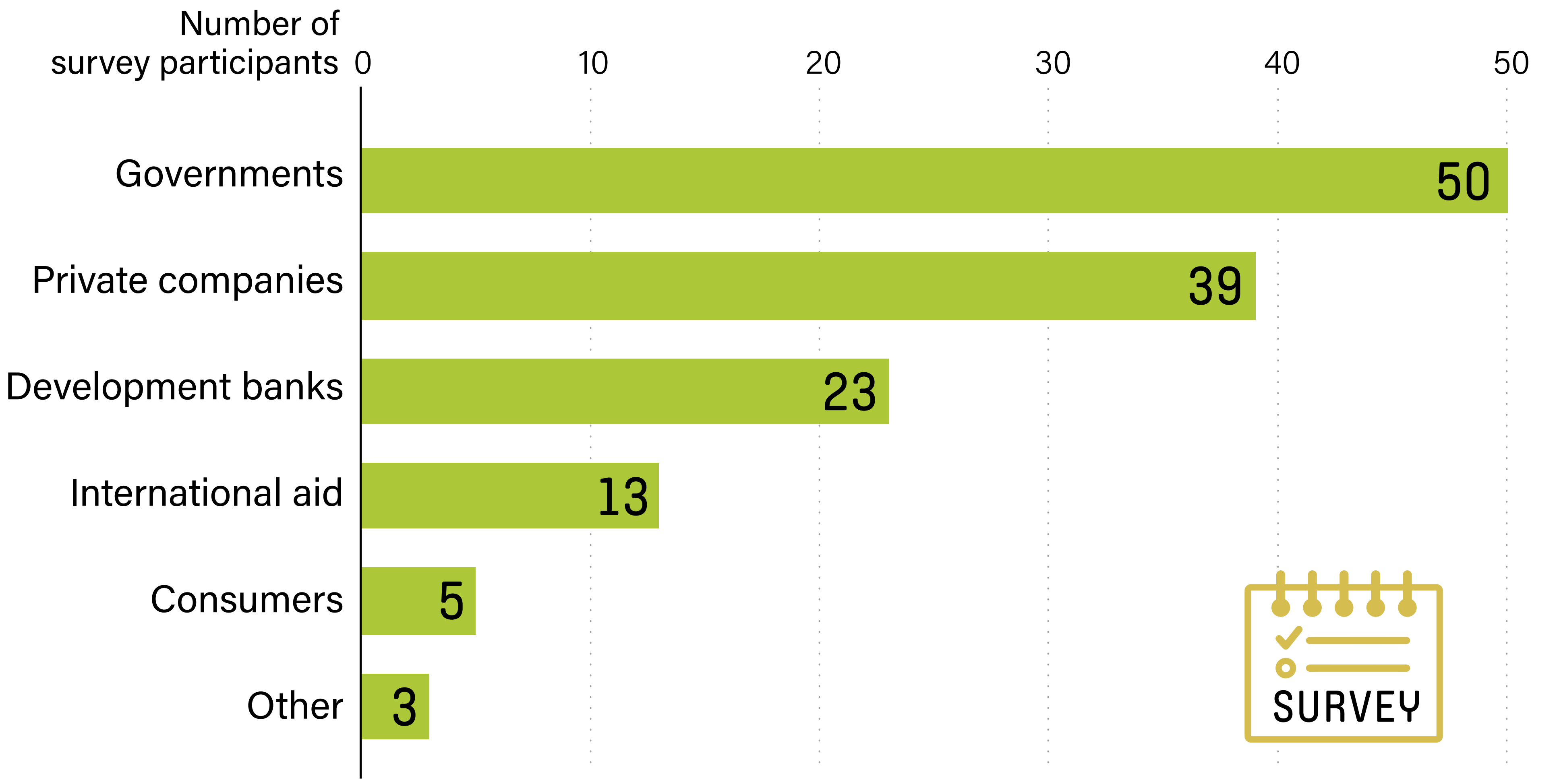
Some argue that public involvement is very likely needed for the uptake of new technologies, while the high up-front cost of vehicles prevents large-scale deployment. Incentives for vehicles can be in the form of direct cash transfers, tax breaks, low-interest (or no-interest) loans or other, non-financial, benefits that increase the attractiveness of the investment, such as preferential parking or use of bus lanes.[46]

They reason that the need to support the uptake of BEVs and FCEVs will decrease over time as more affordable models become more widely available. This process is already much further along for BEVs, with around 500 car models and many bus and truck models across all segments available.[47] Compared to this, the model range available for FCEVs is very limited, especially for cars.[48] By 2023, around 50 FCEV models of various trucks and buses were available.[49] Reflecting these developments, many developed countries are moving from purchase or tax subsidies to other forms of incentives, including regulations such as emission standards, ZEV mandates or ICE bans.[50]

Others reason that in many countries, especially poorer developing countries, governments cannot afford to financially support vehicle purchases. There are also concerns that such incentives benefit the already more affluent parts of the population and ultimately sustain the profit margins of car makers. Additionally, there are challenges regarding how to incentivise actors in the informal transport sector, which plays an important role in many developing countries.

Survey respondents largely saw public funding as the primary source for transport decarbonisation, although it must be noted that this includes investment in nonfuel related measures in the transport sector, such as avoid and shift measures, that are typically funded from public budgets or in developing countries through development banks and international aid (→ *see Figure 15*).

Figure 15: Survey – Moving forward, what do you think will be the primary source of financing for transport decarbonisation in the country for which you are providing information?



Note: Multiple entries were possible.

> *Both the private and public sectors are contributing to the charging infrastructure deployment. To maintain high sales, car manufacturers need to invest in the deployment of charging infrastructure. Governments also have the responsibility to support these businesses and ensure equitable access as well.*
>
> **Zifei Yang**, ICCT

Half of the experts see governments in the lead in funding the transition, as well as other public funding through development banks and international aid.

Just over one-third see the private sector in the lead.

DISTRIBUTION INFRASTRUCTURE

The critical question is about funding for electric charging and hydrogen fuelling stations, especially considering that specific infrastructure for different types of vehicles is needed, and stations designed for cars will not necessarily allow operation with trucks or buses. While conventional fossil fuel fuelling stations have a clear business model, this is not yet the case for electric charging or hydrogen fuelling, as demand is still limited and future developments in vehicle sales are uncertain.

Distribution infrastructure is at the nexus between the energy and the transport sector, and responsibilities are often not clearly defined. Similarly, **views differ on who will foot the bill for infrastructure investments.**

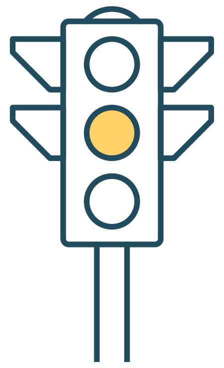
WHO SHOULD FUND NEW DISTRIBUTION INFRASTRUCTURE?

PUBLIC

Public funding is needed to ensure access for all.

If governments want new fuels, they should also foot the bill.

Limited Agreement



PRIVATE

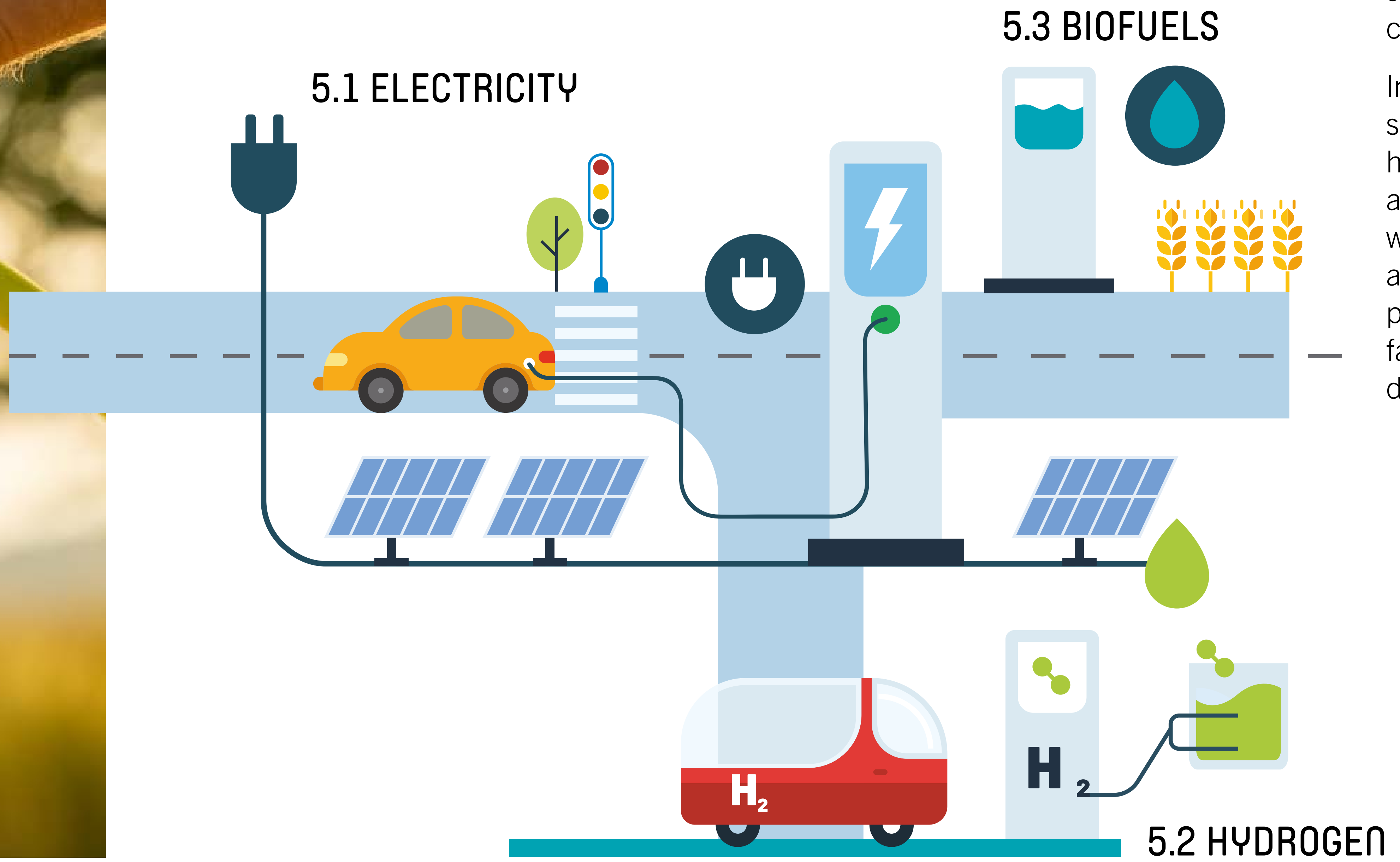
Companies can use infrastructure to support their vehicle sales.

New fuel infrastructure should build on existing infrastructure, which is largely privately owned.

> *"We can't think about sustainable transport development without considering accessibility and inclusiveness. In order to achieve sustainable transport, we need to ensure accessibility for all users, not just the average user but people from all socio-economic groups. If we can improve the accessibility of the system for all, we can make it more efficient, resilient and sustainable in the long term."*
>
> **Wei-Shiuen Ng**, former ITF

> *"Ultimately, I don't see the public sector will play a lasting role in providing charging infrastructure – it will eventually all become privatised."*
>
> **Cornie Huizenga**, Climate and Environment Services Group

5. DIFFERENT VISIONS: THE FUEL OF THE FUTURE



The largest disagreements in the expert community are around the question of what the "right" fuel mix will be for the future low-carbon transport system. As outlined in Chapter 2.2, low-carbon scenarios show large variations in their use of electricity, hydrogen and biofuels for the transport sector. Expert responses to the survey and in interviews have confirmed that there is still substantial disagreement.

In this section we present the diverging arguments about the suitability of each of the renewable fuel choices, i.e. electricity, hydrogen and biofuels. We concentrate on key questions about which disagreements seem most pointed. Additionally, we provide some key facts related to the main themes found across the arguments made on both sides of the spectrum. We present a wide range of sources to provide clear and neutral facts, including in some cases explanations for observed differences in data.

5.1 ELECTRICITY

KEY TENSION POINTS

Is the electricity "green" enough?

Are sufficient and sustainable battery & motor materials available?

Can and should heavy vehicles be electrified?

RELEVANT FACTS[51]

- Electric motors are three times more efficient than ICEs (on a tank-to-wheel basis).
- Current battery designs based on lithium are relatively heavy and expensive.
- The distance that can be travelled between recharges has improved, and charging times reduced, but the range of fully electric cars is generally still lower than that of petrol or diesel vehicles.
- EVs are relatively silent and do not emit air pollutants and GHG emissions at the point of use.
- Electric motors are simpler and contain less parts than ICEs, making them easier to build and maintain.
- EVs can provide more rapid acceleration and regenerative braking, improving driver experience.

> *In terms of how I imagine the future of the transport sector, for light-duty vehicles it certainly should be electrification.*
>
> **Nicholas Wagner**, IRENA

KEY DATA

- The share of renewable electricity in transport grew from 0.2% to 0.4% of total transport demand between 2009 and 2022, driven by a 68% increase in electricity use in transport and an increased share of renewable electricity generation, from 19.5% to 29.6% between 2010 and 2022.[52]
- Over 26 million electric cars were on the road in 2022, up 60% relative to 2021 and more than five times the stock in 2018.[53]
- China is the largest market with nearly half of the global electric car stock, followed by Europe, where electric car sales increased by over 15% in 2022, reaching a market share of 21%. The third-largest market is the United States, where sales increased 55% in 2022, with a sales share of 8%.[54]
- The rail sector is the most heavily electrified sector. Electricity supplied nearly 50% of all rail transport in 2021.[55]
- Two- and three-wheel vehicles are currently the most electrified road transport segment. The global stock of electric two/three-wheelers is now around 290 million. Electric two/three-wheelers account for one-third of all two/three-wheeler sales.[56]
- Electric light commercial vehicle sales worldwide nearly doubled in 2022 to more than 310,000 vehicles, making up 3.6% of the total market.[57]
- In 2022, global sales amounted to nearly 66,000 electric buses, about 4.5% of all bus sales. China dominates the production and sales of electric trucks and buses with over 80% of global sales.[58]
- In 2022, global sales of electric trucks amounted to 60,000 medium- and heavy-duty trucks, or 1.2% of truck sales worldwide.[59]

Table 1: Market development of EVs by vehicle category

	Stock share 2018	Stock share 2022	Market share 2018	Market share 2022
Cars	0.4%	2.1%	2.3%	14.0%
Busses	1.9%	3.1%	5.8%	3.8%
Light commercial	0.2%	0.6%	0.8%	3.6%
Heavy-duty trucks	0.2%	0.4%	1.0%	1.2%

Source: IEA Global EV Data Explorer

5.1 ELECTRICITY

IS THE ELECTRICITY "GREEN" ENOUGH?

In many regions where EVs are being rapidly deployed, electricity is still largely based on coal and gas-fired generation. Some experts argue that the benefits of switching to EVs may therefore to some extent be compromised. Others see electrification as a viable way forward even in countries with highly carbon-intensive power generation systems.

Views differ on whether it is useful to push for a mass rollout of EVs while a lot of electricity is still non-renewable.

GHG benefits of EVs

Emissions from EV manufacturing are higher than for ICEs, mostly due to battery production. However, for both vehicle types, most emissions over the lifetime of the vehicle come from fuel production and use.[60] The current determining factors for EVs' overall GHG effect are the GHG intensity of the production of vehicles and of the grid.[i]

Studies use different approaches in assessing GHG effects. Some compare specific EV models to conventional vehicles using a pre-defined mileage over the lifetime of the vehicle (→ *see Figure 16*).[61] Others determine how long it takes for the EV to break even with its conventional counterparts (→ *see Figure 17*).[62] Because grid intensity plays such a large role, most studies look at a range of assumptions, either using data from different countries or generation mixes.

i In countries with predominantly renewable electricity, effects from manufacturing and disposal become the main driver of EV emissions, while for ICEs fuel use remains the main driver.

DO EVs GENERATE GHG BENEFITS?

Medium agreement PRO

PRO

- There are already GHG benefits even with fossil electricity.
- RE shares are growing quickly, increasing future GHG benefits of EVs.

> *"Transitioning to trains, trams, cars, buses, and bikes that run on renewable electricity is a key strategy in achieving total decarbonization of the transportation sector."*
> **One Earth**, *Renewable Transport*

> *"A 100% renewable electricity mix is challenging but possible. But there really has to be an acceleration of pace."*
> **Oliver Lah**, Wuppertal Institute

CON

- The focus should be on decarbonisation of the power sector.
- There are concerns about the stability of 100% renewable grids.

> *"In some countries it will be a challenge to roll out renewable electricity production and supply."*
> **Henrik Gudmundsson**, CONCITO

> *"Renewable electricity is sometimes seen as a problem for security of electricity supply."*
> **Ery Wijaya**, Climate Policy Initiative

ARE EVs AND RE A COST-COMPETITIVE SOLUTION?

Limited agreement Location specific

PRO

- Efforts need to start today because of slow turnover of fleets.
- Large-scale deployment is essential to enable innovation and drive down cost.
- Electrification offers opportunities for local industrial development.

> *"EV sales in leading market will help EVs reach cost parity (with ICE) as soon as possible. Developing countries should build up local EV manufacturing or assembling (of components) capacity. It is a great economic opportunity as countries can become EV manufacturing hubs."*
> **Zifei Yang**, ICCT

CON

- Focus should be on low-cost solutions first, e.g. vehicle efficiency.

> *"Emissions from transport have not increased in the last decade, mostly due to efficiency."*
> **Nick Wagner**, IRENA

5.1 ELECTRICITY IS ELECTRICITY "GREEN" ENOUGH?

Reasons for variations in the estimates of GHG effects of EVs compared to ICEs in different studies include:[63]

- Use of actual vehicle models or average data.
- The type of ICE vehicle model/data used for comparison.
- Different data sources for fuel efficiency of ICE vehicles (real world vs. test cycle; which test cycle).
- Assumptions on mileage per year and/or total mileage over the lifetime of the vehicle.
- Assumptions on emissions from battery manufacturing, including where they are produced.

Results show large differences in GHG benefits and break-even times depending on the electricity mix, but experts broadly agree that even in countries with high-carbon electricity generation there are GHG benefits over the lifetime of the vehicle. With the current fuel mix for electricity generation, the IEA estimates that there was already a global benefit of around 80 million tonnes (Mt) of GHG emissions in 2022, on a well-to-wheels basis.[64]

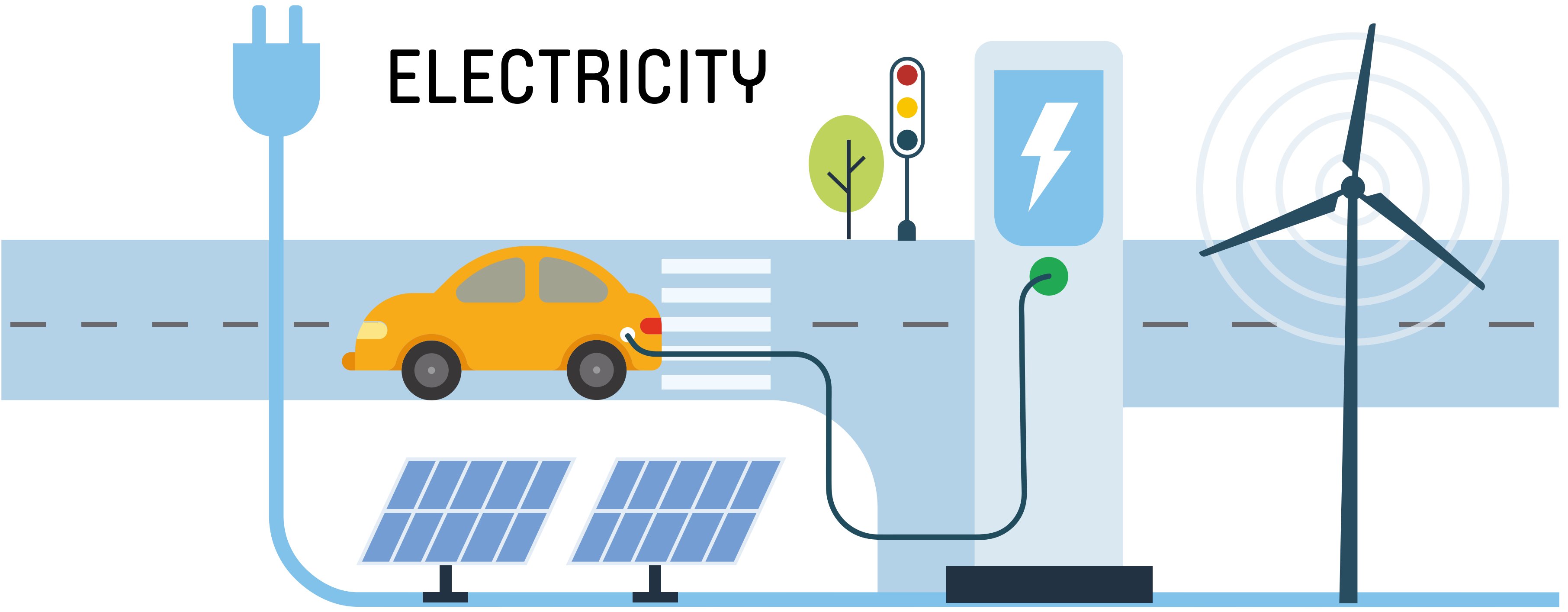
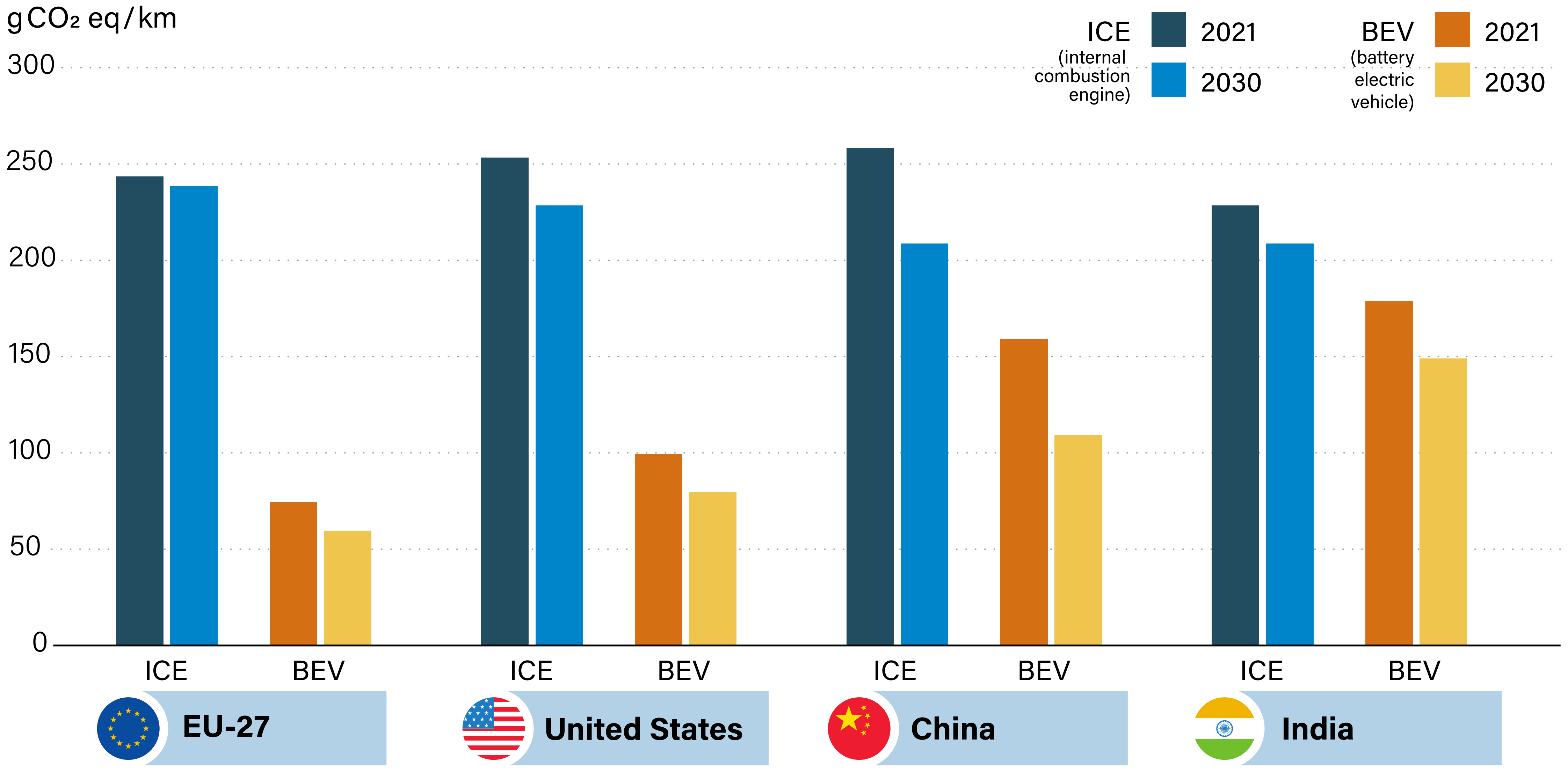
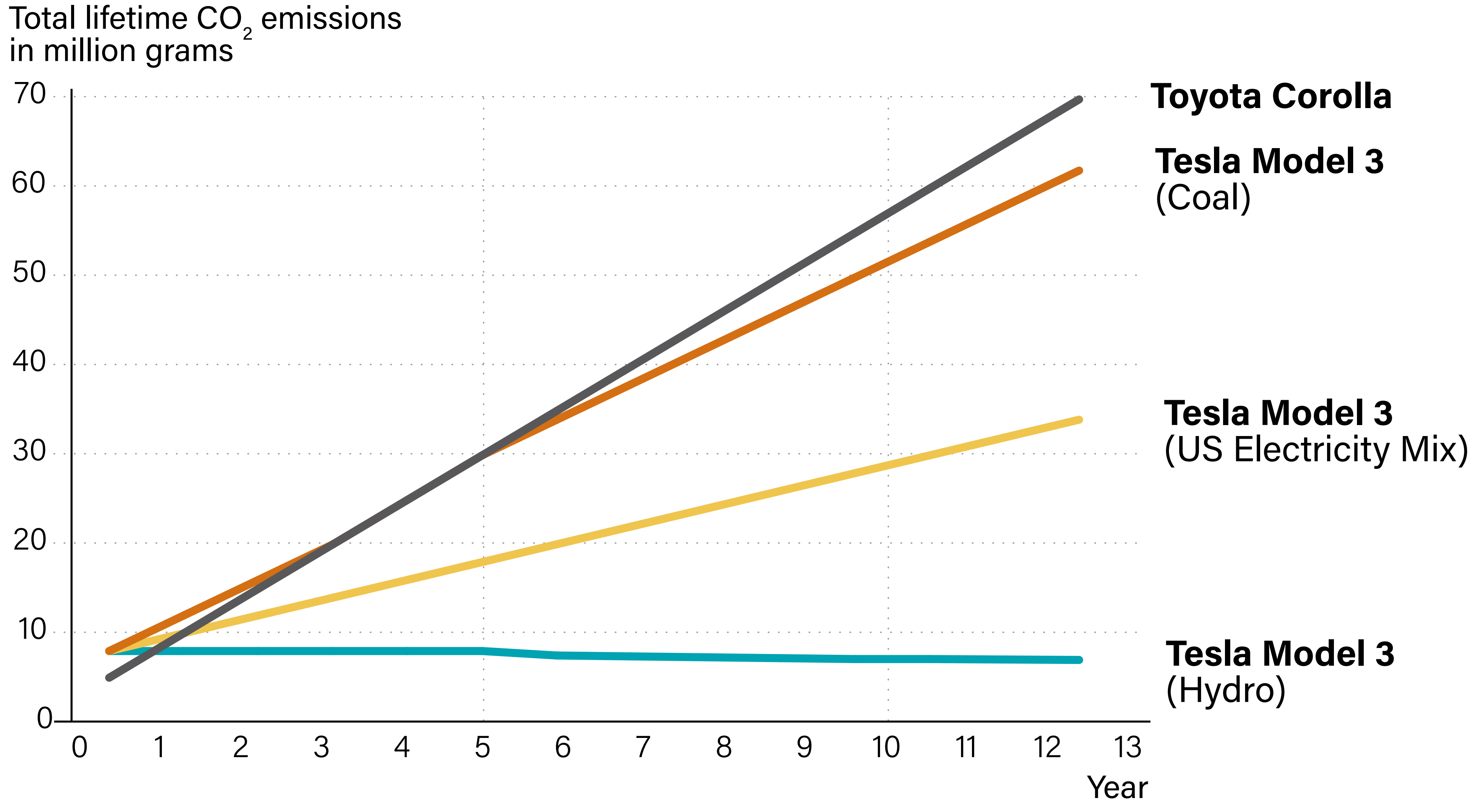


Figure 16: Comparison of GHG emissions intensity of ICEs and EVs in 2021 and 2030 in Europe, the United States, China and India



Source: ICCT. See endnote 61.

Figure 17: Comparison of break-even points between a Toyota Corolla and a Tesla Model 3 under different electricity mix assumptions



Source: Reuters. See endnote 62.

Renewable electricity production more than doubled between 2010 and 2022, from 4,201 terawatt hours (TWh) in 2010 to 8,690 TWh in 2022. While hydropower is still the largest source, the rapid growth has been led by expansion in wind and solar PV generation (→ *see Figure 18*).[65] Since 2010, the renewables share of total electricity generation increased from 19.5% to 29.6%.[66]

Although there is still a long way to go to reach a fully decarbonised power system, additions to renewable power generation capacity have outpaced new fossil fuel capacity for over a decade, driven by the strong business case and policy.[67]

This trend can be expected to continue, further increasing the share of renewable electricity even under current policies. The global average GHG intensity of electricity generation and delivery is expected to decline by between 28% and by 37% and the net GHG emissions avoided through the use of EVs to reach nearly 700 Mt CO_2-equivalent (CO_2e) in 2030.[68]

Increased renewable energy generation, particularly from variable sources such as solar and wind, is posing challenges for grid management. Especially in countries with an already fragile power system, the additional flexibility required from renewables requires substantial updates to the grid.[69]

Additional demand from transport users can exacerbate such challenges, if not managed well, especially if vehicle charging collides with peak demand from other sectors. However, power demand from EVs is building up slowly over time, giving policymakers and grid operators the opportunity to implement a wide range of measures to address upcoming issues through strategies, technology, changes in systems operations, regulation and market design. In its advanced stages, this can include bidirectional charging, enabling EVs to provide system services to the grid and thus help in stabilisation.[70]

Cost and economics for EVs and renewable energy

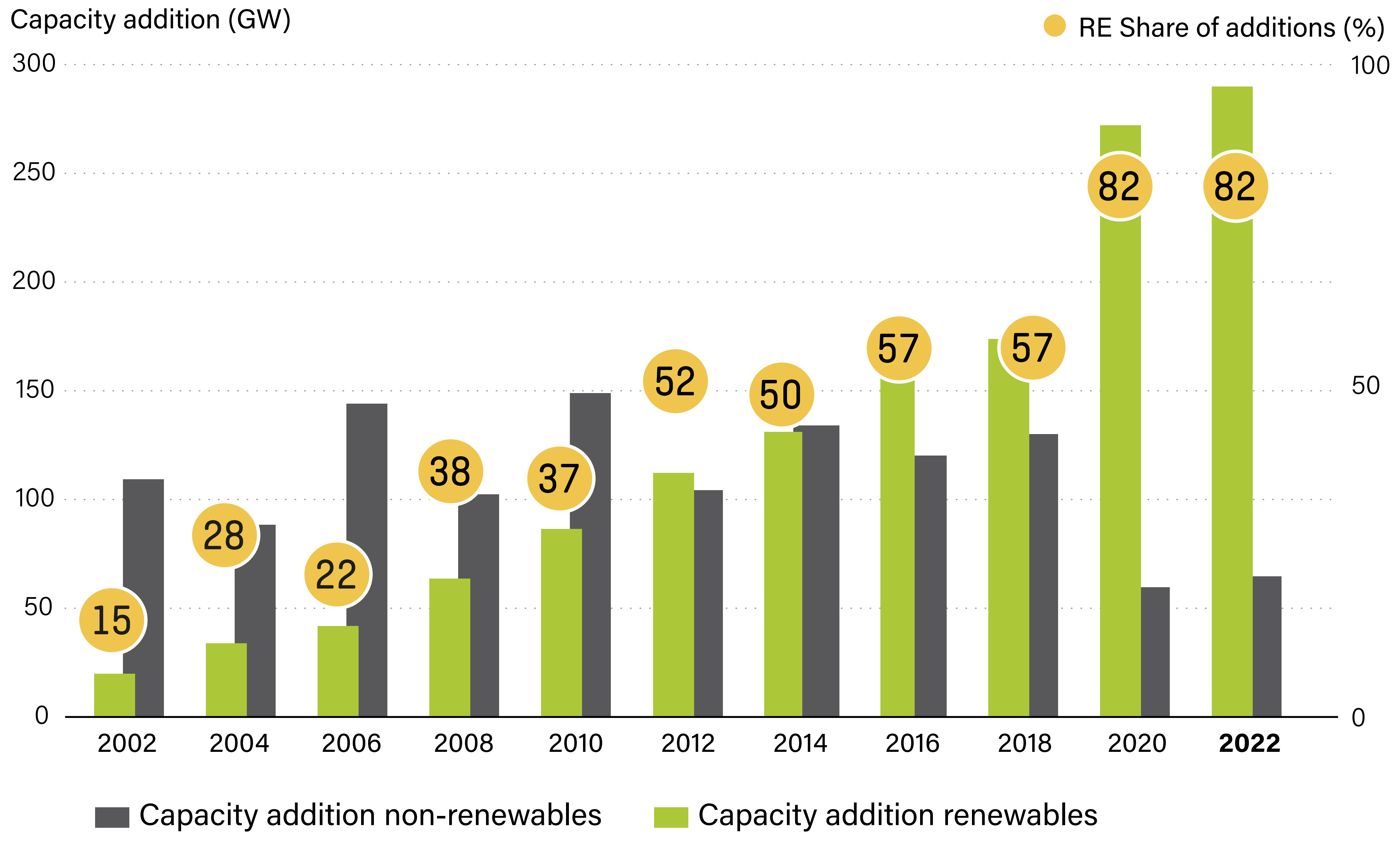
Encouraged by ambitious EV sales targets and climate reduction commitments, automakers have made various efforts. For example, the number of available EV models reached 500 in 2022,[71] and automakers around the world have over 70 EV models coming up by 2030.[72] They are also planning to invest nearly USD 515 billion in EVs and batteries,[73] and these plans will likely continue increasing in the next few years, driving down the cost of vehicles.

Apart from the purchase price, the total cost of ownership looks at all costs related to owning and operating a vehicle over a given time period and the mileage driven. This allows the comparison of different vehicle technologies. However, assessments depend on many assumptions as well as local conditions, such as fuel and charging prices, use cases (e.g. home charging vs. using public fast chargers), insurance costs, and vehicle prices in the specific market. Financing costs for different technologies and types of vehicles can also make a difference. Accordingly, some assessments come to the conclusion that EVs are overall more expensive than their ICE counterparts,[74] while others find that they are already cheaper[75] or are set to become cheaper in the near future.[76]

For renewables, the levelised cost of electricity (LCOE) generation has already seen a substantial drop over the last decade. Globally, some are already cheaper on average than the fossil fuel alternatives (→ *see Figure 19*).[77] This competitive cost development, together with policy support, continues to drive enhanced renewable electricity generation.[78]

Development of the EV supply chain has increased other types of local production and increased job opportunities locally. For example, Kenya currently has over 2,700 megawatts (MW) of installed capacity of electricity per year,[79] with 90% of electricity coming from renewable sources; this provides a strong foundation to support electric mobility. As the government started to periodise the development of electric mobility, Kenya has become a hub for e-mobility start-ups,[80] bringing more green investment and jobs.

Figure 18: Annual power capacity expansion, 2002-2022



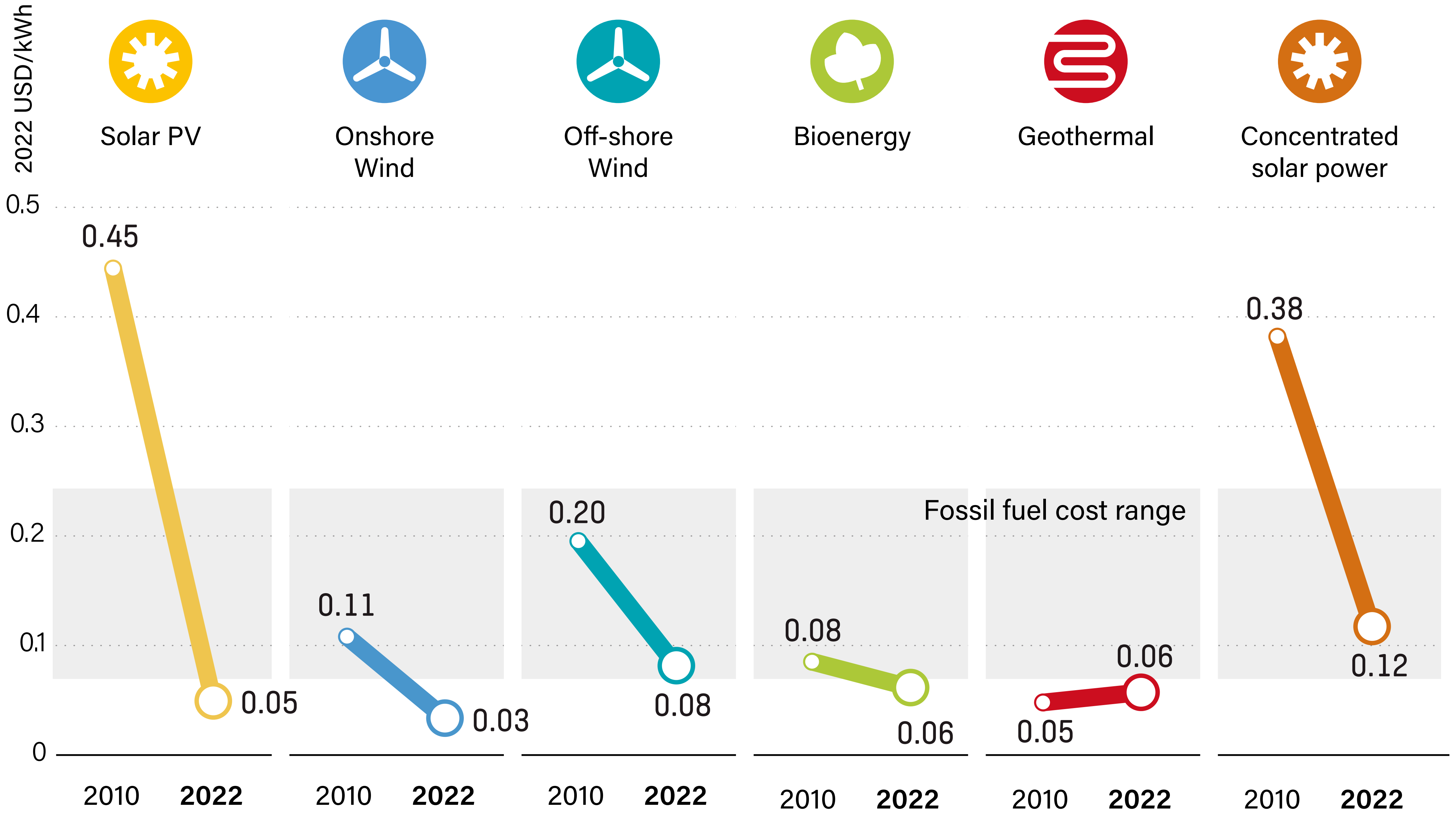
Note: GW = gigawatt
Source: IRENA. See endnote 65.

5.1 ELECTRICITY IS ELECTRICITY "GREEN" ENOUGH?

In Vietnam, there is an abundant amount of high-quality nickel reserve. This makes Vietnam a global hub for lithium-ion battery production,[81] attracting more business and jobs. Also in Vietnam, electric two-wheeler sales almost doubled from 163,000 vehicles in 2019 to 237,000 vehicles in 2020 – sales that are dominated by local brands after local production was initiated in 2018.[82]

However, there are also limits to such opportunities. Not all countries have their own vehicle production, especially for larger vehicles. Countries without an established automotive industry can nevertheless use opportunities in the production of electric two- to three-wheelers, as seen in the case of Vietnam.

Figure 19: LCOE of renewable electricity generation by technology



Source: IRENA. See Endnote 77.

SOCIAL AND ECONOMIC IMPLICATIONS

In countries that still suffer from electricity shortages, or where demand is rising very sharply (such as in Southeast Asia), it may be difficult to meet extra demand for green electricity for transport (for more prosperous users) while providing universal access to sustainable electricity. However, as mentioned in Chapter 4.1, transport can also provide additional demand that can make grid extension, mini-grids or off-grid solutions more economically viable and thus help improve access.

GEOGRAPHIC DIFFERENCES

The generation mix varies widely between regions. For example, in China, two-thirds of generation is fossil fuel based, and mostly from coal, whereas in the United States the share of fossil fuel-based generation is 60%, with 20% coal-fired generation and 39% gas.[83]

The regional share of renewables in the power generation mix ranges from 4% in the Middle East to 68% in Central and South America and 80% in Brazil.[84]

5.1 ELECTRICITY

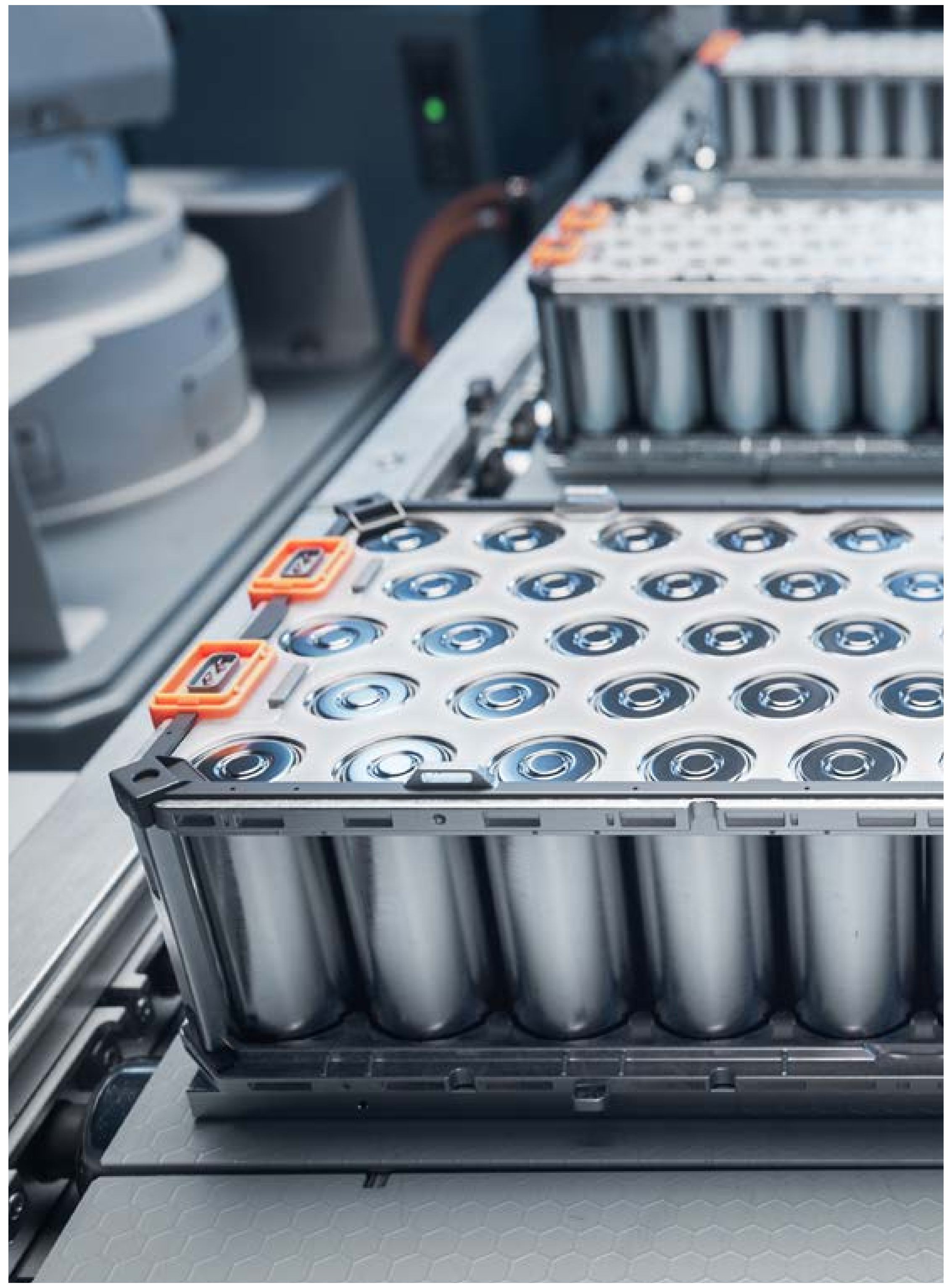
WILL SUFFICIENT AND SUSTAINABLE BATTERY AND MOTOR MATERIALS BE AVAILABLE?

The growth in demand for EVs and their batteries, along with the expansion of renewable energy technologies such as wind and solar PV and of storage systems, has pushed up demand for several critical minerals. From 2017 to 2022, demand from the energy sector drove a tripling in overall demand for lithium, a 70% jump in demand for cobalt and a 40% rise in demand for nickel, pushing up prices.[85]

Many experts expect that the growth of EVs will put further pressure on the supply chains for these minerals, especially as the mineral ores and processing and refining capacity are concentrated in a relatively small number of countries.[86]

The concentration in ore supply and refining capacity has given rise to concerns about the security of supply. Due to these concerns, other countries and regions, including the United States and the European Union, are looking to diversify sources and refining capacity.

Experts also raise concerns about the environmental and social implications of increased mining and refining activities and their impacts on local communities, which are often located in remote areas of developing countries. These include concerns about the GHG emissions associated with mining and refining, water use and impacts on water quality, and deforestation. At the same time, there are concerns about human rights violations, poor labour conditions and the use of child labour.



Others argue that supply will keep up with demand – based on technology innovation, enhanced capacity and increasing rates of recycling – and that the negative environmental and social impacts of minerals mining and refining can be minimised through technology and policies. Additionally, fossil fuel exploration and production are also cause for considerable environmental and social concerns.

Views vary on whether critical materials will be available at the required scale and in a sustainably produced way to support the large-scale electrification of vehicles.

WILL BATTERY & MOTOR TECHNOLOGY DEVELOPMENT PROVIDE SOLUTIONS?

Limited agreement

PRO

New technologies less dependent on scarce minerals can minimise demand.

"The discovery of an energy-dense battery that outperforms li-ion will revolutionise the transport sector. Battery breakthroughs could significantly reduce the costs/weights of EVs."

Doug Vine, C2ES

CON

EVs are already pushing up the price and demand for critical materials.

"Lithium Carbonate price reached its all-time high in November 2022, after a 200% increase in one year."

Trading Economics, Lithium

CAN RECYCLING MINIMISE DEMAND?

Inconclusive

PRO

Recycling can minimise concerns about supply shortages or energy security.

"Batteries today are already much more sustainable than oil on every dimension, and with increased recycling, they can be even more so."

Anthony Eggert, Climate Works

CON

The geographic concentration of ores and refining capacity pose threats to supply and energy security.

"Scaling up recycling will require support from the government and international coordination on standards and policies."

Zifei Yang, ICCT

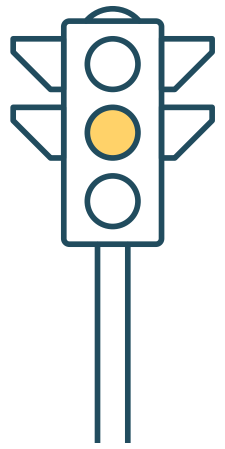
5.1 ELECTRICITY WILL SUFFICIENT AND SUSTAINABLE BATTERY AND MOTOR MATERIALS BE AVAILABLE?

IS SUFFICIENT MATERIAL AVAILABLE?

PRO

- Investment is growing and will keep up with demand.
- Exploration, mining & refining present an economic opportunity.
- New technologies and policies can minimise negative impacts.

Limited agreement



CON

- Mining & refining will struggle to keep up with demand.
- Mining & refining have significant environmental and social impacts.

> *We keep discovering more lithium, and we get better at mining it.*
>
> **Hannah Ritchie**, Oxford University

> *An electric bike's lithium-ion battery carries approximately 200 times less rare earth materials than that of an EV car, yet in large part carries the same single person load.*
>
> **Mark Sutton**, Cycling Electric

Battery and motor technologies

BEVs use six times more minerals than conventional vehicles, especially copper, lithium, manganese, cobalt and graphite, which are used primarily in the battery systems. In addition, copper, cobalt and rare earth metals (especially neodymium, dysprosium, praseodymium and terbium) are required for the electric motors.[87]

Lithium-ion batteries are the most popular and regularly used batteries in today's EV industry. There are three different lithium-based chemistries in use, with lithium manganese cobalt oxide (NMC) being the most popular. This is followed by lithium iron phosphate (LFP) cathode chemistries, which have seen increasing popularity in the last years driven by the preferences of Chinese equipment manufacturing companies.[88]

Solid-state batteries are an option to solve some of the problems with lithium-ion batteries. They are smaller and lighter and deliver higher energy density. They can also be charged faster and more often over their lifetimes,[89] but the technology is still under development. For example, ProLogium signed a technical cooperation agreement with Mercedes-Benz in early 2020 to invest in solid-state battery development and production preparations.[90]

Other new battery designs are also under development. For example, sodium-ion batteries, which rely on sodium rather than lithium as the main conducting element, completely avoid the use of critical elements.[91] Other developments aim to optimise existing chemistry designs. The recently announced NMC 811 increases the share of nickel and reduces the shares of manganese and cobalt from the normally used 33% to 10%.[92]

Efforts to improve anode chemistry to improve energy density and reduce the need for critical materials are also underway. Silicon is used to replace some of the graphite, and around 30% of anodes now contain silicon. Still under development is the use of lithium metal anodes, which could further increase energy density.[93]

The only commercially deployed motor types at present are brushless permanent magnet (BPM) and alternating current (AC) induction motors.[94] Permanent magnet synchronous motors dominate the market but depend greatly on rare earth elements, mostly neodymium and samarium.[95] So far, only Tesla and a few other manufacturers have used AC motors, which do not rely on rare earth materials for the magnets. However, AC motors have lower overall efficiency, and further efficiency losses at higher temperatures must be managed with effective cooling systems.

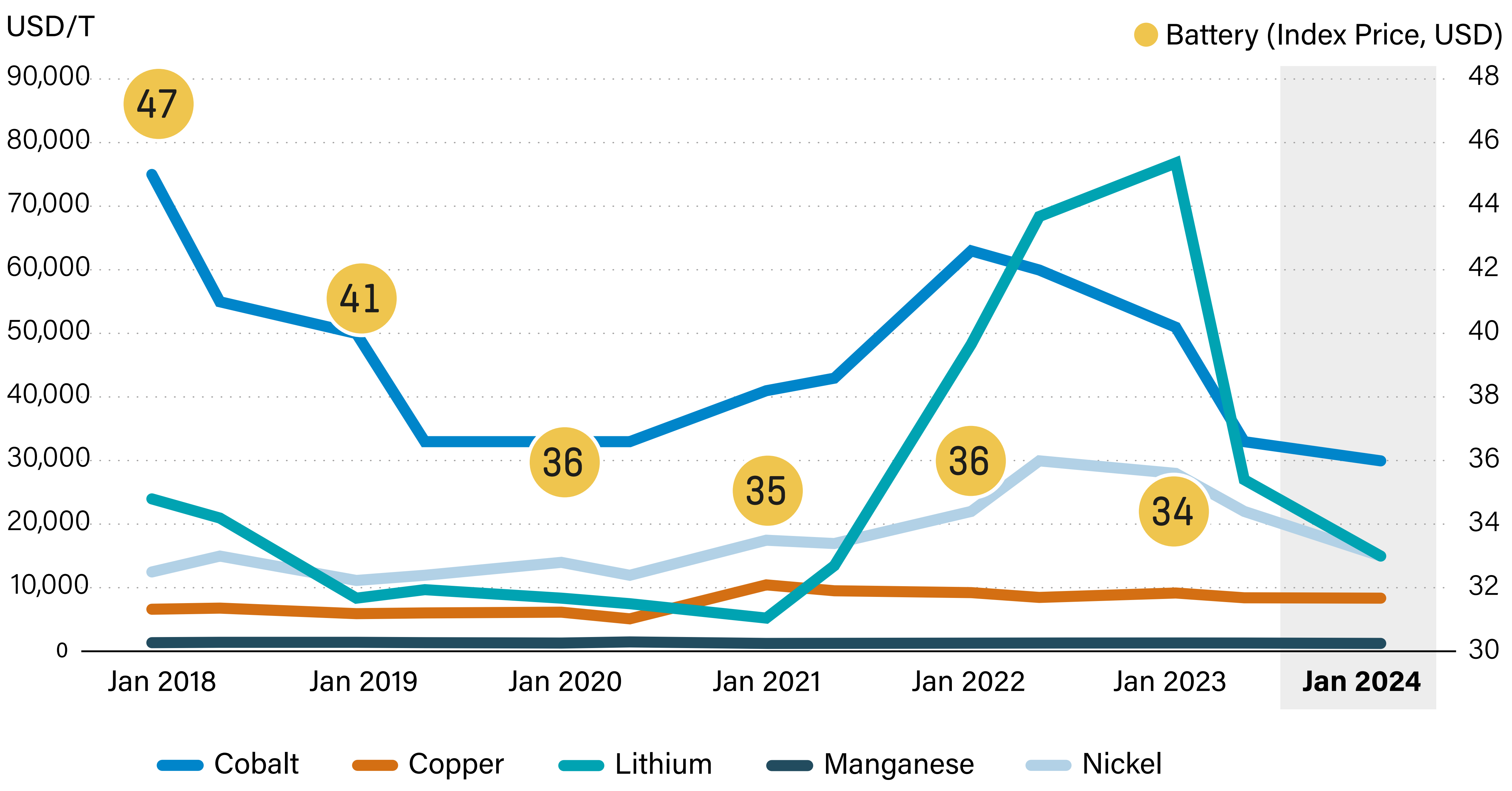
Other motor technologies being explored for EV applications include switched reluctance motors (SRMs), which potentially offer a high-efficiency and low-cost alternative. However, SRMs suffer from high noise, vibrations and torque ripple. Controlling and reducing these effects is the focus of development for this motor type.[96]

The increasing demand for EVs is one factor impacting mineral prices, but in return, mineral prices also influence battery chemistry developments (→ *see Figure 20*).[97] Cobalt prices, for example, increased between 2016 and 2018 due to concerns about public acceptance of cobalt mining, leading to the development of batteries with lower cobalt content.[98] The influence of increasing demand on prices can be clearly seen for lithium, for which prices spiked in 2022 owing to demand outpacing supply. Expected increases in supply and a projected slowdown in demand growth led to prices dropping by around 20% in early 2023 compared to the peak price.[99]

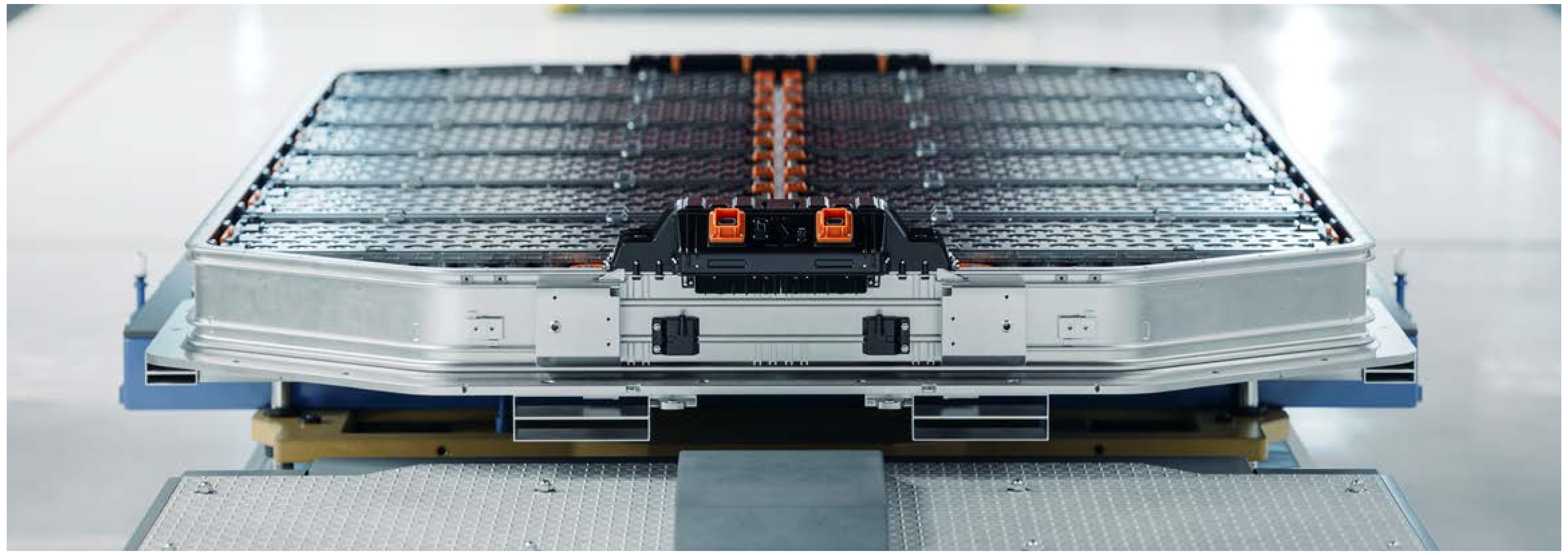
The cost of batteries can vary from USD 4,000 to USD 20,000, depending on the vehicle brand and model.[100] The price of batteries also varies across regions, with China having the lowest prices on average. This price discrepancy, according to the IEA, may be the result of 65% of battery cells and nearly 80% of cathodes being made in China.

5.1 ELECTRICITY WILL SUFFICIENT AND SUSTAINABLE BATTERY AND MOTOR MATERIALS BE AVAILABLE?

Figure 20: Price of selected battery materials and lithium-ion batteries



Source: IEA, Trading Economics. See endnote 97.



Recycling of materials

Approaches to mitigate these risks include increased efforts to recycle components containing critical minerals and to develop alternative battery and engine technologies that are less dependent on scarce resources.

With lithium-based batteries being mostly used today, recycling capacity is being installed at nearly a 25% increase annually, starting at 250 kilotonnes (kt) globally.[101]

Increased recycling efforts are mostly driven by government incentives and regulation.[102] In the United States, for example, more investments have been announced for battery recycling. The US Department of Energy is set to invest USD 2 million to advance lithium-ion battery recycling and remanufacturing technologies.[103] At the same time, the domestic content requirements of the Clean Vehicle credits under the Inflation Reduction Act also incentivise local recycling to meet the required local content thresholds.[104] Similarly, the European Union's Critical Raw Materials Act requires 15% of annual consumption to be from recycled sources by 2030. The Republic of Korea also passed a bill that requires manufacturers to meet battery recycling targets.[105]

Available deposits, investment and ongoing exploration

Some 70% of cobalt is produced in the Democratic Republic of Congo, and 70% of refining capacity is in China. China's share of global production of rare earth ores was over 95% in 2010, but this fell to just over 60% in 2019 as the United States and other countries boosted production. Rare earth separation and refining operations are still heavily concentrated in China, which has almost 90% of the market share.

As demand for EVs and battery storage rises, the demand for the minerals required for these technologies is projected to increase 30 times by 2040. There will be a 21-fold increase in demand for cobalt, a 28-fold increase in demand for copper, a 41-fold increase in demand for nickel and a 43-fold increase in demand for lithium.

Demand for graphite is expected to increase by 25%, silicon by 460% and rare earth elements by 15% by 2040.[106] The energy sector is expected to be the leading end user of lithium and nickel in the future, accounting for 61% of the clean energy use cases for nickel and 40% of global lithium production in 2050 (→ *see Figure 21*).[107]

5.1 ELECTRICITY WILL SUFFICIENT AND SUSTAINABLE BATTERY AND MOTOR MATERIALS BE AVAILABLE?

According to the IEA, an EV requires six times the mineral inputs of a gasoline-powered vehicle, and the mining, manufacturing and disposal of the primary materials can all create **environmental challenges**.[108] For example, nickel usually exists below the topsoil. The removal of topsoil can cause serious degradation and deforestation, as well as causing irreversible negative impacts to groundwater and wildlife habitats.

The largest public debate has been around the environmental impacts related to the extraction of lithium.[109] There are two sources of lithium: salar brine water and spodumene, a hard rock and crystal mix.[110] Lithium can be extracted from brine by direct extraction (although this technology is still being developed for commercialisation) and through evaporation concentration. The latter method can have significant impacts on groundwater and surface water; requires large areas of land; and can add to erosion, air quality deterioration and wildlife habitat destruction. Similar effects are connected to the surface mining of spodumene. The impacts of direct extraction from brine are potentially less than those of spodumene, especially if processed brine is pumped back into the aquifer, but these impacts can still cause disturbance to surrounding lands and are not yet well understood.[111] Underground mining also has fewer impacts above ground, but this can release toxic materials and carries the added risk to workers of tunnel collapses.[112]

Environmental impacts can be minimised, for example, by adding lithium extraction to existing industrial processes that extract chemicals from brine, by re-injecting brine after extraction (which only works for direct extraction), and by managing waste streams resulting from the process.[113] Policies that specify environmental minimum standards could also be used. However, certification of the environmental sustainability of minerals is not yet well established. Despite this, some sustainability initiatives are being more widely used, such as Towards Sustainable Mining (TSM) and the Initiative for Responsible Mining Assurance (IRMA).

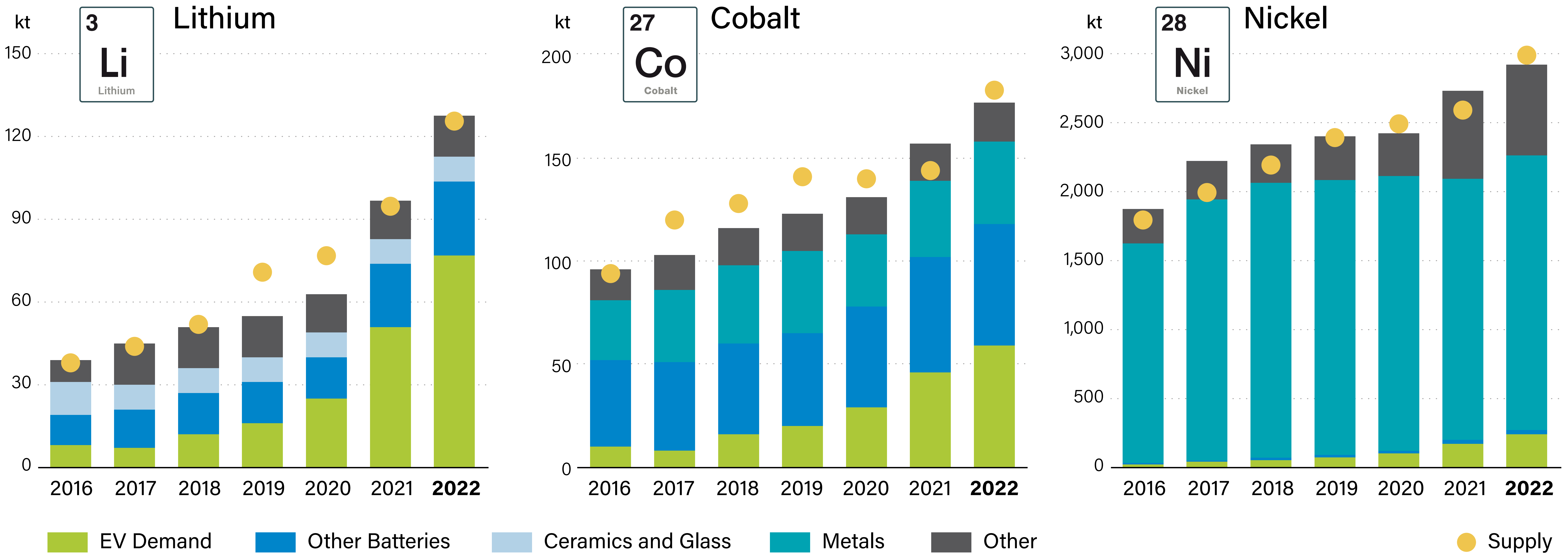
SOCIAL AND ECONOMIC IMPLICATIONS

Battery raw materials are often produced in developing and emerging countries. This gives rise to concerns about the environmental consequences of GHG emissions associated with mining and refining, high levels of water use, and pollution of air and water courses. Concerns also arise about poor labour conditions, including low wages, child labour and poor safety conditions.

GEOGRAPHIC DIFFERENCES

The necessary raw materials are concentrated in a few countries, and China dominates the refining and production industries. This could pose a risk to sustainable supply and is leading countries to diversify their supply chains and install domestic battery production capacity.

Figure 21: Overall supply and demand of battery metals by sector, 2016-2022



Source: IEA. See endnote 107.

5.1 ELECTRICITY

CAN AND SHOULD HEAVY-DUTY TRUCKS BE ELECTRIFIED?

Electric motorbikes, tricycles, cars and vans are well established, and electric buses for local public transport are increasingly deployed. In all these sectors, range requirements are relatively limited, and the vehicles stay close to their base where charging can be facilitated. Their utilisation rates are largely compatible with charging cycles, say overnight.

Efforts are underway to extend battery vehicles to heavy goods transport. Some argue that technology development of vehicles and charging options will enable their widespread use for many heavy-duty applications as well.

Others are of the view that electrification is too expensive for these applications to allow for meaningful decarbonisation in the required time frame.

Overall, experts have different opinions on whether battery technology developments will allow their widespread use in heavy-duty and long-haul applications and whether electrification is the best option for these vehicles (→ *see Figure 22*).

ARE APPROPRIATE VEHICLES AVAILABLE?

Medium agreement PRO

PRO

More models for heavy-duty trucks are becoming available.

"By 2050, it can be expected that a fossil-free heavy-duty transport system is possible (in the EU it can be already 2040). So, fossil-free but not necessarily net-zero emissions - to be careful. By 2050 it can be expected that all heavy-duty applications also can be electrified."

Jonas Stromberg, SCANIA

CON

Cost considerations and turnover times constrain opportunities for electrification and hydrogen.

Biofuels and synthetic fuels can be a straight replacement for diesel.

"Heavy-duty transport is a fragmented sector in Southeast Asia. Fleets of heavy-duty vehicles often consist of only a few vehicles owned and operated by small business-owners, who find it challenging to invest in advanced conventional and/or electric vehicles. Also, we are talking almost exclusively about second-hand hand trucks running on diesel fuel. However, the direction taken by governments to require biofuels to be blended with diesel, helps reduce emissions from this sector."

Glynda Bathan Baterina, Clean Air Asia

IS BATTERY TECHNOLOGY SUITABLE FOR TRUCKS?

No agreement

PRO

Battery technology development will enable heavy-duty use in the near future.

"Battery technology, which continues to improve, should be capable of meeting the needs of all road vehicle applications (from rickshaws to heavy trucks)."

Anthony Eggert, Climate Works

CON

The specific energy density of the battery is not sufficient for the heavy weight and long distances.

"The longer the daily operations, the heavier and larger the load, the more suitable hydrogen-powered vehicle becomes. At the current technology development range, batteries are at a disadvantage, as the more range is needed, the larger and heavier the battery is – meaning less cargo space."

Hydrogen Europe, *Long-term outlook on zero-emission mobility*, 2024

5.1 ELECTRICITY CAN AND SHOULD HEAVY-DUTY TRUCKS BE ELECTRIFIED?

ARE CHARGING OPTIONS COMPATIBLE WITH FREIGHT LOGISTICS?

Limited agreement

PRO

- High-powered charging stations and battery-swapping speed up charging.
- Recuperation and charging on-the-go can support batteries & increase range.

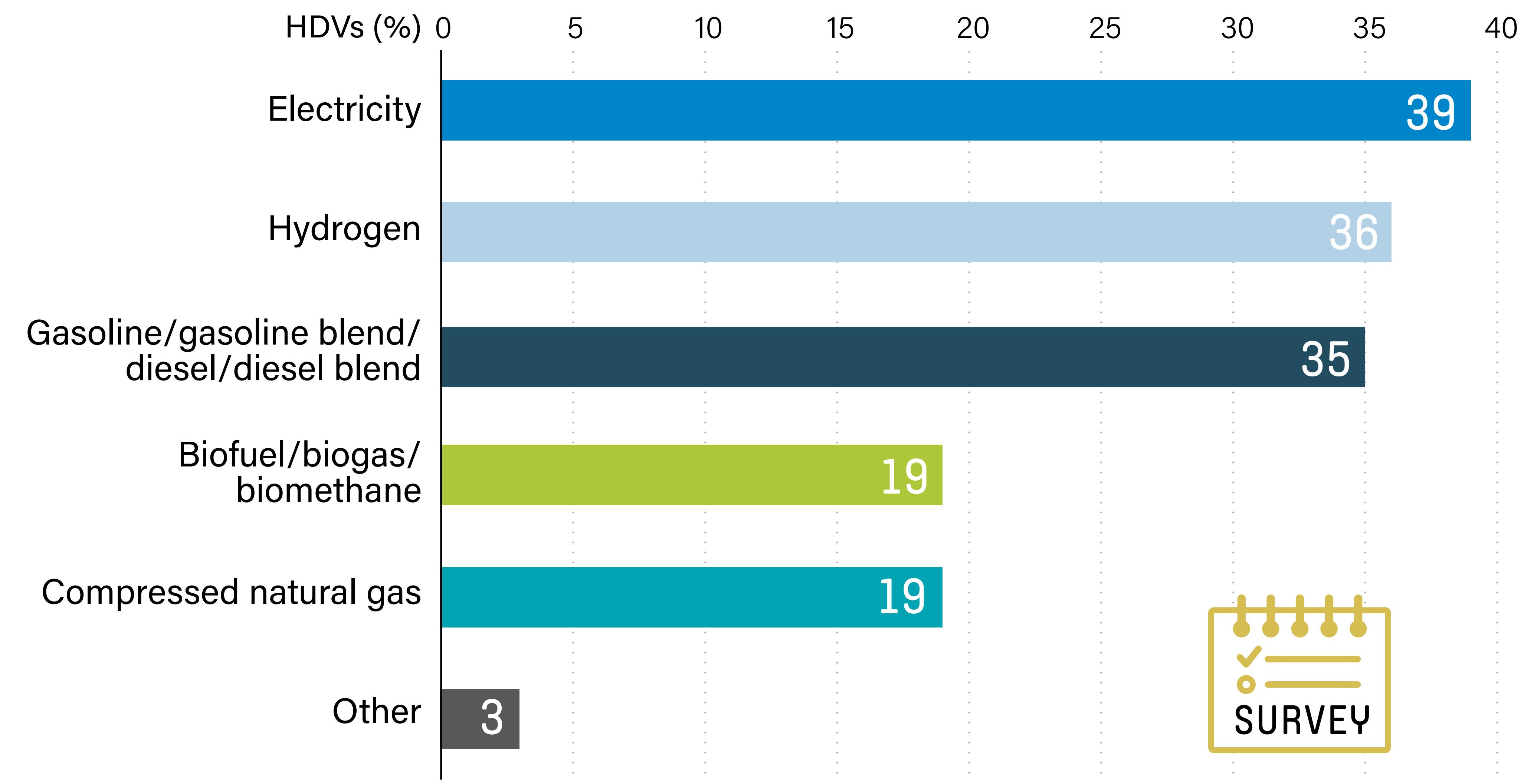
CON

- Charging time requirements make it impractical and uneconomic for freight.

> *"Battery swapping is rapidly gaining traction as an efficient alternative to traditional plug-in charging for commercial vehicle fleets."*
>
> **ICCT**, *How it works? Battery Swapping for Commercial Vehicles*, 2024

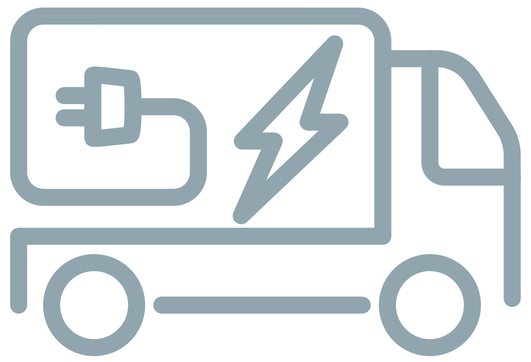
> *"Hydrogen trucks will dominate road freight in the future, due to the ability to refuel a truck in only a few minutes, compared to potentially hours for battery recharging."*
>
> **Hydrogeninsight**, *Transport*, 2022

Figure 22: Survey – What do you think will be the most consumed fuel type in the country for which you are providing information by 2050?



Note: Experts were able to name multiple fuels, which is why shares do not add up to 100%.

There is no clear agreement among experts regarding the most important fuel for heavy-duty trucks in the future. Many see electrification as the way to go, while others envisage hydrogen as the fuel of choice.



Availability of vehicles

In 2022, 60,000 medium- and heavy-duty electric trucks were sold worldwide, representing 1.2% of truck sales. China continues to dominate electric truck production and sales. Elsewhere, electric truck sale shares remain low across most major markets, with sales shares generally under 1%. However, the majority of trucks sold are light- and medium-sized, with 90% of trucks sold in China being under 4.5 tonnes gross vehicle weight.[114]

The IEA estimates that sales of electric and fuel cell heavy trucks would need to reach 37% by 2030 and 65% by 2035 to be on track to meet NZE ambitions by 2050.[115] The ITF estimates that a fleet share of 18% zero-carbon heavy trucks is required by 2035, but expected developments under current policies would only achieve around 9%.[116]

Developments are influenced by the availability of models for medium- and heavy-duty applications. The range of models has significantly increased in recent years. In 2022, more than half of the 220 new models entering the market were medium and heavy-duty trucks, bringing the total number of available models to 840. Of all models currently available on the market, over 90% are battery electric. Only 12 models for fuel cell heavy-duty trucks were available by 2022, with 8 more announced for 2023-2024.[117]

The cost of an electric truck varies depending on the class. As major advances in zero-emissions technology continue and more infrastructure is deployed, clean trucks can become cost-effective and more readily available.

According to the US National Renewable Energy Lab (NREL), zero-emission electric medium- and heavy-duty trucks can reach total-cost-of-driving parity with diesel counterparts for many vehicle types by 2030 and for all trucks by 2035.[118] To drive down the costs, governments are investing more in trucking innovation and next-generation clean technologies.[119]

BOX 5 ELECTRIFYING SHIPS

For maritime transport, electricity is being more widely used in pleasure boats and for short-haul shipping, such as ferries, using batteries or hybrid systems. Such vessels go short distances and can recharge frequently. There are over 70 such ferries in operation in Norway and more under construction.[120] Several ferry connections in Asia, the United States, Denmark and Sweden have also been electrified in recent years.[121] A key challenge for moving towards alternative drive technologies in shipping is the long lifetime of vessels. Cargo ships generally operate for 30 years, inland vessels for about 45 years and passenger ships often longer,[122] which leads to a slow turnover in stock.

For cargo transport, electric vessels are not yet common. In November 2021, the first fully electric – and potentially autonomous – container vessel, the Yara Birkeland, was launched with a battery capacity of 6.8 megawatt hours (MWh) and a carrying capacity of 120 containers.[123] In July 2023, an electric feeder container vessel was launched for use on the Yangtze River with 1,800 kilowatts (kW) of installed power and battery swapping technology. The vessel is set to cover up to 600 nautical miles. The construction of a second vessel started in May 2023.[124]

BOX 6 ELECTRIFYING AVIATION

In aviation, the key challenge in electrification is the weight of the batteries. Energy density in current battery designs limits the efficiency of electric aircraft.[132] This is one of the reasons why the net zero strategy of the International Air Transport Association (IATA) expects that 65% of emission reductions needed for net zero by 2050 will come from sustainable aviation fuels and only 13% from new technologies, such as electrification and hydrogen-based solutions.[133]

The ICCT estimates that currently available battery technology limits aeroplanes to a range of 200-500 km.[134] Similarly, the ITF estimates that battery electric aircraft could supply 18% of passenger-km for flights up to 500 km, but does not foresee any role in longer distances by 2050. The ITF projects a very limited role for hydrogen aircraft at this short distance with a share of 4% and an 8% contribution in the medium distance, covering 8% of passenger-km on flights between 500 km and 3,000 km.[135]

Several aeroplanes designed to carry small numbers of passengers over relatively short distances are under development[136] and, as of October 2022, efforts to develop electric aircraft were in process in Australia, Brazil, China, France, Germany, India, Indonesia, Japan, the Republic of Korea, the Russian Federation, the United Kingdom and the United States. In 2021, DHL Express ordered 12 electric aircraft to be used for cargo from US-based Eviation, which successfully completed the maiden flight of its commuter plane, Alice, in September 2022, and already had 253 aircraft orders valued at over USD 2 billion by May 2023.[137]

Challenges for hydrogen use in aviation include the needs for innovative fuel storage methods. So far, there are no commercial models available, but several companies are developing hydrogen-based aircraft. Airbus aims to bring a hydrogen-powered commercial aircraft to the market by 2035 with ranges of up to 2,000 km and a capacity of up to 200 passengers,[138] while a Dutch consortium plans to launch the first hydrogen-fuelled flight of 40-80 passengers as early as 2028.[139]

5.1 ELECTRICITY CAN AND SHOULD HEAVY-DUTY TRUCKS BE ELECTRIFIED?

Battery technology and range

More than 95% of heavy-duty trucks produced in China, the largest producer globally, were equipped with batteries incorporating LFP cathode chemistries. These are favoured due to their low cost and high lifetime mileage.[125] The average range of electric trucks produced in China exceeds 300 km.[126] Globally, the range of heavy-duty trucks has increased only marginally between models launched in 2019 and 2022.[127] However, Tesla launched its Semi truck with a range of up to 800 km in 2023, setting new standards, but not revealing the actual battery chemistry.[128]

A collaboration between truck manufacturer Scania and battery manufacturer Northvolt resulted in the development of a new lithium-ion cell with a declared lifetime of 1.5 million km, equivalent to a truck's entire lifetime mileage and produced using 100% renewable electricity. However, there is again no information on the actual battery chemistry to date.[129]

Unlike electric light-duty vehicles (LDVs), heavy-duty electric trucks usually require more than one battery pack. For example, a Volvo battery electric truck is currently fitted with five or six battery packs, each with a capacity of 90 kWh and a weight of 2.5-3 tonnes in total.[130] Batteries are supplied by Samsung SDI and use nickel, cobalt and aluminium (NCA) cathodes.[131]

Charging options

Traditional charging for medium- and heavy-duty vehicles (HDVs) is wired stationary. The available options are overnight slow charging and mid-trip fast and ultra-fast charging. Even more than for cars, time requirements for charging play a critical role for heavy-duty applications, as any additional charging time will impact the profitability of the vehicle. Even charging times of 30 minutes using fast or ultra-fast charging are not realistic during working hours, although breaks for drivers can be used. Such breaks are mandatory in many countries.[140]

The installation of appropriate high-capacity charging stations for rapid truck battery charging is key for the large-scale rollout of electric heavy-duty trucks. This remains a challenge, but many countries have programmes and plans to expand relevant infrastructure.[141] The European Union, for example, is planning to install more than 1,700 fast and ultra-fast (1 MW) charging points across Europe.[142] In North America, several pilot programmes are on the way, in particular along the Pacific Coast, aiming to enhance the fast-charging network for trucks. These programmes are often led by manufacturers. Funding programmes launched by some jurisdictions include financial incentives for truck charging. In China, incentives are not tailored for specific types of chargers but rather cover all types of vehicles.[143]

However, several alternative charging solutions are emerging:

- **Battery swapping:** Discharged batteries are replaced with fully charged ones, taking only a matter of minutes. Such systems are being commercialised in China, where they are typically offered under a battery-as-a-service (BaaS) business model. In 2022 alone, more than 12,000 battery swapping-enabled trucks were sold in China.[144] Outside of China, the deployment is still limited, although activities are increasing. In Australia, for example, Janus Electric offers conversions of diesel trucks with battery swapping systems[145] and truck maker Mitsubishi Fuso and swapping-station provider Ample plan to trial truck battery swapping in Japan.[146]
- **Connected on-road charging (catenary):** Electric road systems are used involving either conductive connections between the vehicle and road, or via overhead lines such as overhead catenary charging. Such systems would be most effective on heavily used freight corridors such as motorways and would reduce the need for battery capacity and recharging facilities. Electric road systems have been demonstrated in Germany and Sweden, and system pilots are being considered in China, India, the United Kingdom and the United States.[147]
- **Wireless in-road charging:** Batteries are charged by transferring electricity from magnetic coils embedded in the road to receiving coils fitted to EVs. The advantage of this technology is that it can also be used by electric cars, but its disadvantages include high infrastructure costs and additional space requirements for charging coils within trucks.[148]
- **Vehicle-integrated solar PV:** Solar PV systems are directly integrated into the vehicle. For trucks in particular, the generated electricity while on the road can help power auxiliary systems and extend travel range.[149]

SOCIAL AND ECONOMIC IMPLICATIONS

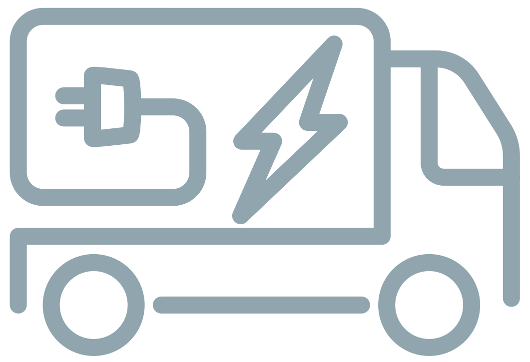
Enhanced electrification of heavy vehicles would impact the cost of transport, especially freight, and consequently end-user goods. The extent of the cost and in which direction it would go depend not only on the cost of technologies, but also on price developments for fossil fuels and electricity as well as policy frameworks, such as energy subsidies. Depending on these factors, potential price increases for transport would be reflected in consumer prices, which are likely to affect poorer households disproportionately.

GEOGRAPHIC DIFFERENCES

Countries with high import costs for fossil transport fuels (or biofuels) could benefit from increasing the use of locally produced renewable electricity for heavy-duty applications.

Countries with high potential for producing biofuels or hydrogen are likely to favour that as a solution. Countries with lower potential may not favour importing these fuels because this may be seen as an energy security risk, and they may have concerns about sustainability governance in regions beyond their control.

Countries with large areas would face higher challenges and upfront investment costs for the required installation of infrastructure.



5.2 HYDROGEN

Experts generally agree that a dramatic rise in the production and use of sustainably produced hydrogen – mostly produced by the electrolysis of water using renewable or other low GHG electricity (→ *see Figure 7*) – is essential to the energy transition, complementing electrification and other measures.

There is much less agreement about the role of hydrogen in the transport sector and for which modes and applications it is most appropriate.

Experts also hold different views on the feasibility of resulting trade and long-distance transport of hydrogen and hydrogen-based fuels under scenarios with high use. Additional concerns arise around the safety of hydrogen and ammonia. The latter two tension points are not strictly transport specific, but feature in many discussions in the sector and will influence decisions on future technology.

KEY TENSION POINTS

- **Is road transport the best application for hydrogen use?**
- **Are large-scale trade and transport of hydrogen practical?**
- **Are hydrogen and ammonia safe?**

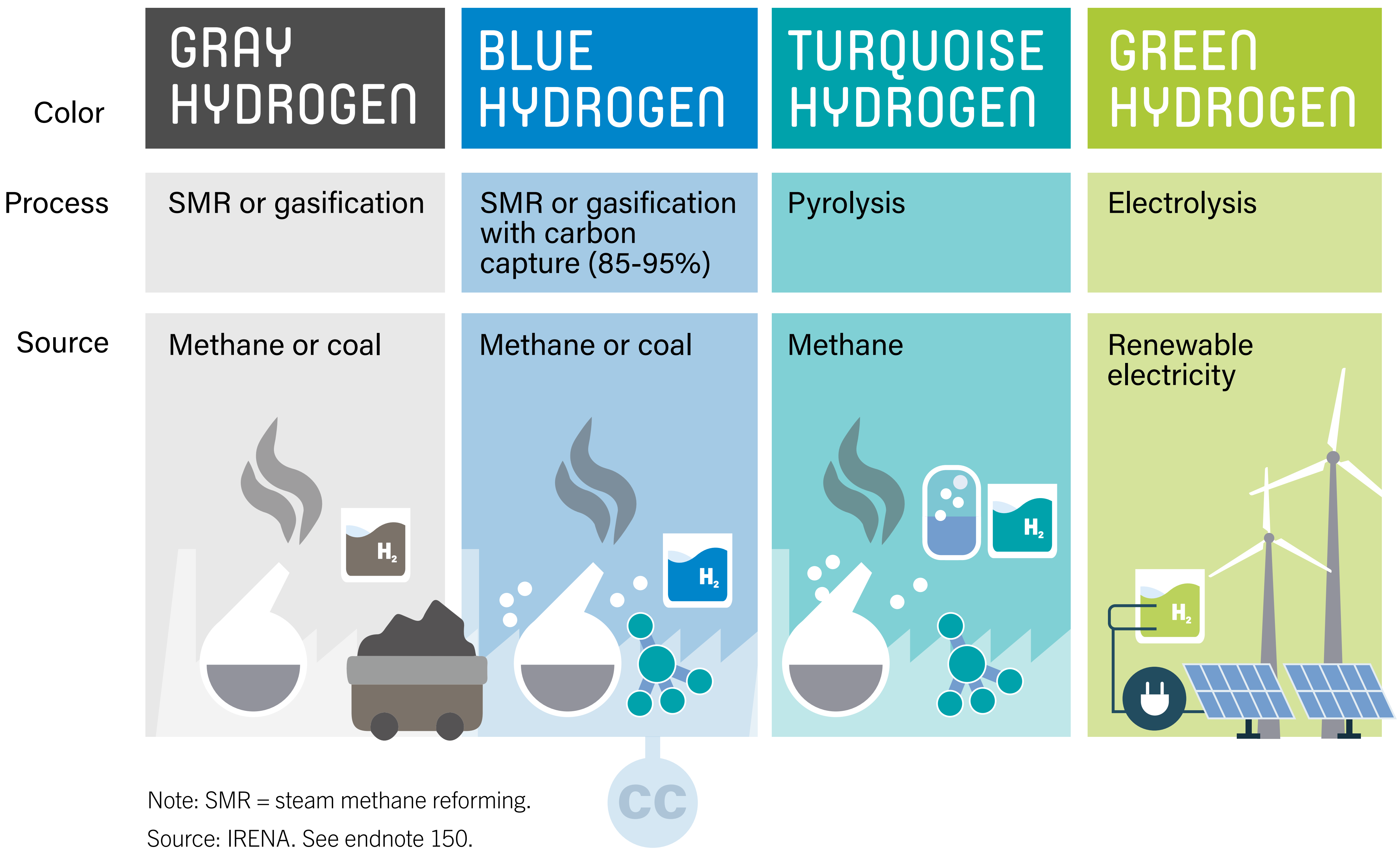
RELEVANT FACTS

- Hydrogen is usually classified into different colours (→ *see Figure 23*).[150] These colours represent different sources or processes used to make hydrogen, with different implications for the resulting CO_2 emissions.
- Green and turquoise hydrogen create no CO_2 emissions during production. The pyrolysis process in turquoise hydrogen production converts carbon directly to solid carbon black and thus does not need carbon capture, unlike blue carbon. Green hydrogen is produced based on renewable energy, mostly electrolysis using renewable electricity. However, other processes exist using biomass or biogases as a basis. Other colours – purple, pink and red – refer to processes based on nuclear energy.

The production of hydrogen through electrolysis is relatively energy inefficient. It takes three units of electricity to make one energy unit of hydrogen, with additional energy needed to compress hydrogen to allow its transfer by pipeline, and even more to convert it to its liquid form to allow long-distance transport.[151]

- There are many potential applications for hydrogen in addition to current uses. Apart from applications in transport, it can be used for heating, in various heavy-industry applications, and to provide storage in the power grid to address variable renewable electricity generation.
- Hydrogen can be used directly – in gaseous or liquid form – or be transformed to synthetic fuels or ammonia.

Figure 23: Selected shades of hydrogen



Note: SMR = steam methane reforming.
Source: IRENA. See endnote 150.

5.2 HYDROGEN

KEY DATA

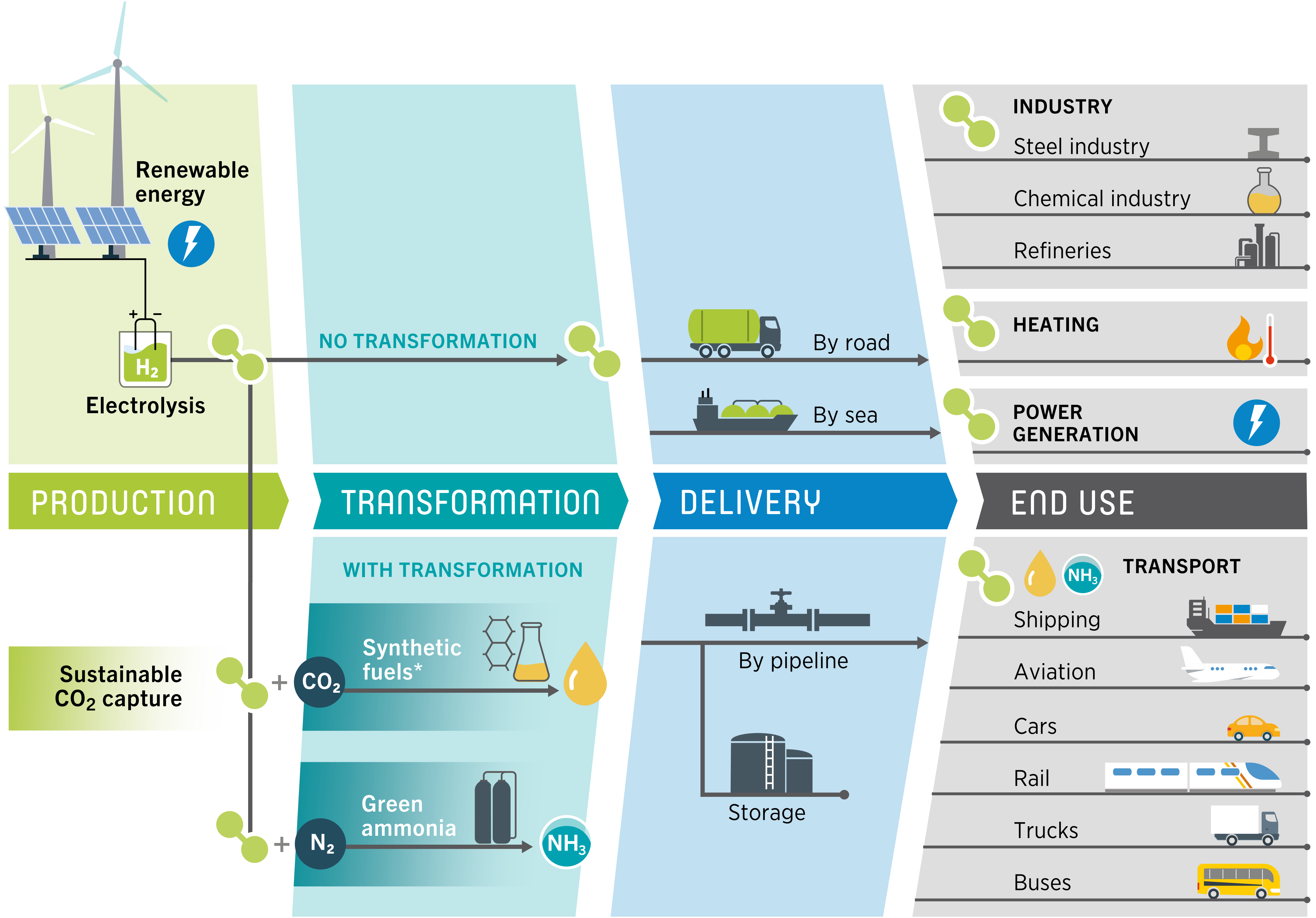
Hydrogen production and use

- In 2021, total global production was 94 million tonnes of hydrogen (Mt H_2), only 0.04% of which was produced by electrolysis.[152]
- In 2022, 99.9% of hydrogen was produced using fossil fuels,[153] resulting in GHG emissions of around 900 Mt CO_2e per year.[154]
- In 2021, around 60% of hydrogen was used in industry, mostly in the chemical industry for ammonia production, and most of the rest for refining. Only 0.1% was used for new applications, such as in heavy industry, transport, power generation and the buildings sectors or the production of hydrogen-derived fuels.[155]
- Despite the small absolute amounts of green hydrogen, on a year-to-year basis, its production increased by nearly 20% in 2021.[156]
- Electrolysis capacity expanded to 510 MW by the end of 2021, an increase of 210 MW, or 70% relative to 2020.[157]
- Today, hydrogen trade is limited to a few existing hydrogen pipelines and a few pilot projects to demonstrate hydrogen trade by ship. Ammonia and methanol are globally traded as feedstocks for industry.

Hydrogen uses in transport

- In 2022, the stock of FCEVs increased 40% compared to 2021, reaching over 72,000 vehicles globally.[159]
- About 80% of the FCEVs are cars, 10% trucks and almost 10% buses. In 2022, the fuel cell truck segment grew at a faster rate than cars and buses, increasing 60%.[160]
- The Republic of Korea is now home to over half of all fuel cell cars globally. Two-thirds of the additional 15,000 fuel cell cars that hit the road in 2022 were in the Republic of Korea. The United States holds the second largest FCEV stock, with over 15,000 FCEVs.[161]
- China dominates the heavy-duty fuel cell vehicle segments (trucks and buses). In 2022, China was home to over 95% of the global fuel cell truck fleet and almost 85% of the global fuel cell bus fleet.[162]

Figure 24: Renewable hydrogen economy: Production, conversion and end uses



Source: IRENA. See endnote 150.

5.2 HYDROGEN

IS ROAD TRANSPORT THE BEST APPLICATION FOR HYDROGEN USE?

Sustainable hydrogen can play a role in decarbonising many sectors:

- For power generation, reducing emissions from base load power through co-firing with coal[163] or helping to keep up generation levels when generation from variable renewables sources such as wind and solar are at low levels.
- For industrial processes, including for high-temperature applications such as steel manufacture.
- For heating buildings, replacing natural gas and making use of existing distribution infrastructure.
- For transport, being used across the whole spectrum of vehicle types. Hydrogen can be used in fuel cell-powered cars and light vehicles through to heavy road transport, rail, shipping and air travel (especially through the use of hydrogen carriers such as ammonia or synthetic fuels).

Some voices argue strongly for the widespread use of hydrogen, describing it as the "Swiss Army knife" for GHG reduction and believing that there are few technical limits to how much hydrogen could be produced, especially from wind and solar power and potentially from biomass.

Others argue that its use should be limited to those applications where it provides almost the only solution for reducing GHG, as the production of green hydrogen will be limited in the foreseeable future and existing hydrogen production needs to be replaced by sustainable alternatives first.[164]

For transport, the main controversy revolves around the question of whether the use of hydrogen in road transport is needed and desirable.

IS HYDROGEN SUITABLE FOR ROAD TRANSPORT?

Medium agreement
CON

PRO

Hydrogen derivatives can be used as fuels in existing engine designs.

Electrification will not be possible in remote regions.

"Hydrogen-based fuels...are easier to store and transport than pure hydrogen, and can often make use of existing infrastructure."

IEA, *Global Hydrogen Review*, 2023

CON

Major motor manufacturers are concentrating on BEVs.

High cost of vehicles and fuelling infrastructure.

"The Japanese car industry pushed fuel-cell cars, because they had R&D advantages to make hydrogen vehicles. But a fuel-cell vehicle is so expensive and difficult to introduce in the market. In the LDV segment, EVs are the mainstream."

Hironao Matsubara, Institute for Sustainable Energy Policies

IS HYDROGEN EFFICIENT AND AFFORDABLE?

Limited agreement
Location specific

PRO

Hydrogen trade allows low-carbon transport where domestic RE production is limited.

"Hydrogen and other low-carbon alternatives will be necessary for energy security when solar and wind capacity are not high. We will not be able to electrify everything by 2050. We will need alternative solutions to complement the electrification process like hydrogen, sustainable biofuels, low-carbon gaseous and liquid fuels."

Doug Vine, C2ES

CON

Hydrogen production is much less efficient than the direct use of electricity.

Cost are higher than direct electrification.

Hydrogen will be more effective in other hard to decarbonise sectors.

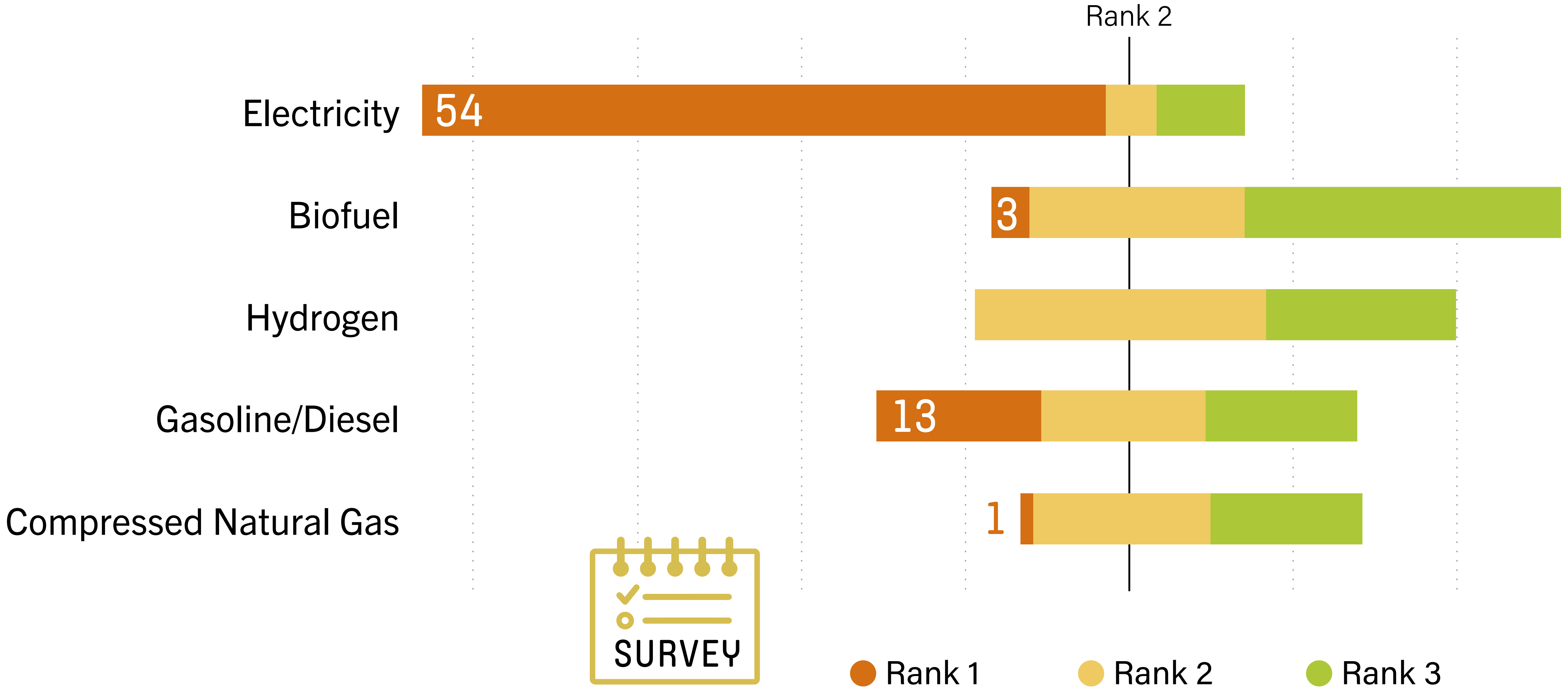
"We should focus on direct electrification first because conversion through H2 is poorly efficient. At least, hydrogen should only be used when electrification is really not possible."

Henrik Gudmundsson, CONCITO

"For hydrogen there is also the competition with other sectors such as industry and it is also poorly efficient."

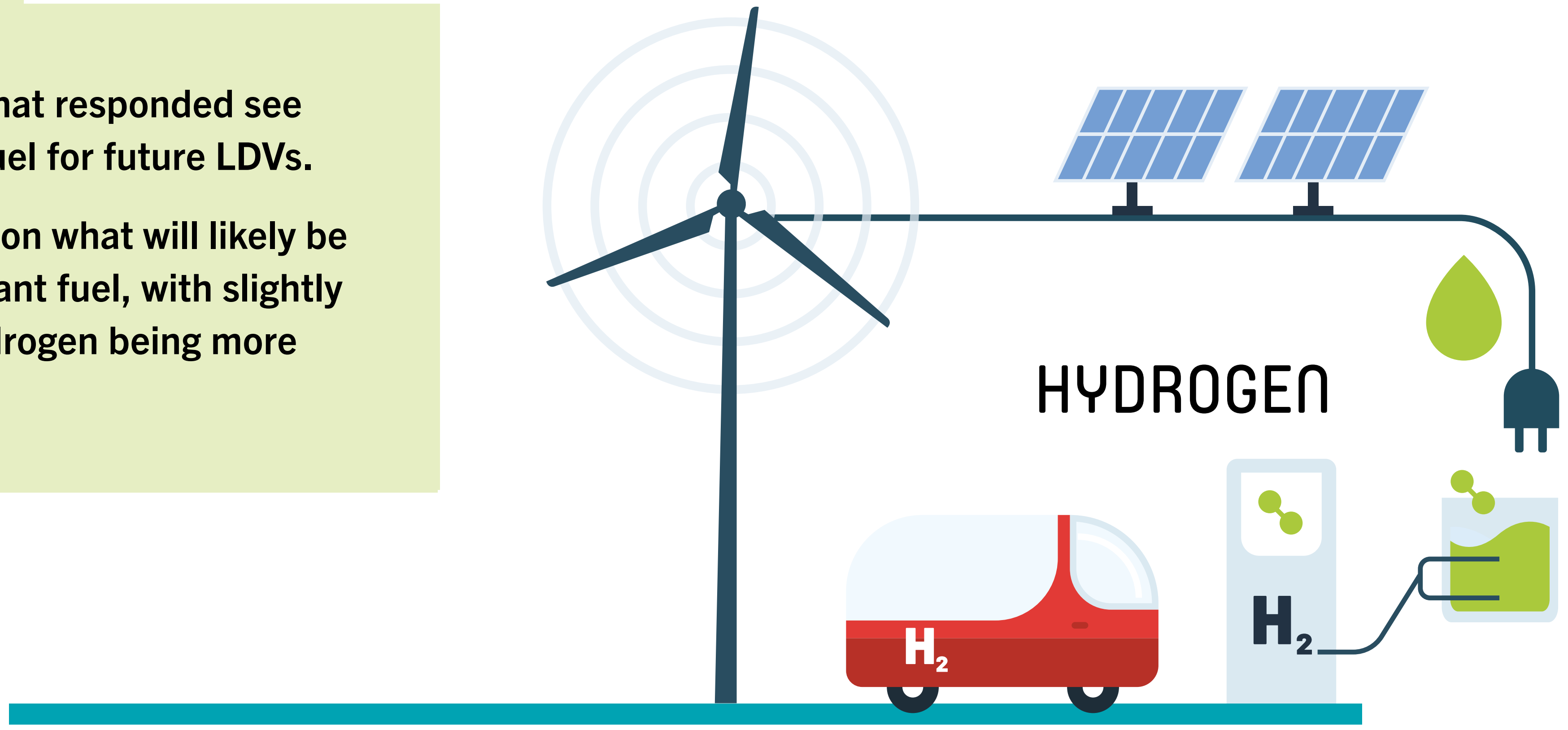
Oliver Lah, Wuppertal Institute

Figure 25: Survey – Please rank the share of fuel type for LDVs that you expect to see in the country for which you are providing information by 2050



Over 50 of the experts that responded see electricity as the main fuel for future LDVs.

There is less agreement on what will likely be the second most important fuel, with slightly more experts seeing hydrogen being more important than biofuels.



Efficiency, availability and cost of hydrogen

Both BEVs and FCEVs are far more efficient than using ICEs with hydrogen-based synthetic fuels. BEVs have a distinct advantage over FCEVs in that they store energy directly in their batteries without requiring an intermediate step (→ *Figure 26*).[165]

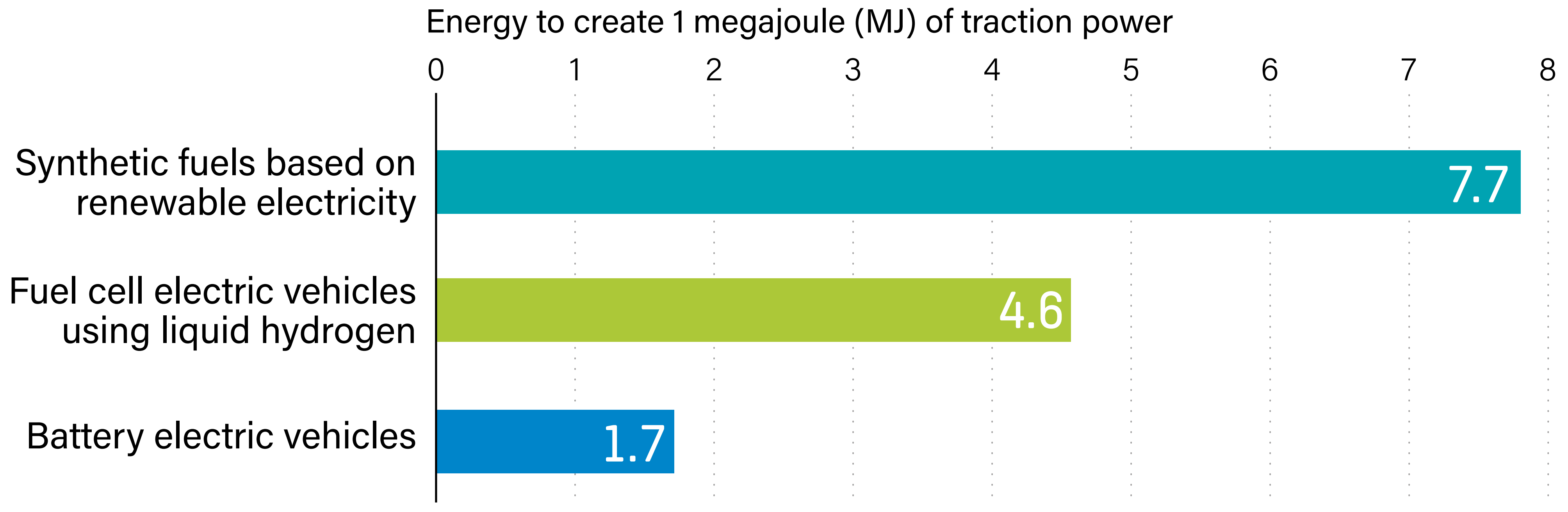
While the exact numbers may be up for debate, it is a fact that each conversion step for creating hydrogen from water using electricity and then converting it back to electricity or converting it even further to synthetic fuels comes with great energy efficiency losses. This means that electricity-based hydrogen production impacts the renewable electricity generation capacity required to meet the rising demand. This also influences the need for additional grid infrastructure and the grid design, which would be very different for a system with multiple new demand sources, such as BEVs, from a system with a limited number of high-demand sources, such as industrial-size electrolysers.

FCEVs, however, do offer upsides including reduced vehicle weight and, importantly for trucks and buses, increased range with a short refuelling time. The extra weight associated with the large batteries required for long-haul freight transport also reduces the amount of freight they can carry. Technology advancements in battery technology are anticipated to reduce battery weight allowing EVs to potentially carry weights similar to those carried by FCEVs or ICEs.[166] Synthetic fuels have the advantage of not requiring any changes to existing infrastructure and vehicles.

Depending on regional gas prices, the levelised cost of hydrogen production from natural gas ranges from USD 1 to USD 3 per kilogramme (kg). Using carbon capture, usage and storage (CCUS) technologies to reduce the CO_2 emissions from hydrogen production increases the levelised cost of production to around USD 1.5 per kg to USD 3.6 per kg. Right now, using electricity to produce hydrogen leads to cost ranges from USD 3.4 per kg to USD 12 per kg. However, in regions with excellent solar radiation, a further decline in the cost of electricity from solar PV could drive the cost of hydrogen production to USD 1.6 per kg.[167] This would be equivalent to USD 0.05 per kWh for an EV.

In transport, FCEV prices are still high. On average, hydrogen trucks are twice as expensive as their electric counterparts, hydrogen buses at least 10% more expensive and, as of 2023, the cheapest hydrogen passenger car was selling for USD 50,000 in the United States and Japan. Similar BEVs can be bought for less than USD 30,000 in the same markets.[168]

Figure 26: Individual and overall efficiency of cars with different fully renewable vehicle drive technologies



Source: SLOCAT. See Endnote 165.

Vehicles and infrastructure

As of the end of 2022, there were 72,000 hydrogen FCEVs on the road, about 20,500 of which were sold in 2022 (up 40%) and with 15,000 of those being cars. In comparison, 10.5 million EVs were sold in 2022 (up 55%). The market for FCEVs slowed during the first seven months of 2023, with sales falling by 9.6% on a year on-year basis. Japan saw the highest fall in sales, with a 63% reduction (from 642 units to 235 units). China witnessed the only growth market, with a rise of 66% (from 1,842 units to 3,073 units) from January to July 2023. In the Republic of Korea, FCEV sales dropped 38% during the same period, and the Republic of Korea saw its market share plummet from 52% in 2022 to 35% during the first seven months of 2023.[169]

Although passenger cars still represent a large portion of sales, some governments are abandoning subsidy supports for passenger cars and turning their focus to buses, vans, trucks and filling stations. The Republic of Korea's 2024 budget set out cuts to support for hydrogen-powered passenger vehicles but doubled its subsidies for hydrogen-powered buses.[170] In September 2023, the Netherlands announced an increase to its hydrogen mobility subsidy scheme from the initial EUR 22 million (USD 24 million) approved in 2022 to EUR 150 million (USD 163 million). The plan offers subsidies for up to EUR 300,000 (USD 326,000) per truck, van or bus, and EUR 2 million (USD 2.17 million) per filling station.[171]

Estimates of existing refuelling stations for hydrogen vary. The IEA estimated that there were around 1,100 stations in operation as of June 2023,[172] while the H2 Stations database shows 921 stations as of February 2024,[173] with the difference likely owing to high uncertainties around the actual numbers in China. In 2023, the majority of new stations were equipped to refuel passenger vehicles, trucks and buses. Concrete plans are already in place for 338 additional refuelling station locations worldwide outside of China,[174] but there are also closures of existing stations, such as the example in Denmark (→ *see Chapter 4.1*).

Additionally, Shell closed all but one of its hydrogen stations for cars in California,[175] and closures for car refuelling stations in the United Kingdom continue,[176] with companies increasingly focusing on refuelling stations for trucks and busses.

GEOGRAPHIC DIFFERENCES

Most countries are concentrating their efforts on BEVs. However, some countries – notably Japan and the Republic of Korea – still have strong interest in hydrogen for transport and in fuel cell vehicles. This may be because of their perceived limited scope to produce renewable electricity and their access to green hydrogen in large quantities from the Pacific region and, notably, Australia.

In regions where electricity demand is stable or falling (such as North America or Europe), an increase in demand for direct electrification of transport can probably be absorbed in the short term.

In regions where electricity demand is rising quickly as populations and living standards are rising (such as Southeast Asia), additional electricity demand from transport will be more difficult to integrate.

5.2 HYDROGEN

ARE LARGE-SCALE TRADE AND TRANSPORT OF HYDROGEN PRACTICAL?

Large-scale use of hydrogen will require very significant trade and transport of hydrogen. Experts agree that production of the necessary renewable power for hydrogen production at low costs is constrained in many of the large demand centres, including Japan, the Republic of Korea and Europe.

For these locations, some experts argue that it will be cheaper to import much of their hydrogen requirements from places with high low-cost renewables potential such as Africa, Australia and South America. They expect that production capacity could outstrip local demand in these areas.[177] Additionally, hydrogen needs to be transported within countries from production points or ports to end users.

Experts expressed widespread agreement that hydrogen pipelines and trucks are the best solutions for transport over smaller distances. However, when quantities or distances become greater, other techniques are needed. In principle, there are three options for long-distance transport: ammonia, liquid organic hydrogen carriers (LOHCs) and liquid hydrogen.

IRENA predicts that about one-quarter of total global hydrogen demand could be satisfied through international trade by 2050.[178] Similarly, the IEA predicts that more than 20% of merchant demand for hydrogen and hydrogen-based fuels will be met through international trade by 2030.[179]

However, views differ about the practicality and costs of such long-haul transport. Some argue that hydrogen trade offers cheap renewable fuel options for countries with lower renewables potential and economic opportunities for those with a lot. Others find that the economics do not stack up and that large-scale trade will lead to new energy dependencies.

Overall, views differ on how practical and desirable the trading of hydrogen and transporting it over large distances is.

DOES HYDROGEN TRADE PROVIDE AN ECONOMIC OPPORTUNITY?

Medium agreement
CON

PRO

- Hydrogen production can be an important source of revenue and employment for exporting countries.

CON

- Long-distance transport of hydrogen and derivatives is too inefficient and costly.
- Large-scale trade in hydrogen can lead to energy security issues.

> *Hydrogen can awaken the biggest economic opportunity of our lifetime, create countless skilled jobs.*
>
> **Hydrogen Council**, *Why Hydrogen?*, 2023

> *Because of its unusual physical properties, some estimates indicate that hydrogen liquefaction uses up to 40% of its energy content (compared to 10% for LNG), and that ship costs would be higher than those used for LNG because of the lower temperature that liquid hydrogen must be stored at. Together, these factors, it is argued, render long-distance hydrogen transport inefficient and very expensive.*
>
> **BloombergNEF**, *The Unbearable Lightness of Hydrogen*, 2022

IS SUFFICIENT LOCAL RE POWER GENERATION FEASIBLE AND ECONOMIC?

Limited agreement
Location specific

PRO

- Not all countries have the local capacity to produce enough renewable electricity for transport while meeting overall electricity demand.
- It is better to produce green hydrogen in countries with high potential for low-cost renewable electricity.

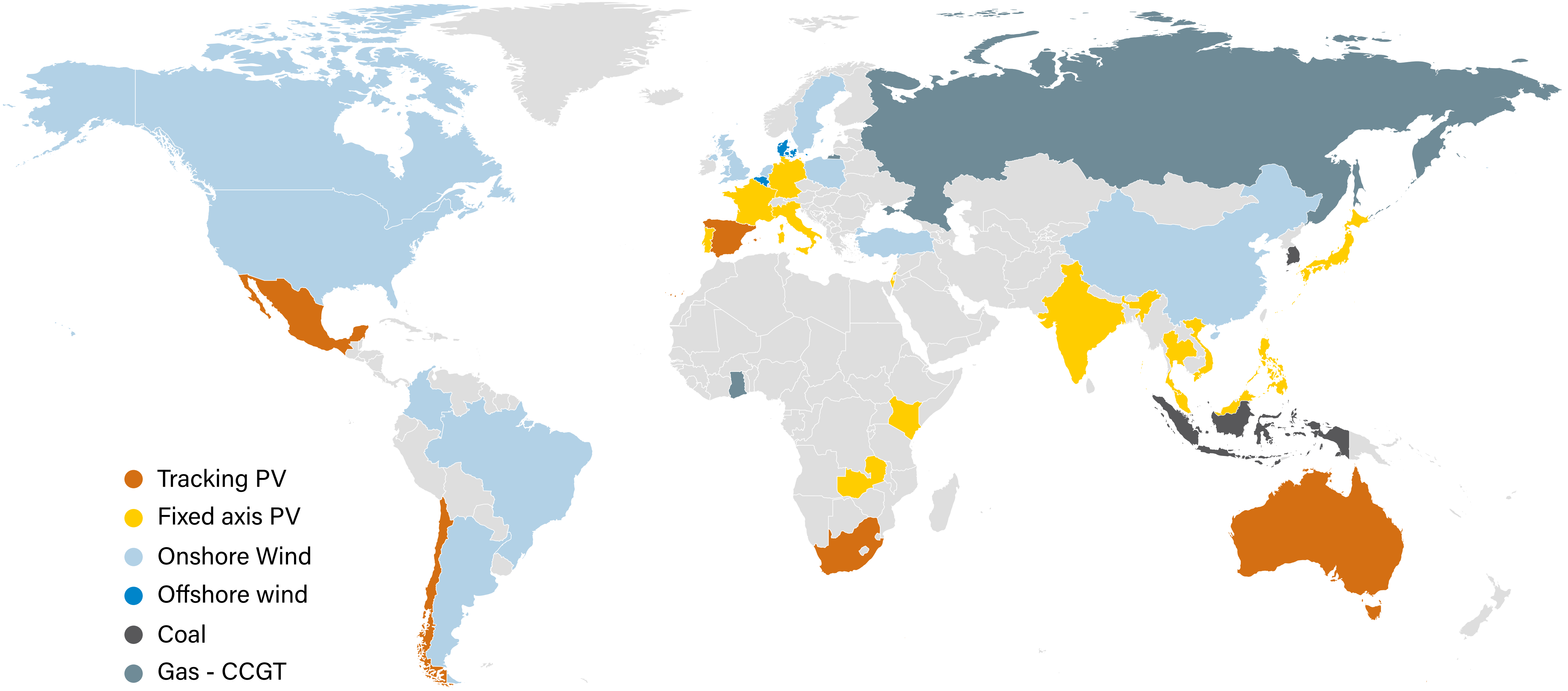
CON

- Hydrogen and renewable electricity should be used locally first.
- Hydrogen production for trade can affect energy access for people in the producing country.

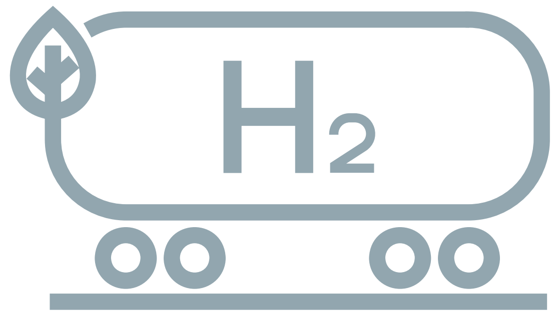
> *Hydrogen is an important ingredient in future economy: it is a storable form of renewable energy. We can store wind and solar in hydrogen. We can use more hydrogen and less carbon for cleaner fuels.*
>
> **Henrik Gudmundsson**, CONCITO

> *Energy access is a fundamental problem which could be solved by off-grid renewable generation. Charging infra will depend on economic development (ability to pay) of the region and also on the energy production.*
>
> **Warren Ondanje**, Association for Electric Mobility and Development in Africa

Figure 27: Countries where new-build solar and/or wind are cheaper than new-build coal- and gas-fired power, H1 2023



Note: The map shows technologies with the lowest LCOE excluding subsidies and grid connection costs and includes a carbon price where applicable.
Source: BloombergNEF. See endnote 181.



Local renewable power generation potential, local demand and renewable energy cost

Potential and cost

Looking at global renewable energy potential, it becomes apparent that the cost of production of renewable electricity can vary significantly depending on the location. New-build renewables are becoming the cheapest energy resources in most major economies.[180] However, this is a very dynamic process. With decreasing costs for renewable technologies and increasing costs for fossil fuels in many countries due to carbon pricing or reduced subsidies, renewables have become the most competitive solutions in many countries. In Japan, for example, coal remained the cheapest option for electricity generation in 2022. In 2023, for the first time, solar PV constituted the cheapest option (→ *see Figure 27*).[181]

The high level of interest in hydrogen can be attributed to the possibilities it offers in terms of transporting renewable energy from areas with a low cost of renewable electricity generation to areas of high demand.

Local electricity demand

In 2022, 59 countries had no universal access to electricity, and around 770 million people had no electricity access.[182] Global electricity demand was set to increase by slightly less than 2% in 2023, down from a rate of 2.3% in 2022. Assuming an improving world economic outlook, demand growth is expected to pick up again in 2024, rebounding to 3.3%.[183]

Electricity demand growth is mostly driven by the electrification of energy systems as efforts ramp up to reduce emissions, by the increasing use of indoor cooling as temperatures climb, and by robust demand growth in emerging and developing economies.[184]

However, clear differences exist across regions and among developed countries, emerging economies and developing countries. In most developed countries, there are few people without access to electricity, and demand based on income levels is already high. Growth is mostly due to increasing electrification across sectors, and additional demand from the decarbonisation of transport will largely need to compete with other sectors – even more so if electrification is not direct.

In emerging economies, further demand comes from increasing income levels and associated growth in energy use. Developing countries additionally often still need to provide basic access to parts of their population. This varies by region, with more than 80% of the global population lacking access to electricity living in sub-Saharan Africa.[185] In such cases, producing extra energy for export can compete with increasing local energy demand and the need to decarbonise locally consumed electricity.

Cost and economics

Cost of transporting hydrogen

According to IRENA, in a 1.5°C future, around 25% of hydrogen could be globally traded: half in the form of ammonia transported by sea, and half through gaseous hydrogen pipelines concentrated in Europe and Latin America. Around 70% of hydrogen traded would be used as feedstock and fuel, rather than reconverted to hydrogen following transport.[186] In the IEA NZE Scenario, more than 20% of merchant demand for hydrogen and hydrogen-based fuels is met through international trade by 2030.[187]

Currently, the transport cost of hydrogen by ship ranges from USD 6.5 per kg of H_2 to USD 17.3 per kg of H_2.[i] Furthermore, transport costs depend on the size of the project and the distance that needs to be travelled. With increased scale, costs could potentially be reduced to USD 1.6-2.7 per kg of H_2. For short distances, pipelines and liquid hydrogen are to be favoured, while for long-distance transport, transport via ammonia is the preferred choice.[188] Shipping costs are expected to decrease in the coming years. However, the conversion of gaseous hydrogen to more energy-dense carriers (liquid hydrogen, ammonia or other LOHCs) and back to gaseous hydrogen will still constitute a large share of the total cost.[189]

5.2 HYDROGEN ARE LARGE-SCALE TRADE AND TRANSPORT OF HYDROGEN PRACTICAL?

According to BNEF, whichever way you look at it, the minimum cost of internationally traded hydrogen is between USD 3 per kg and USD 5 per kg.[190]

Indeed, other solutions need to be considered when weighing the different options for decarbonisation: ultra- and high-voltage direct current (DC) cables are becoming more cost-competitive to build, and the cost of locally producing hydrogen in areas where renewable energy is relatively more expensive can become the preferred option in the medium to long term (→ *see Figure 28*).[191]

Local industry development

Many countries see an opportunity to build up local industry around green hydrogen production and create new jobs and added value for their economies. The Moroccan Ministry of Energy, Mines and Environment, for example, set out a roadmap on green hydrogen in 2021 under the National Hydrogen Commission (created in 2019). The country is expecting demand of up to 30 TWh by 2030, which would double its current electricity demand, and reach 307 TWh by 2050.[192]

The Chilean government announced its hydrogen strategy in 2020. It aims to build on the country's renewable energy potential to develop local and export markets for green hydrogen with an estimated increase of renewable energy capacity from 13 GW in 2023 to 300 GW in 2050.[193] The European Union aims to reach 10 million tonnes of domestic renewable hydrogen production and 10 million tonnes of imported renewable hydrogen by 2030 in line with the REPowerEU Plan.[194]

Australia had the largest number of announced renewable hydrogen plants worldwide as of 2022; due to its abundant solar and wind resources, the country is expected to see some of the lowest levelised costs for producing renewable hydrogen by 2050.[195] China was the largest producer of hydrogen in 2022, at around 25 million tonnes.[196] The Chinese government has laid out a medium and long-term development plan for hydrogen (2021-2035), with the goals of bringing 50,000 FCEVs onto the road by 2025; producing green hydrogen using renewables to reach 100,000 to 200,000 tonnes annually by 2025; and using clean hydrogen in energy storage, electricity generation and industry.[197]

SOCIAL AND ECONOMIC IMPLICATIONS

The large-scale production of hydrogen in developing and emerging countries for export – mostly to developed nations – raises concerns regarding social equity.

Most developing countries have growing energy demand and are facing challenges in decarbonising their own energy systems. The question is raised as to whether additional capacity should first ensure local access to clean energy sources before exports are initiated.

Additional concerns are raised about the water demand for hydrogen electrolysis. Many countries with ample solar power potential have scarce water resources, which can lead to demand competition between hydrogen production, drinking water, agriculture and other uses.

GEOGRAPHIC DIFFERENCES

Potential exporting countries and regions are starting to gear up for hydrogen production and trade, while some countries that expect to have considerable hydrogen import requirements are also working to secure long-term supplies.

Between 2020 and 2021, 80 announcements were made for projects or collaborations that relate to global hydrogen or ammonia trade. Based on these announcements, the most active prospective importers are Germany, Japan and the Netherlands, and the most active prospective exporter is Australia.[198]

i USD 6.5 per kg of H_2 for LOHC, USD 8 per kg H_2 for ammonia, USD 17.3 per kg H_2 for liquid hydrogen.

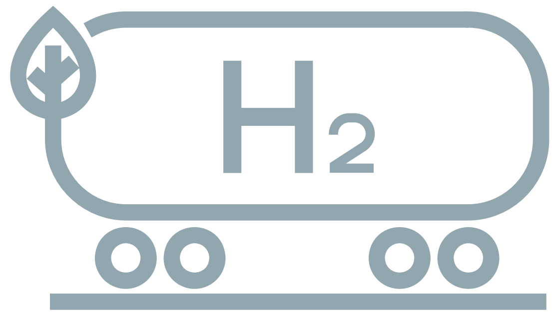
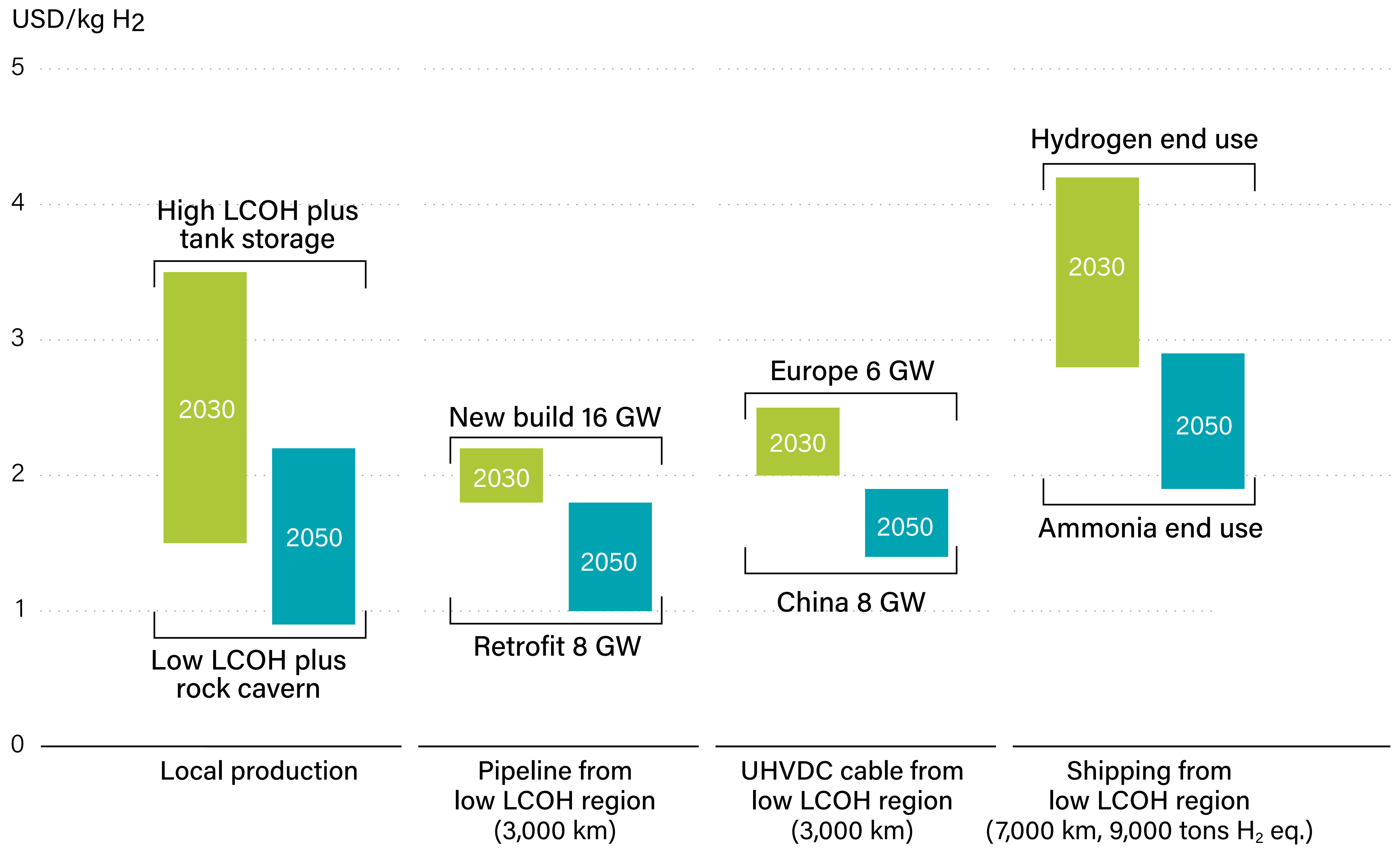


Figure 28: Economics of delivered hydrogen



Note: LCOH = levelised cost of hydrogen. UHVDC = Ultra High Voltage Direct Current

Source: Agora. See end note 191.

5.2 HYDROGEN

ARE HYDROGEN AND AMMONIA SAFE?

By their nature, all fuels have some degree of danger associated with them. The most obvious is from their desired property of being flammable and potentially explosive. If this happens outside the intended use, it can cause death, injury and damage. Additionally, fuels may have toxic properties that can affect human health and the environment if the fuel is released into the environment, for example through leakage, spills or accidents.

This applies to fossil fuels as well as to many renewable fuels, except for electricity, which has its own, but different, safety concerns. Drop-in fuels and biofuels have largely the same properties as their fossil fuel counterparts, so the risks involved are the same and well understood.

The risk profile is different for hydrogen and ammonia as energy carriers and fuels for transport. While both are being widely used today in chemical and industrial processes, we have little experience in their use as transport fuel.

Some experts argue that this new application requires a new and widespread infrastructure. With larger volumes being handled and many more users handling these substances, the risk is increased. Others focus on the existing experiences with the fuels and argue that this expertise can be used in the scale-up of operations.

Views vary on how safe extensive transport infrastructure and trade of hydrogen and ammonia are.

IS HYDROGEN SAFE REGARDING LEAKAGE & EXPLOSIVENESS?

Limited agreement

PRO

- Because hydrogen is much lighter than air, it dissipates rapidly when released.
- Hydrogen-based drop-in fuels have the same properties as the fuels they replace.

CON

- Hydrogen has a lower autoignition temperature than conventional fuels.
- Hydrogen is highly combustible.
- Hydrogen can easily cause material failure, which in turn can lead to leakage.

> *“As more and more hydrogen demonstrations get underway, hydrogen's safety record can grow and build confidence that hydrogen can be as safe as the fuels in widespread use today.”*
>
> **EIA**, *Safe Use of Hydrogen*

> *“One safety concern with hydrogen is that it takes very little energy to ignite.”*
>
> **Center for Hydrogen Safety**, *Hydrogen Flammability*

ARE HYDROGEN AND AMMONIA SAFE REGARDING TOXICITY?

No agreement

PRO

- Hydrogen is non-toxic.
- Ammonia has been produced, transported and used for a long time.

CON

- Ammonia is highly toxic and transport poses risk to human health and biodiversity.
- There is limited experience with highly distributed handling of ammonia.

> *“The level of maturity of the process for ammonia production, handling and supply has been optimized for over a century.”*
>
> **V. Negro et al.**, *The Potential Role of Ammonia for Hydrogen Storage and Transport*, 2023

> *“Bunkering it ‘wherever’ and burning it in a cramped engine room comes with much greater risks for workers and aquatic life compared to ‘just’ loading it as a commodity. There is limited experience with a highly distributed handling of ammonia, especially as a fuel.”*
>
> **Stefanie Sohm**, Kühne Foundation

Leakage and explosiveness

Hydrogen is the simplest and lightest element; it has low volumetric energy density and a very low boiling point. Storing hydrogen becomes a challenge because it requires low temperature or high pressure. Liquid hydrogen boils at -252.8°C, which means that it needs to be stored at low temperatures. Storing hydrogen as a gas also has challenges because it typically requires the use of high-pressure tanks (350-700 bar).[199]

The safety issues associated with hydrogen are similar to those of other flammable gases.[200] Hydrogen has a low minimum ignition temperature, but leaks of hydrogen are safer than those of hydrocarbon-based fuels such as gasoline because they rise rapidly and dissipate quickly into the atmosphere. Hydrogen can easily cause material failure, which in turn can lead to leakage. If a leak is unidentified and the gas collects in a confined area, it can eventually cause an explosion. In hydrogen pipelines and steel storage vessels, hydrogen molecules are prone to react with metals, causing failure of the pipeline or storage vessel.

Even without ignition sources, high-pressure hydrogen leakage may cause spontaneous combustion and explosion. In 2019, there were several hydrogen explosions in Norway, the Republic of Korea and the United States. The explosion of a hydrogen fuel storage tank in the Republic of Korea caused two deaths and six injuries.[201] The causes of the accidents were hydrogen cloud explosions and chain explosions caused by hydrogen spontaneous combustion. These once again caused widespread public concern about hydrogen energy safety.[202]

Moreover, hydrogen burns with a nearly invisible flame that requires special flame detectors. Hydrogen is currently used in a variety of common applications. Staff handling hydrogen need rigorous safety training, and systems need regular testing for leaks and other potential problems, ensuring it is produced, stored and dispensed safely. Rigorous safety regulations, safety codes and standards, the use of specific equipment to detect leakage, and the availability of specific fire extinguishers for hydrogen flames can mitigate, although not eliminate, such risks.[203]

While hydrogen itself is not a direct GHG, its chemical reactions change the abundance of the GHGs methane, ozone and stratospheric water vapor, as well as aerosols, and thus affect global warming indirectly. A recent Nature paper estimated a Global Warming Potential of 11.6,[204] indicating that hydrogen leakage could dramatically reduce the GHG benefits of hydrogen use.[205]

Ammonia is colourless and characterised by a pungent and distinctive odour, perceptible by humans at low concentrations, which makes it easy to detect leaks. The risk of explosions generated by ammonia is lower than for traditional fuels, owing to its narrow explosion limit.[206] It is also easier to store than hydrogen, with storage conditions similar to those of liquefied petroleum gas (LPG).[207]

Ammonia is also corrosive and will react with metals, which needs to be considered in designing fuel systems.[208] However, even if the explosion risk is lower than traditional fuels, the risk remains, as does the risk of fire.[209] Incidents of combustion and explosion of ammonia have been limited over the last decades, but with projected increases in its trade and use in vessels as fuel, experts expect an increase in such incidents.[210]

Toxicity

Hydrogen is not toxic, unlike conventional fuels. A hydrogen leak or spill will not contaminate the environment or threaten the health of humans or wildlife. In addition, because hydrogen is much lighter than air, it dissipates rapidly when it is released, allowing for relatively rapid dispersal of the fuel in case of a leak.

Transporting hydrogen using a LOHC or in liquid hydrogen form does not present toxicity concerns. Concerns do arise regarding environmental effects in the case of LOHC and cost and energy inefficiencies for both carriers.

Ammonia also has disadvantages. Although the infrastructures for producing ammonia are in place, ammonia is a toxic substance that, if it leaks, has a negative impact on air, soil and water quality as well as the health of people living in the vicinity of the leak.[211] Even in low concentrations, inhalation or contact with ammonia can cause burns, cough and irritation, and blindness; high levels can be fatal.[212]

Increasing the transport of ammonia will increase the likelihood of accidents, both on land and at sea. Spills at sea can be particularly difficult because the gas reacts with condensation in the air to form a toxic mist that does not dissipate easily and can harm personnel on the vessel. Additionally, any ammonia leaking into the water can kill sea life in a wide area, especially fish, and threaten important coastal ecosystems, such as mangroves and coral reefs, if spills occur in their vicinity.[213]

5.3 BIOFUELS

Biofuels can be used as fuel in most transport vehicles. Most biofuels are currently used in road transport, but there is growing attention to the use of these fuels in the aviation and shipping sectors.

Biofuels can be used in existing engines and fuel distribution systems and so can be deployed rapidly.

The most contentious topic regarding biofuels is the sustainability of their production and use. Sustainability concerns revolve around the actual GHG savings that can be achieved and the impact of biofuels on biodiversity, air quality, water and food availability.

KEY TENSION POINTS

Do biofuels lead to real GHG savings?

Are large-scale biofuel production and use sustainable?

Is sufficient sustainable biomass available without impacting food supply and security?

RELEVANT FACTS

- Many routes are available to convert biomass feedstocks to biofuels (→ *see Figure 7*).
- Most biofuels today are produced from sugar and starch crops, vegetable oils, or animal fats. The most common routes are:
  - The sugars within crops such as sugarcane, corn, wheat and other cereal crops are extracted and then converted by fermentation into ethanol.
  - Vegetable oils or animal fats (including waste products such as used cooking oil) are chemically treated to produce biodiesel.
  - Vegetable oil-based feedstocks can also be reacted with hydrogen to produce hydrocarbons, which are direct replacements for diesel (called HVO, HEFA or renewable diesel) or other fuels, including LPG or sustainable aviation fuel (SAF).[i]
  - Biogas and biomethane[ii] are produced by the digestion of organic wastes.
  - A range of options to produce transport fuels from lignocellulosic residues such as crop residues (sometimes described as advanced biofuels) are being developed and commercialised but are not yet contributing significantly to fuel supplies.

Some fuels (biodiesel and ethanol) are usually used in a blend with diesel or gasoline fuels with no engine changes and at higher concentrations would require some minor engine changes. Others (drop-in fuels such as HVO, bio-jet and biogasoline) have very similar properties to fossil fuels and can be used alone.

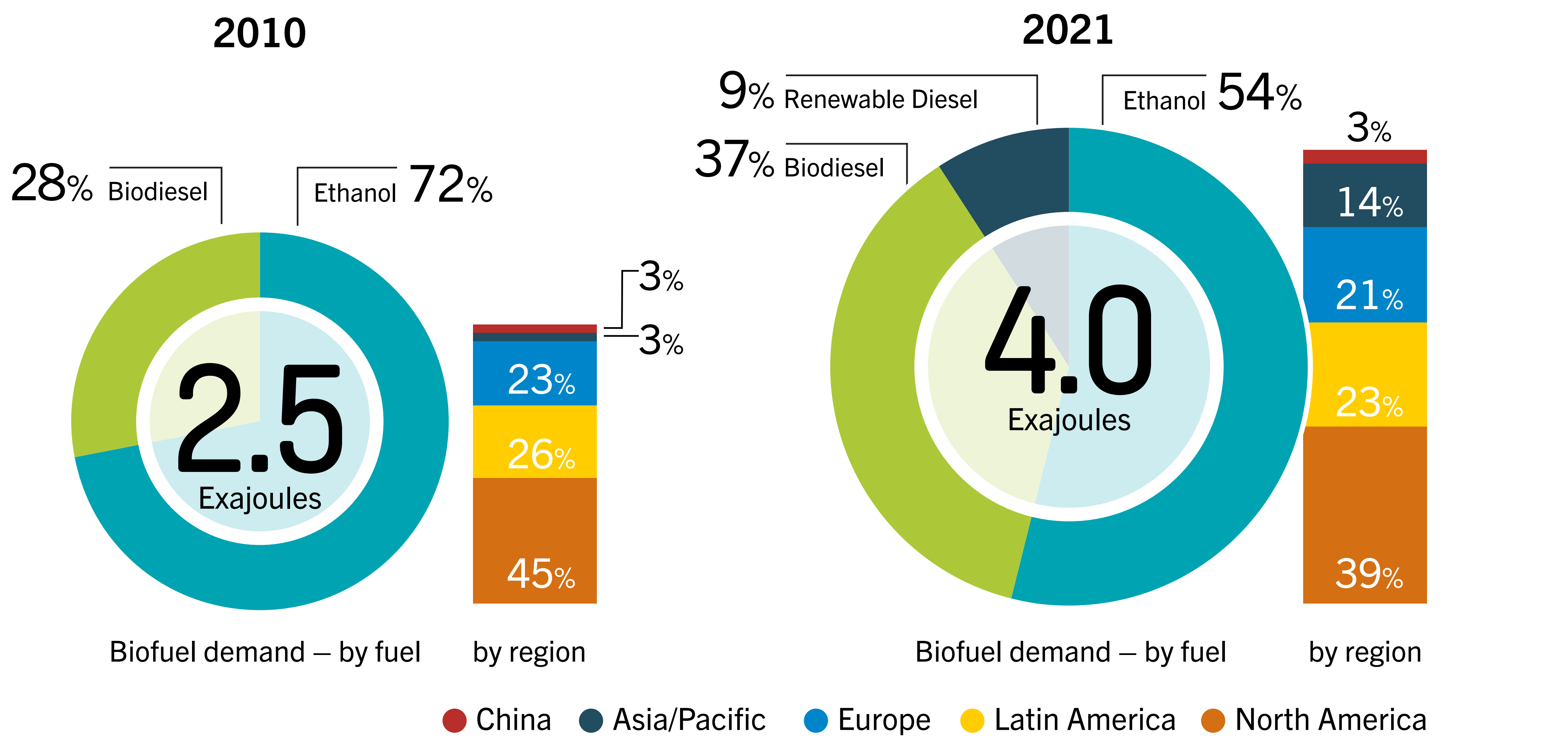
i SAF is also known as bio-jet.

ii Also known as renewable natural gas (RNG).

KEY DATA[214]

- Bioenergy currently provides 12.3% of global energy supply, with 6.7% of this coming from the traditional use of biomass for cooking and heating in developing countries, which is generally considered to be unsustainable.
- Modern and efficient forms of bioenergy provided 5.6% of global energy supply in 2022. This is principally used for heating, where it provides 7.9% of energy requirements, with smaller contributions to electricity generation (2.4% of generation) and to transport energy (3.6%).
- Global biofuel demand reached 4.1 EJ in 2022, representing over 3.5% of global transport energy demand, mainly for road transport.
- The use of biofuels has expanded at nearly 6% a year for the past five years, except in 2020 (due to impacts of the Covid-19 crisis on overall transport demand).
- Advanced renewable diesel and SAF represented only 8.7% and less than 0.1% of global biofuel production in 2021, respectively.
- The production of ethanol is concentrated in Brazil and the United States, which produce 80% of global supply between them. Biodiesel production is more widely dispersed, with Brazil, the European Union, Indonesia and the United States being major producers (→ *see Figure 29*).[215]

Figure 29: Global biofuel demand by fuel type and region, 2010 and 2021



Source: IEA. See endnote 215.

5.3 BIOFUELS

DO BIOFUELS LEAD TO REAL GHG SAVINGS?

Bioenergy systems usually produce CO_2 at their point of use, when the fuels are combusted, releasing energy. However, they are widely considered as renewable energy sources because these emissions form part of a natural cycle, where CO_2 emissions are removed from the atmosphere during the growth of biomass. In contrast, fossil oil and gas use releases CO_2 from the fossil storage. Bioenergy production and use therefore are considered to have much less impact on global GHG levels than the use of fossil fuels. However, this rationale is not universally accepted.

The GHG benefits of using bioenergy are reduced when bioenergy production and use lead to changes in carbon stocks in soils or vegetation or affect the ways in which the carbon cycle normally operates. An example of this is when forests are cleared to make space for agricultural areas to produce biofuels. These biogenic emissions are more difficult to understand and quantify than the supply chain emissions, and there is more controversy about their impacts and how best to mitigate them.

Views and opinions differ about whether different biofuels can achieve substantial GHG savings compared to fossil fuel alternatives.

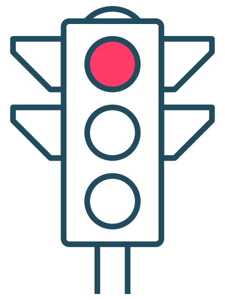
> *Biofuels, if produced sustainably, can have an almost carbon neutral balance and, if BECCS is included, even negative carbon footprint.*
>
> **Suani Coelho**, University of Sao Paolo

ARE METHODOLOGIES FOR GHG ASSESSMENT OF BIOFUELS GENERALLY AGREED?

PRO

The GHG balances associated with fuels made from residues and wastes can be accurately estimated and are usually positive.

No agreement



CON

There are ongoing disagreements about methodology and input data for life-cycle assessment (LCA) calculations.

> *As policies based on actual GHG emission reductions of biofuels become more common, the carbon intensity of current and emerging biofuels is expected to decrease, for example, through the increased use of wastes and biomass residues as raw materials.*
>
> **IEA**, *How Bioenergy Contributes to a Sustainable Future*, 2023

> *Some biofuels are considered first generation in the U.S. but second generation in the EU. The definitions of biofuels (conventional, advanced etc.) vary according to geographies.*
>
> **Bharadwaj Kummamuru**, World Bioenergy Association

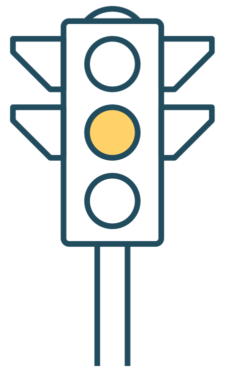
DO BIOFUELS DELIVER GHG BENEFITS?

PRO

Biogenic emissions can be avoided by focusing on biofuels produced from wastes and residues.

Supply chain emissions will decrease as the global economy decarbonises.

Limited agreement



CON

At best biofuels only reduce emissions partially.

Biofuels can promote deforestation leading to net GHG increase.

Crop-based biofuels can lead to indirect land-use change.

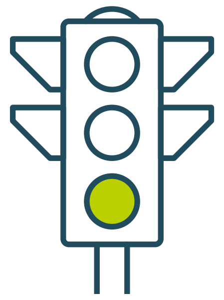
> *For the existing fleet the solution would be liquid biofuels and biogas from waste. From a system perspective, this is a circular solution that could achieve even negative emissions since it not only avoids the diesel that would have been used in the vehicles, recycles nutrients from organic waste that replaces fossil fertilizer, and also avoids the methane that would have been produced from the waste in landfills.*
>
> **Jonas Stromberg**, SCANIA

> *Using biomass and biofuels made from biomass has positive and negative effects on the environment.*
>
> **EIA**, *Bioenergy Explained*, 2023

5.3 BIOFUELS DO BIOFUELS LEAD TO REAL GHG SAVINGS?

CAN POLICY & REGULATION INFLUENCE GHG SAVINGS?

Medium agreement PRO



PRO

Policy and regulation can prevent biofuel production from causing direct land use emissions.

"An integrated approach to waste management can ensure that the use of waste for energy is appropriate, and stringent air and water quality regulations, with regular monitoring and enforcement, can ensure that operations avoid negative impacts on air and water quality."

REN21, *RESR*, 2024

CON

Without effectively implemented and enforced policies to reduce land-use-change, GHG savings will be minimal or negative.

"Our results show: The state of current global land regulation is inadequate to control land-use-change emissions caused by modern biofuels produced from purpose grown feedstocks."

Leon Merfort, Potsdam Institute for Climate Impact Research

Methodologies for GHG assessment

Factors influencing GHG impacts of biofuels

The following elements summarise a number of factors that conceptually contribute to the overall GHG impacts of biofuel production. They may not be applicable in all circumstances but should be considered in assessments.

Supply chain: The GHG benefits of using bioenergy can be reduced if fossil fuels are used to provide energy to the supply chain (for processing or transport, for example) or GHG emissions related to fertiliser production and use are involved. These supply chain emissions can be calculated and compared with those from fossil fuel use using life-cycle assessment (LCA) systems. For biofuels based on residues and wastes, these supply chain emissions are the principal issue that needs to be considered.

Direct land use change: If the production of biofuels or other bioenergy involves a change in land use, this could lead to significant GHG emissions if carbon levels above and below ground are affected. For example, if natural forests are cut down and burned to make way for energy crops, the one-time emissions would far exceed the GHG reductions that might come from displacing end-use GHG emissions.

Indirect land use change: Using or displacing crops usually grown for food by energy crops could also in principle have an effect that increases indirect land use change (ILUC) emissions. If food production just moves elsewhere to meet demand, additional land could be converted into cropland with consequent emissions increases.

GHG emissions from direct and indirect land use change are also referred to as biogenic emissions. Depending on the previous use of the land, land use change can have a positive or negative impact on GHG emissions.[216]

Differences in methodologies

LCA is a well-established methodology used for determining the GHG benefits of biofuels compared to fossil fuel alternatives. It is applied in many support schemes, including the European Union's Renewable Energy Directive (RED), the US Renewable Fuel Standard (RFS) and Brazil's Renova Bio programmes. Since many assumptions used in the assessments are very specific to the location, results usually only apply to the region and conditions set out in the study parameters.[217]

There is wide consensus around calculations relating to supply chain emissions, although we also find differences in methodology that can lead to different results. However, differences in biogenic emissions are usually much larger and largely determine overall effects. Apart from differences based on the feedstock used and the production process, differences in results are usually based on:[218]

METHODOLOGICAL CHOICES

- Inclusion or exclusion of direct and/or indirect **land use change**.
- Assumptions to estimate the **level of indirect land use change** induced through biofuel production, including for the price and demand development of a wide range of crops and products as well as land demand from settlements and infrastructure.
- Inclusion or exclusion of GHG effects from **co-products**, such as electricity or heat generated and used during biofuel production, or of marketable by-products, such as animal feed or biochemicals.
- Method of **attribution of GHG effects** between the biofuel and co-products.
- Methodology used for emissions from **soil nitrous oxide**, where the IPCC Tier 1 method is often used, with potentially very different results compared to higher-tier methods using site-specific parameters.
- Assumptions on emissions or removal of **soil organic carbon**, for example through the removal of agricultural residues that would otherwise have been left on the field and would have increased soil carbon content.
- Different approaches to account for the **temporal impact of carbon emissions**, i.e. the potential imbalance and time difference between the amount of carbon taken up through the growth of the feedstock and the amount released during burning of the biofuel.

REGIONAL DIFFERENCES

- Differences in **energy demand** for production (this also depends on technology) and transport of feedstock, intermediate products and fuels.
- Differences in the **carbon intensity of energy used** in the production process, leading to lower GHG benefits of biofuels in regions with a high-carbon energy mix.
- Assumptions on **yields** of used feedstocks, based on regional circumstances.
- Assumptions on **fertiliser input** use, based on local soil properties and farming practices.
- Assumptions on **carbon stock released** from land use change, which would be typically higher in tropical regions and where forests are replaced by cropland.[219]

It is also important to note that studies use a variety of units as the basis for their emissions comparison. Some compare emissions per unit of energy (MJ), while others use distance travelled (vehicle km), volume (litre), mass (kg/tonne) of biofuel or units related to the production, such as mass of biofuel feedstock or agricultural area. This makes it difficult to compare individual results.[220] The results of LCAs therefore need to be carefully interpreted. Assumptions and methods used need to fit the intended purpose, so not every study can be used in any context.

> *Arguments over which ILUC model is best are not terribly helpful, because all ILUC models require making several subjective assumptions that significantly impact their results. Instead, we should look at the range of ILUC estimates we get from different approaches to ILUC assessment and make a risk-aware decision about policy from there.*
>
> **Colin Murphy**, UC Davis

GHG benefits from biofuels

As outlined above, there are many reasons for the GHG emission results of LCAs of biofuels to vary across studies, even for the same feedstock and the same region, let alone across feedstocks and regions.

A meta-study analysing 179 articles including 613 assessments of different types of biofuels published between 2009 and 2020 found that estimated results of GHG emissions benefits vary significantly across studies:[221]

- Looking at first-generation biofuels without land use change, biofuels from all feedstock sources show clear GHG benefits compared to their fossil fuel counterparts. However, estimates vary strongly for most feedstocks, except sugarcane, with the largest variety found for palm oil.
- Assessments of first-generation biofuels that include direct (and sometimes also indirect) land use change show a much higher variation. Only biofuels based on sugar beet show clear benefits compared to fossil fuels across all analysed studies. For some feedstocks, such as molasses and soybeans, most assessments find that lifecycle emissions are substantially higher than those of fossil fuels.
- For advanced biofuels based on agricultural residues, land use change is not normally an issue, although there may be some indirect land use involved. Most studies analysed found clear GHG benefits for those biofuels, some even with overall negative emissions, based on benefits from co-products. An assessment by the IEA Bioenergy Task Force further concludes that the conversion of marginal lands to the managed cultivation of lignocellulosic crops could also result in overall negative emissions.[222]
- A limited number of studies looked at biodiesel from algae. The results of these studies differ widely, from producing absolute negative emissions to emissions that are multiple times those of fossil diesel. The differences are mostly a result of great uncertainties about algae yields and energy needs.

Overall, this shows that results are highly sensitive to assumptions and methods and need to be used carefully.

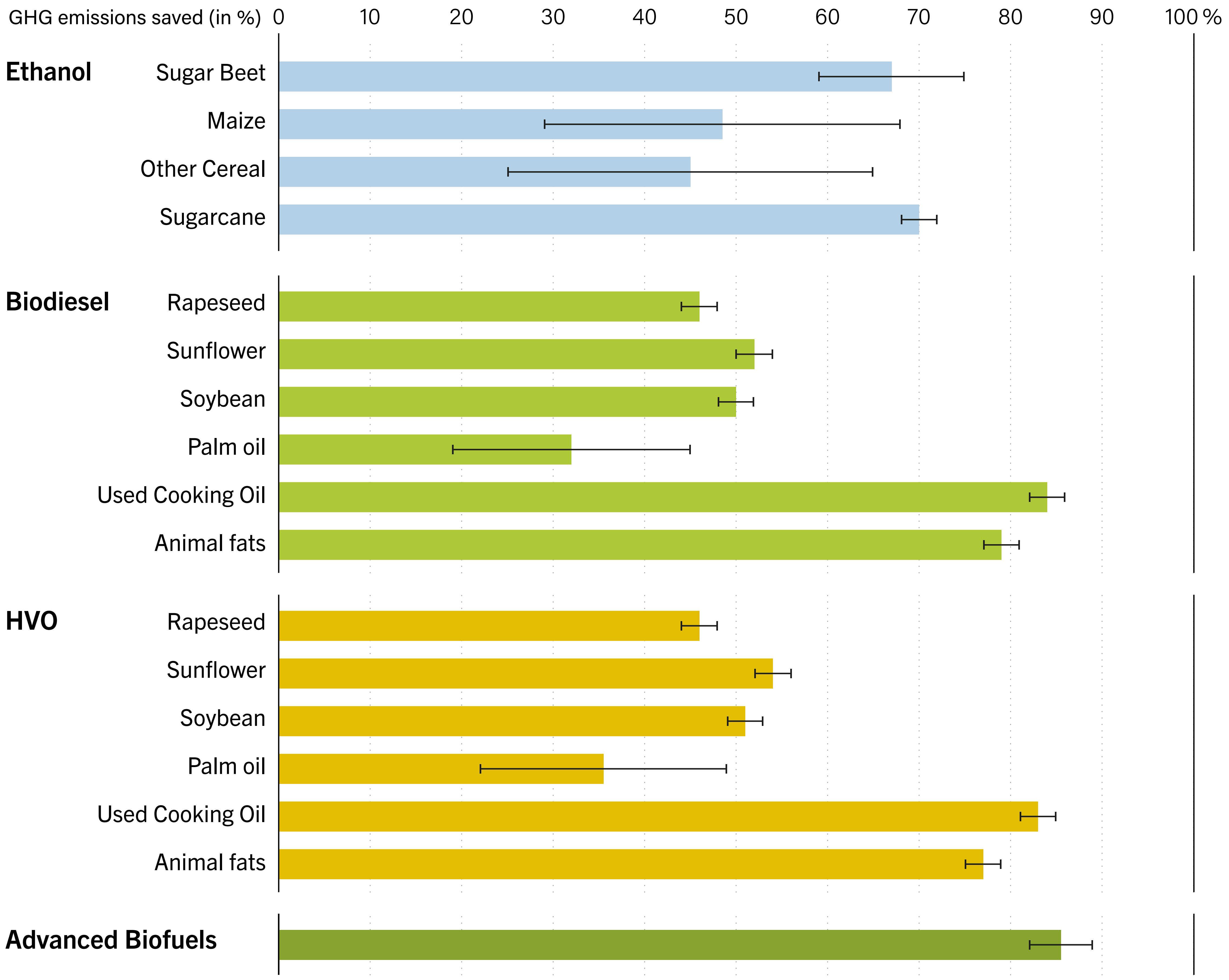
Policy and regulation influencing GHG savings

There is widespread agreement that clearing high-carbon stock land for biofuels production is undesirable (both from an emissions and biodiversity perspective). Constraints to using such land is incorporated in regulation in the European Union and other jurisdictions, but doubts remain about the extent to which such regulations are enforced and monitored.

Policy measures, such as the revised EU RED (EU RED II), are increasingly encouraging the use of residues and the production and use of non-food crops for biofuels production, especially on lower grade land, to reduce competition with food production and avoid potential ILUC emissions.[223] The EU RED II provides default values for GHG reductions when biofuels replace fossil fuels (excluding ILUC emissions).[224] The GHG emissions vary between 20% and 90% depending on feedstocks and production routes (→ *see Figure 30*).[225]

5.3 BIOFUELS DO BIOFUELS LEAD TO REAL GHG SAVINGS?

Figure 30: EU RED II: Range of default values for GHG savings from biofuels compared to fossil fuel alternatives



Source: See endnote 225.

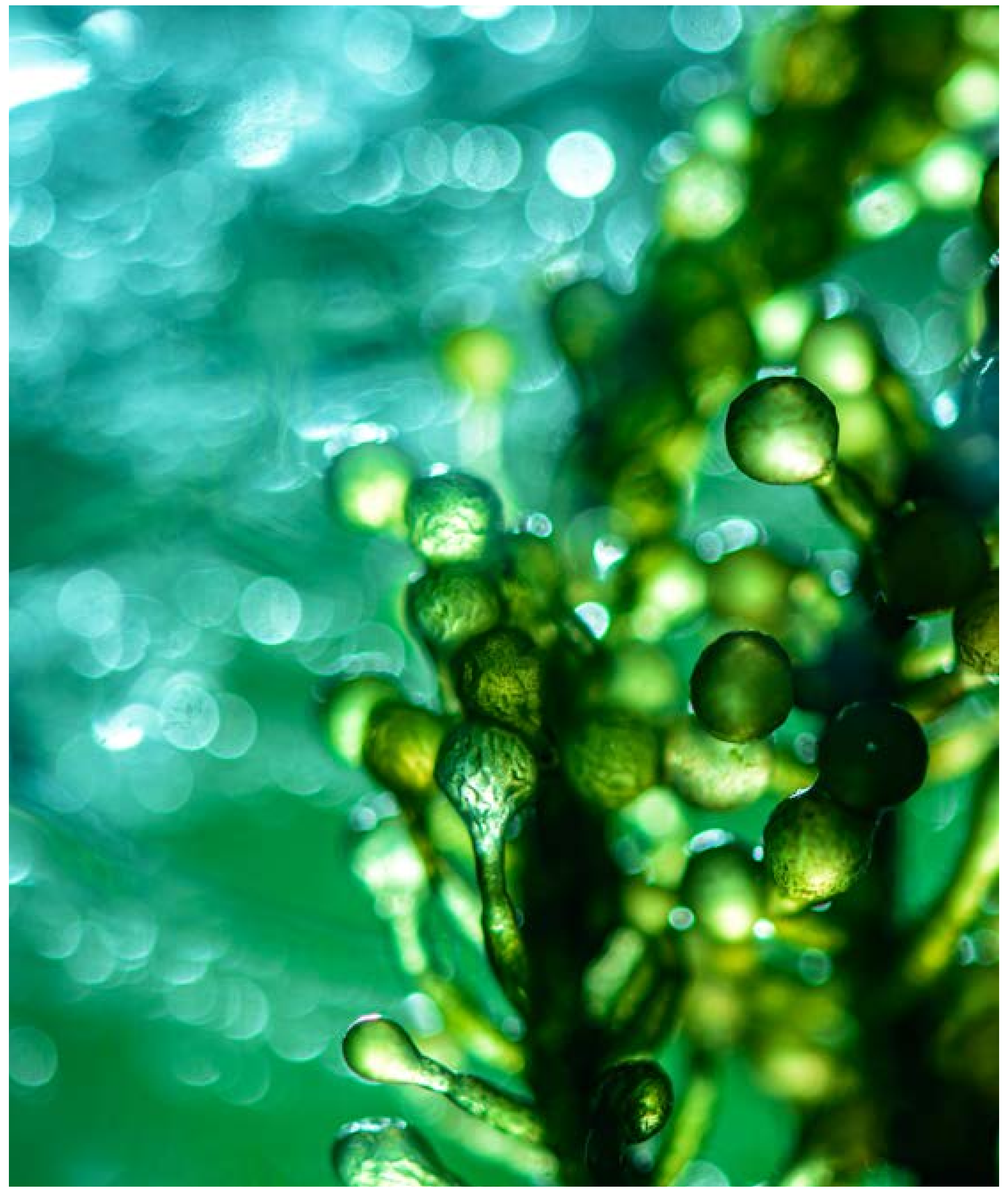
Within the European Union, biofuels contributing to the renewables share must provide at least 70% GHG savings compared to fossil fuels. Further measures constrain the amount of crop-based biofuels that are considered likely to pose a risk of emissions from ILUC, with these sources due to be phased out by 2030.[226]

Other support schemes, such as the California Low Carbon Fuel Standard (CLCFS) and the Brazilian Renova Bio system, directly incentivise higher levels of GHG reductions and make allowances for ILUC in their calculations.[227] Japan also established a minimum GHG savings of 55% for biofuels compared to fossil fuels, based on LCA. Switzerland has a threshold of 40% minimum GHG emission savings to be eligible for tax benefits. Other countries, such as Norway, require mandatory shares of advanced biofuels, similar to the EU RED II.[228]

In Brazil, a law only allows oil palm plantations on areas that were deforested before 2007,[229] but as with many other sustainability requirements, concerns have been raised about the enforcement of such rules and the indirect effects from pressuring other production into forest areas.[230]

The more widespread use of support systems that either set increasingly stringent minimum GHG reduction thresholds or incentivise GHG reductions will encourage higher levels of GHG reduction by minimising supply chain emissions and favouring feedstocks with a low risk of ILUC and other biogenic emissions. This will be complemented by the further development of routes to produce biofuels from a wider range of cellulosic feedstocks, especially to produce greater quantities of fuels for maritime and aviation transport.

Emissions can be further reduced through the collection and use of by-products. For example, collecting and using forestry by-products can form part of a sustainable forestry management plan that aims to reduce the risks of uncontrolled fires and thus preserve forest carbon stocks.[231] Supporting such activities through policy could further enhance the sustainability of biofuel production.



5.3 BIOFUELS

ARE LARGE-SCALE BIOFUEL PRODUCTION AND USE SUSTAINABLE?

The wider debate about the sustainability of biofuels is a complex topic, given the many potential feedstocks, conversion processes and products. Potential environmental, social and economic impacts depend on the entire supply chain and on local circumstances.

Apart from the sustainability concerns regarding the actual GHG impact of biofuels discussed above and the potential competition with food production discussed in the next tension point, many experts express concerns that the inappropriate production and harvesting of biomass could lead to a loss of biodiversity or to the proliferation of invasive species. For example, natural forest could be replaced by monocultures (e.g., oil palm). Alternatively, over-harvesting of forestry residues can lead to negative impacts on forest biodiversity.

Experts argue that biofuels production and use can also have other environmental impacts – for example, on air quality due to emissions during the production and use of fuels. Water quality and availability can also be impacted by the release of untreated effluents during fuel processing or by water overuse in feedstock production.

Others, however, promote the positive effects of biofuels, such as the strengthening of local economies and positive co-benefits from using fuels that would otherwise cause worse harm. They argue that negative effects can largely be managed through appropriate policy and regulation.

Opinions differ on the magnitude of such potentially negative impacts and whether they can be adequately prevented or managed.

CAN POLICY & REGULATION ENHANCE SUSTAINABILITY?

Limited agreement

PRO

- Policy and regulatory measures can reduce negative impacts.
- Policy can constrain use of feedstocks produced in sensitive areas.
- Sustainable forest management practices can reduce negative impacts.

CON

- Sustainability measures are not implemented in all jurisdictions.
- Criteria for sustainability vary.
- Monitoring and enforcement are lacking.
- Using marginal land can threaten biodiversity.

“Stakeholders have called for the implementation of stringent sustainability criteria for bioenergy, related to land-use change, deforestation, pollution, greenhouse gas emissions and biodiversity. National or regional policies and regulations, and requirements imposed by supporting programmes, can ensure that such criteria are met.”

REN21, *RESR*, 2024

“It will be a major challenge to scale up biomass production to those levels while avoiding adverse environmental or social consequences.”

IRENA, *WETO*, 2023

DO BIOFUELS PROVIDE CO-BENEFITS?

Inconclusive

PRO

- Use of materials for bioenergy can have positive impacts.
- Biofuels can be based on local resources.
- Biofuels production can stimulate economic activity, especially in rural areas.

CON

- Combustion of biofuels continues air pollutant emissions.
- Feedstock production can pollute water.
- Feedstock production requires water.
- Biofuel trade creates new dependence.

“The short supply chains could create many skilled jobs, providing additional revenues in rural areas and driving industrial competitiveness.”

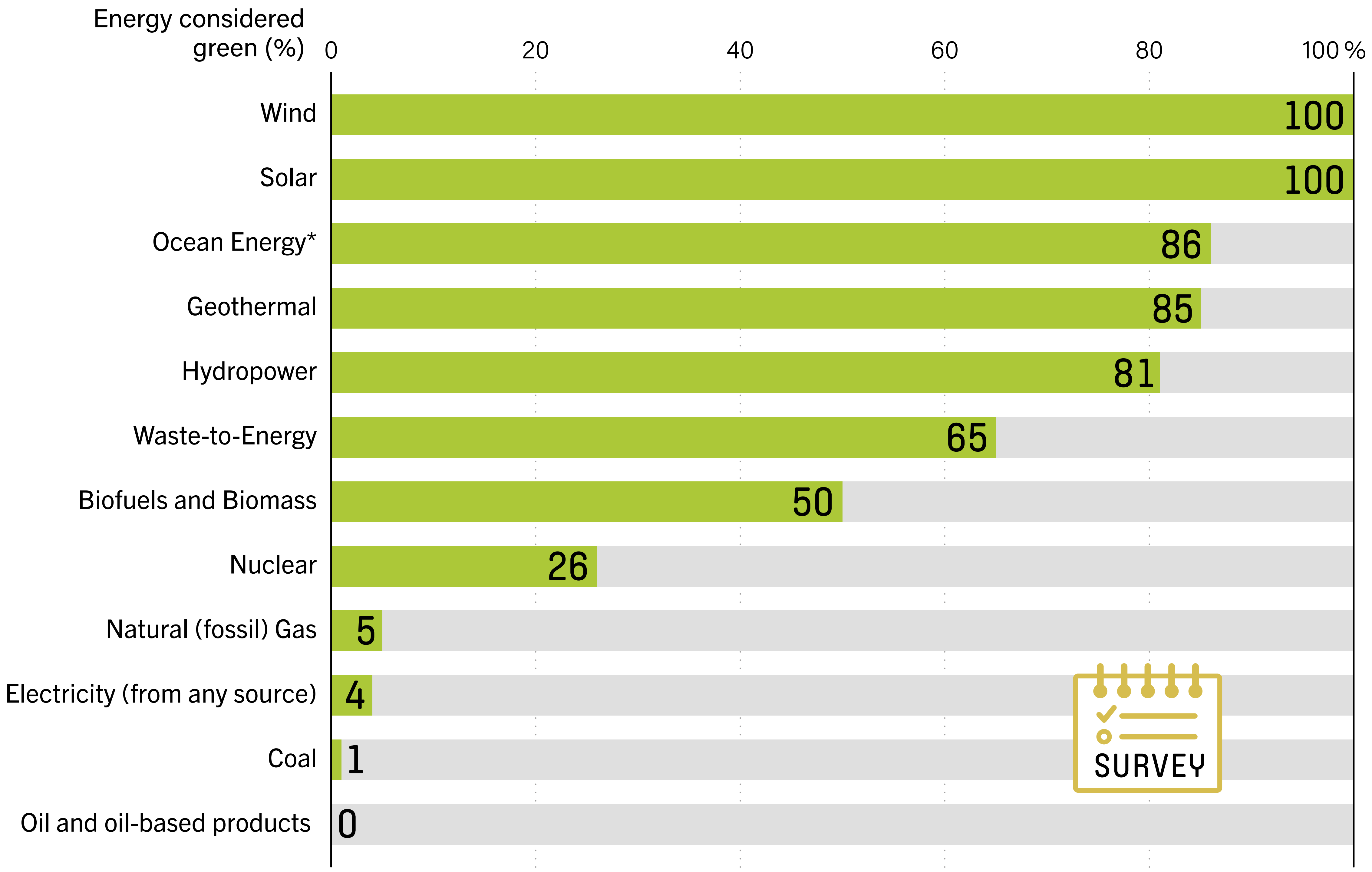
JRC, *Advanced Biofuels in the European Union*, 2023

“We can never reach zero. If we use biogas, there are some lifecycle emissions. There are no zero-pollution solutions in the real world. All our creative efforts must be aimed at achieving net zero through appropriate engineering.”

Patrick Oliva, Transport Expert

5.3 BIOFUELS ARE LARGE-SCALE BIOFUEL PRODUCTION AND USE SUSTAINABLE?

Figure 31: Survey - What energy source(s) do you consider to be "clean" and/or "sustainable"?



*from wave, tidal, current energy and ocean thermal energy

Only half of the experts responding to the survey think that biofuels and biomass are a clean and/or sustainable energy source.

The reasons for this are varied and explored in more detail below.

Policy and regulation on sustainability

Policy and regulatory measures can be designed to favour bioenergy sources that rely on wastes, residues and crops grown on unused or underproductive land.

At a global level, various initiatives support sustainability for biofuels. For example, the Food and Agriculture Organization of the United Nations (FAO) has developed the Bioenergy and Food Security (BEFS) approach to support countries in designing and implementing sustainable bioenergy programmes, policies and strategies that promote food and energy security while advancing agricultural and rural development.[232]

The Global Bioenergy Partnership (GBEP) established 24 voluntary indicators to guide and inform national analysis, policy development and monitoring.[233] The Glasgow Declaration on Sustainable Bioenergy is an industry-led initiative to guide and support sustainability practices in woody biomass.[234] Additionally, the International Organization for Standardization (ISO) developed sustainability criteria for bioenergy (ISO 13065:2015).[235]

At the national level, some countries have adopted regulations or standards to ensure that locally produced or consumed biofuels meet minimum sustainability standards.[i] Apart from the minimum requirements for GHG savings outlined above, the EU RED II prohibits the use of all biomass from primary and highly biodiverse forests (rather than just agricultural biomass, as under the previous rules) and the use of stumps and roots.[236]

Overall, awareness of the need for strict sustainability standards is growing, and this is leading to a widespread coupling of sustainability governance with schemes designed to provide financial support for biofuels use. This trend is expected to continue.

Certification plays a key role in verifying that sustainability regulations are met. Various certification schemes have been developed over the years, including by the Roundtable on Sustainable Biomaterials (RSB), the Council on Sustainable Biomass Production (CSBP), the International Sustainability & Carbon Certification (ISCC), the Roundtable on Sustainable Palm Oil (RSPO), the Roundtable on Responsible Soy (RTRS), Bonsucro, and the Forest Stewardship Council (FSC).[237]

The European Union developed detailed rules for the process for sustainability certification under the EU RED II, and the Commission has so far approved 15 certification schemes.[238]

Co-benefits of biofuels

Renewables can bring a host of other co-benefits, such as job creation and investment in local value chains. Unlike many renewable energy systems, many biofuels require considerable labour to produce, process and transport feedstocks as well as to manage conversion processes. This means biofuels production can be a stimulus to economic activity and create employment, especially in rural areas. This is further enhanced through the utilisation of co-products from the production process, such as organic fertilisers, oil cake and other commercial products, including opportunities for carbon storage.

IRENA estimated that in 2022 biofuel provided 2.5 million jobs.[239] Under its 1.5°C Pathway, it estimated that 11 million additional jobs would be created by 2030 compared to the baseline scenario in agriculture and forestry to provide biomass feedstock.[ii] Additional jobs would be created for the installation and maintenance of infrastructure as well as business services.[240]

Renewables can co-exist with other activities, such as agriculture, as well as add value to existing infrastructure and degraded land.

i Policies that aim to ensure minimum GHG emission savings from fuels were discussed in the chapter 5.3. "Do biofuels lead to real GHG savings?", so we focus on other provisions here.

ii This includes biomass supply for non-transport uses.

5.3 BIOFUELS ARE LARGE-SCALE BIOFUEL PRODUCTION AND USE SUSTAINABLE?

Biofuel production can have positive impacts. Anaerobic digestion of effluents to produce biogas and biomethane can be an important driver for improved treatment methods.[241] Using crop residues as fuel rather than burning them in the fields can improve air quality.[242]

Enhanced energy security and reduced import dependence were major drivers for the implementation of biofuels policies in Brazil and the United States. Today, these same drivers are steering increased attention to biofuels for transport in India, Indonesia and other Southeast Asian countries. The increased use of bioenergy is also an important element in the European Union's efforts to improve energy security.[243]

Overall, the contribution of biofuels to energy security depends on various factors:

- the potential for feedstock and biofuel production
- the demand for available biomass from other sectors
- the reliance on fossil fuel imports.

Countries with high oil or gasoline and diesel imports are more likely to promote biofuels to promote energy security. Even oil-producing countries, such as Brazil, often import refined gasoline and diesel and benefit from lowering these imports.[244]

SOCIAL AND ECONOMIC IMPLICATIONS

A danger concerning biomass production is the possibility that it could employ low-paid (below minimum wage) labour or involve child labour in the agricultural sector.[i] Large-scale biomass production in particular could potentially infringe on local land rights and protected tribal areas or out-compete small-scale local producers. Biomass certification schemes address these issues by requiring high labour standards, fair payment and informed local consent, but concerns that such standards may not be properly enforced persist.

GEOGRAPHIC DIFFERENCES

Biofuel production's potential for negative effects on biodiversity and the quality and availability of air and water differs depending on local circumstances. Socio-economic factors such as demographics, politics (e.g. when involving land ownership) and culture influence whether bioenergy can be deployed at a site in a sustainable manner.[245]

Cars operated exclusively by ethanol were introduced in Brazil in 1979[246] and flex-fuel vehicles in 2003, and the country is home to the largest fleet of flex-fuel vehicles in the world.[247] Flex-fuel vehicles are also available in other countries.

These are mostly E85 versions able to run on a mix with up to 85% of ethanol, although their deployment has been less successful compared to that of Brazil.

Generally, the effects of conventional energy crops are higher in all regions. This is however particularly the case in arid regions, where water use for energy crops can compete with other water uses. Similarly, effects on water quality from fertiliser and pesticides use could be higher in regions with low soil fertility, but this also depends on the potential alternative use of the land.

For biofuels from residues and waste, regional differences are less relevant. This is because negative impacts are mostly related to the actual production facilities and to the end use, which could be local or somewhere else if biofuels or feedstocks are traded internationally.

i Similar to concerns outlined regarding mineral mining in Chapter 5, Section 1 above.

IS SUFFICIENT SUSTAINABLE BIOMASS AVAILABLE WITHOUT IMPACTING FOOD SUPPLY AND SECURITY?

The amount of biomass feedstock needed to supply an enhanced contribution of bioenergy and biochemicals rises strongly in net zero and low-carbon scenarios compatible with ambitious GHG reduction ambitions.

Most biofuels are still produced using traditional feedstocks, such as maize, sugarcane, cereals such as wheat, and vegetable oils. The production of HVO and bio-jet fuels relies on an increased use of waste products, such as used cooking oil, but the supply of such materials is limited. Organic wastes can also be used to produce biomethane.

Many experts argue that the total available waste resource is constrained, with feedstock prices rising. The supply of such raw materials will not support a large increase in production if these fuels are envisaged in low GHG scenarios.[248] Growth is therefore projected to rely on the use of other biomass feedstocks. Biofuels can also be produced from a wider range of crop and wood residues using a range of thermal and biological processes, but such processes are not yet widely deployed.

Experts also raise concerns that using food crops, such as wheat, corn, sugar and oil crops, as feedstocks for energy products could lead to food shortages or increase food prices. Others argue that there are many ways to improve the efficiency of food production and reduce waste, and that there is potential to supply both requirements.

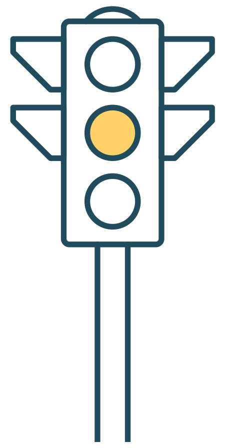
Significant uncertainties therefore persist about the potential supply of feedstocks for bioenergy, especially when the concerns about the overall sustainability of biofuels and potential impacts on food supply are taken into account.

Views differ on whether large amounts of biofuels can be produced using feedstock that actually reduces GHG emissions and does not have negative effects on food production.

5.3 BIOFUELS IS SUFFICIENT SUSTAINABLE BIOMASS AVAILABLE WITHOUT IMPACTING FOOD SUPPLY AND SECURITY?

IS THERE ENOUGH FEEDSTOCK SUPPLY?

Limited agreement



PRO

New technologies will allow the large-scale processing of new feedstocks.

Using marginal lands can enable enhanced biofuel production.

New feedstocks, such as algae, can provide additional feedstock.

"Energy from waste is undoubtedly becoming more important in Asia, while China is rapidly rolling out these solutions, its potential is underexploited in other Asian countries."

IEA, *Will energy from waste become the key form of bioenergy in Asia?*, 2018

CON

Availability of continuous, and high-quality feedstock for individual large-scale processing plants is difficult to achieve economically.

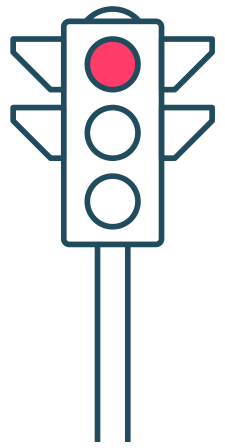
The availability of wastes and residues is limited.

"We know how to make biofuels, including bio-jet-fuel. But we don't know how to make large volumes sustainably. We might need on the order of exajoules if we want to run most ships and planes on biofuels. Trucks are another potential market vying for these fuels. We can probably supply all of this with oil-seed crops but it is probably unsustainable with respect to global agriculture and land-use change."

Lewis Fulton, UC Davis

CAN AGRICULTURE PRODUCE SUFFICIENT FOOD AND FEEDSTOCK?

No agreement



PRO

The agricultural system is able to meet the demand for food and fuel.

Improved distribution of available food production can enhance efficiency.

Co-production of food and fuels can be mutually beneficial.

"Asia will overtake the world in production of biofuels. India experiences regular excess in grain and cereals production that are usually dumped and wasted. These can be used for bioenergy production. Similarly in China straw and cereals are currently underutilised and can be used to produce ethanol. This over production of food in Asia has potential for providing farmers with new income streams."

Bharadwaj Kummamuru, World Bioenergy Association

CON

It will not be possible to produce enough for growing food and fuel needs.

Climate change threatens agricultural production in many regions.

Production of biofuels can push up food prices.

"In practice, biofuels are not much considered right now. Feedstocks are not enough. There might be no competition with food production in Vietnam, in fact, food production is more attractive and crucial for food domestic consumption and for export purpose, so it is difficult to use edible feedstocks for biofuel production."

Le Anh Tuan, Hanoi University of Science & Technology

Feedstock demand and supply

Feedstock requirements

The role of bioenergy in other low-emission scenarios varies widely, depending on the extent to which it replaces fossil fuels and other sources in primary energy supply and the role that bioenergy with carbon capture and storage (BECCS) plays in carbon removals.[249] In the IPCC scenarios, the biomass requirements vary from 40 EJ to 312 EJ. A review of other scenarios found a range of 45 EJ to 153 EJ.[250]

In 2020, global biomass supply for energy (excluding traditional biomass) amounted to some 38 EJ (up from 27 EJ in 2010). The IEA NZE scenario assumes that 100 EJ per year of biomass feedstock will be needed by 2050 for uses across all sectors.[251] IRENA estimates that by 2050, 135 EJ per year of biomass would be required to remain below 1.5°C,[252] with both organisations projecting a phase-out for the traditional use of biomass.

IRENA projects the use of bioenergy for transport to be 12 EJ by 2050, up from 9.1 EJ by 2030,[253] and the IEA estimates that 11 EJ of modern liquid bioenergy will be required by 2050, although demand peaks at 13 EJ in 2035.[254]

Feedstock availability

At present, feedstock availability is not a major impediment to short-term increases in biofuel production and use. However, there are indications that some preferred feedstocks, such as waste and virgin vegetable oils, are becoming short in supply.[255]

For example, total available vegetable oil supply is constrained, with feedstock prices already rising in some countries, such as the United States. The supply of alternatives, such as used cooking oil and animal fats, provides limited relief, even if all supply were directed towards bioenergy use. Additional supply will be needed from a broader range of wastes, such as palm oil mill effluent, tall oil and other agribusiness waste oils. Growth is therefore projected to rely on the use of other biomass feedstocks. These include feedstocks suitable for conversion via hydrogenation through the conversion of ethanol to renewable diesel, bio-jet and other hydrocarbons, or particularly of cellulosic residues such as crop and forestry residues.[256]

Bioenergy and overall development in the agricultural and forestry sectors are closely linked, and it is not possible to precisely determine the scale of bioenergy and BECCS deployment at which negative impacts outweigh benefits. Biomass availability also depends on many factors, including market demand, climate features, management, interactions with other markets, and sustainability criteria.

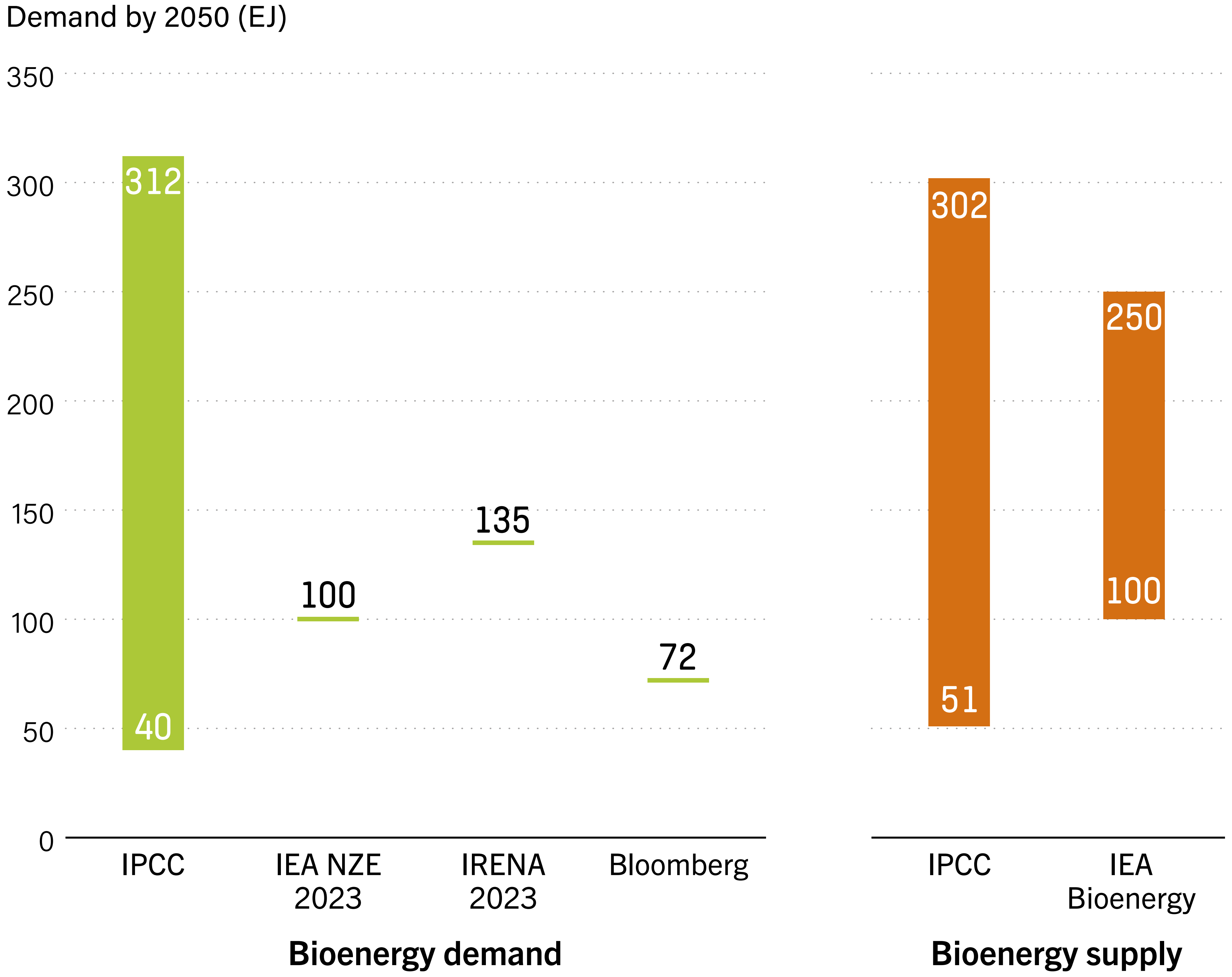
The IPCC has summarised recent assessments of the technical biomass potential, considering constraints for food security and environmental considerations. Its results indicate a potential of 4-57 EJ per year for residues and 46-245 EJ per year for dedicated biomass crops.[257] A recent study by IRENA came to similar conclusions and estimated that the technical potential for energy from residues is between 30 EJ and 60 EJ per year.[258]

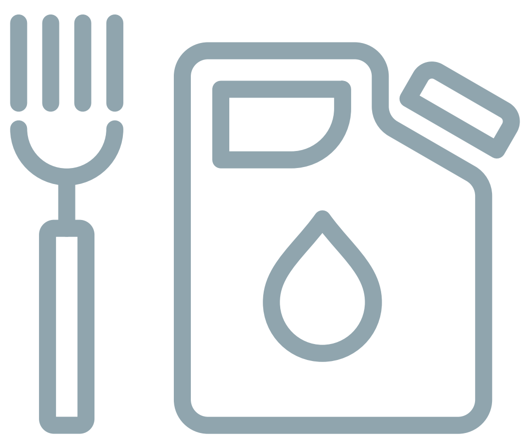
These estimates are generally lower than previous assessments. Earlier estimates varied from 47 EJ to 1,500 EJ for all feedstock sources, especially studies conducted up to 2007. More recent global assessments have a narrower range, particularly because they more strongly reflect likely limits on using land specifically for energy crops, but there is still not a strong convergence in the estimates. A meta-analysis of these estimates by IEA Bioenergy in 2020 concluded that biomass potential for the 2050 to 2100 period probably lies within a range of 100 EJ to 250 EJ.[259]

The wide range of estimates is based on various factors:[260]

- the type of biomass resources considered by studies
- the approaches used to determine the availability of a specific resource for bioenergy use
- the assumptions made about key parameters, such as the availability of arable land, yield and population development
- the definition and availability of marginal and degraded lands
- the sustainability criteria applied.

Figure 32: Annual bioenergy demand and supply potentials according to energy and climate scenarios





5.3 BIOFUELS IS SUFFICIENT SUSTAINABLE BIOMASS AVAILABLE WITHOUT IMPACTING FOOD SUPPLY AND SECURITY?

Agricultural production and food distribution

The total production of calories is currently sufficient to feed the world population. However, availability and access to food is unequally distributed, and there is a lack of nutrient-dense foods, fruit and vegetables.[261] Hunger affected between 691 million and 783 million people in the world in 2022, some 9.2% of the global population.[262] It follows that both the overall production of calories and their distribution across regions are important.

The number of people affected by hunger has increased since 2019 due to the Covid-19 crisis and the Ukrainian war. The major drivers of food insecurity and malnutrition are poverty, conflict, climate extremes, and economic slowdowns and downturns.[263] However, there are also losses within the food supply chain. According to the FAO, around 14% of the world's food is lost after it is harvested and before it reaches the shops. The United Nations Environment Programme (UNEP) has shown that a further 17% of our food ends up being wasted in retail and by consumers, particularly in households.[264] Reducing such losses can be one element to enhance food security and enable growth in bioenergy supply at the same time.

In addition to the current challenges in many regions, global food consumption (in calories) is projected to increase by 1.3% per year over the next decade, driven by income and population growth. Demand for livestock, aquaculture, milk and dairy products is also projected to grow, increasing overall feed demand.[265]

Calorie intake is however only one factor in human diets. "Sustainable healthy diets" have been defined by the FAO and WHO as "dietary patterns that promote all dimensions of individuals' health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable".[266] While some people lack access to calories, others lack access to nutritious foods or favour harmful foods based on cost or cultural conventions. Improving the nutritional balance of diets could improve the overall health of societies and reduce pressures on food systems.[267]

Measures to improve food production

Several actions related to improved land and resource management and efficiency would make the required food supply easier to achieve, and therefore potentially release land for bioenergy production.[268] These include, for example, improving food crop yields through improved crop varieties and management practices. Narrowing the "yield gap" between best practice and achieved food production in particular will enable more to be produced on less land.

Improvements can also be made in the land efficiency of animal husbandry, which could make more efficient use of the land used to raise animals for meat and dairy products. Moreover, efficiency in food production can be improved notably by reducing food waste and losses. Afforestation of derelict and abandoned land could also provide significant resources for local food and energy use.

The FAO supports the co-production of food and fuel when done appropriately. It has developed the BEFS Approach to support countries in designing and implementing sustainable bioenergy programmes, policies and strategies. The approach promotes food and energy security and contributes to agricultural and rural development. It consists of tools and guidance to support countries through the main stages of the bioenergy policy development and implementation process.[269]

Biofuel production and food price development

In 2008 and 2009, concerns were raised when a period of strong increases in global biofuel production coincided with increasing food prices. However, subsequent analysis showed that many factors (including high energy prices and market speculation) also contributed to these increases, with bioenergy being only one factor in a complicated picture.[270] The general increase in energy prices at that time was considered to be the dominant influence on developments in commodity, and especially food, markets. The use of commodities by financial investors (the so-called financialisation of commodities) is also considered to have played an important role.

SOCIAL AND ECONOMIC IMPLICATIONS

Biofuels production can create new employment opportunities for skilled and unskilled workers. It can also provide additional opportunities for farmers to diversify their income. Its impacts on food prices are as yet not well understood and will be lower for biofuels based on residues and waste feedstocks. However, if there are effects on local food prices or availability, the most vulnerable populations will be affected most as the share of income spent on food is higher in lower income households.

GEOGRAPHIC DIFFERENCES

There are large differences in the potential for biofuel production, based on the local availability of biomass. For traditional biofuels, this depends mostly on the available land area and climatic conditions. For advanced biofuels from residues, production potential relies additionally on the types of crops typically grown and forestry practices deployed, which determine the amount of residues available. Waste-based fuels rely more on the size of the population and any industries that produce usable waste products.

Views on the potential to scale up biofuel production without compromising food security vary depending on the available production potential for biofuels and agricultural products. Countries with significant potential often focus on the opportunities from enhanced biofuels production, while regions with low local potential and the need for imports often take a much more cautious approach.

6. GUIDING QUESTIONS FOR INFORMED DECISION MAKING

We are not providing any conclusions or policy recommendations for this report. The objective is to explore different perspectives and to pinpoint areas with significant disagreement on the "right" path forward. Decisions are not taken at a global level, as a look at global scenarios may suggest, but at a national, and sometimes local, level. They are highly dependent on national circumstances, influenced by existing infrastructure, fuel mix, renewables potential, available funds and governance structures. Accordingly, chosen solutions will differ across the globe.

The previous sections highlight arguments on both sides of the spectrum to help decision-makers and stakeholders understand what the relevant issues are. The facts and resources supporting these arguments hopefully provide a sound basis for national debates. We are not providing final answers.

This section provides a set of guiding questions to help focus the discussion and enable well-informed decision-making at the policy level as well as for individual project developers. The questions aim to ensure that decisions are based on a broad consideration of the issues and on their relevance in the respective local context. Not all questions will apply in all settings and to all stakeholder groups.

PRODUCTION OF RENEWABLE FUELS

CURRENT SITUATION

- ☐ Which renewable energy sources are available in your country and region? How much are you already using them?
- ☐ Is electricity generation owned privately or by the state (including state-owned enterprises)?
- ☐ Is the transport fuel production owned privately or by the state?
- ☐ What is the cost of different renewable electricity generation technologies in your country? Are they competitive with fossil fuel alternatives yet? Which policy frameworks influence the competitiveness of different fuels?
- ☐ Do you already have local biomass feedstock production? Is that used locally or exported? Are there any sustainability concerns with the current production?
- ☐ Are policies in place to ensure the sustainability of renewable fuels?

OUTLOOK

- ☐ What are the existing plans to expand? Are renewable capacity projects in the pipeline?
- ☐ Could changes in ownership structures of power generation facilitate sustainable development?
- ☐ Are there any plans to change the ownership structures of transport fuel production?
- ☐ Can additional renewable energy production and use improve local economic development? Which renewable fuels are most likely to provide the largest added value locally? Which policy frameworks could support the competitiveness of renewable fuels?
- ☐ What are the biomass potentials available in your country?
- ☐ Are there further possibilities to enhance the sustainability of renewable fuels in your country?

ENERGY DEMAND

CURRENT SITUATION

- ☐ Do you have universal access to electricity?
- ☐ Is transport already using renewable fuel in your country? Which fuels and to what extent? For which types of vehicles?
- ☐ How much is invested in research and development and innovation for renewable transport fuels in your country? How much by public entities? How active is the private sector?
- ☐ What is the energy mix for each end-use sector? Is all demand met?
- ☐ How much fossil fuel do you import? How much of this is for transport purposes? How much of your GDP is used for this purpose?
- ☐ Are vehicle users allowed to generate their own renewable electricity (e.g. for public transport or fleet operators)?
- ☐ What is the share of different modes in your country? What measures are in place to avoid motorised transport and shift to more efficient modes of transport?
- ☐ Does your country have vehicle energy or CO_2 efficiency standards or import restrictions? For which types of vehicles?

OUTLOOK

- ☐ Are renewables likely sufficient to meet local electricity demand across all sectors?
- ☐ Do you foresee the need for renewable fuel from transport increasing? For which fuels and for which vehicles? Is any demand growth based on customer choices or policy?
- ☐ What energy mix do you expect for each sector in the future? How does that fit with existing plans for electricity and fuel production capacity?
- ☐ If you have your own oil resources: are different uses possible? What is the economic value of such alternatives?
- ☐ Is decentralised electricity production considered as an option in energy planning?
- ☐ Which mode shares do you expect for the future? Are there plans in place for how to achieve these? How are these funded?
- ☐ Are there plans to implement new or enhance (scope, i.e. including more vehicle types or levels) existing standards or import restrictions?

DISTRIBUTION OF RENEWABLE FUELS

CURRENT SITUATION

- ☐ How reliable is your power grid?
- ☐ Do you have gas infrastructure that could be upgraded for hydrogen use?
- ☐ Who owns and operates transport fuel distribution systems in your country? Is it publicly or privately operated?

OUTLOOK

- ☐ Are there existing plans to upgrade? Do you need additional upgrades for enhanced electricity use in transport? Are there options for off-grid solutions?
- ☐ Are there plans or projects under development to upgrade gas infrastructure?
- ☐ What would new renewable fuels for transport mean for those transport fuel distribution systems? What are the cost implications for different fuel types? Who would fund this?

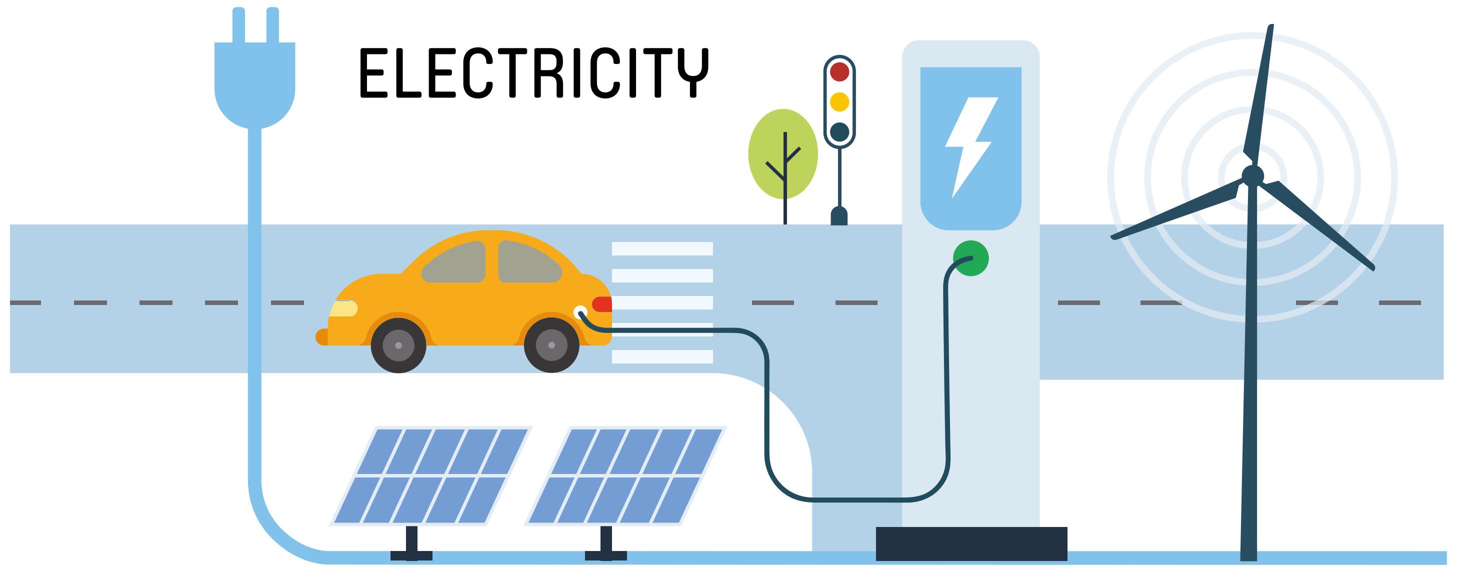
VEHICLES

CURRENT SITUATION

- ☐ Do you have local vehicle production? For which type of vehicles?
- ☐ Do you have battery production capacity in the country?
- ☐ Does your labour force have the necessary skills to build and maintain new vehicle technologies?
- ☐ Which policies and incentives exist to influence the vehicle technology choices of manufacturers and/or customers?
- ☐ What are the requirements of fleet operators in your country? What types of vehicles do they use? How are they typically operated?
- ☐ Are policies in place to address the re-use and recycling of vehicles and components? What about regulations for safe disposal?

OUTLOOK

- ☐ Do plans exist to expand existing capacity or develop new production capacity? Are there plans to transition to alternative fuel vehicles (EV, FCEV)?
- ☐ Are you planning to expand or develop new production capacity?
- ☐ Are new or additional measures to influence vehicle technology choices of manufacturers and/or customers planned?



COST AND BENEFITS

CURRENT SITUATION

- ☐ How much do you earn from taxes on transport fuels? How much do you spend on subsidies for transport fuels?
- ☐ How do renewable transport fuels compare to fossil fuel alternatives for customers at the petrol station and over the vehicle lifetime?
- ☐ Which negative externalities do you experience from the use of fossil fuels in transportation (e.g. trade balance, health effects)?
- ☐ Where are public budgets invested in today (regarding electricity, fuel and transport infrastructure)?

OUTLOOK

- ☐ How would renewable fuels change this? Which measures could mitigate these changes, if necessary?
- ☐ Is there any need for action to ensure affordability of mobility?
- ☐ Which benefits can you expect from the enhanced use of different renewable fuels in transport in your specific national circumstances, in addition to reduced GHG emissions?
- ☐ Which benefits can you expect from the enhanced use of more efficient modes of transport, e.g. public transport, rail and shipping for freight? Which benefits can you expect from avoided transport and enhanced non-motorised transport?
- ☐ Could some of these funds be redirected to support a higher uptake of renewables in the sector?

ANNEX 1: SCENARIO DESCRIPTIONS

IPCC SCENARIOS

The IPCC report *Climate Change 2022: Mitigation of Climate Change* contains a chapter on mitigation options for the transport sector. It includes a wide-ranging review of scenario analysis covering modelling by Integrated Assessment Models, as well as sectoral and regional modelling.[271] The report also analyses three Illustrative Mitigation Pathways (IMPs) that limit warming to 1.5°C with no or limited overshoot (C1)[i], including:

IMP-SP: Highlights pathways that align with both Sustainable Development Goals and climate policies. The scenario involves a reduction in energy for transport of about 40% by the end of the century. Fossil fuels are phased out and there is a switch to electricity and biofuels. Hydrogen provides a minor share by 2100. IMP-SP has a steady decline of transport sector CO_2 emissions over the century and, by 2050, this scenario has a 50% reduction in emissions compared to 2020 levels.

IMP-REN: Focuses on deep renewable energy penetration and electrification. The scenario is characterised by a reduction in energy demand until 2050, followed by an increase back to modelled 2020 levels until the end of the century. By 2050, fossil fuels still represent two-thirds of fuel used, supplemented by 25% electricity. The final fuel mix in 2100 relies mostly on electricity and biofuels, with a minor share of hydrogen and a similar share of remaining fossil fuels. CO_2 emissions from the transport sector decrease to 20% of 2020 levels by 2050.

IMP-LD: Emphasises low demand pathways. In this scenario, overall fuel demand decreases by 45% compared to 2020 levels by 2100. Oil is largely phased out by 2050, and electricity and hydrogen become the major fuels in the second half of the century. CO_2 emissions from the transport sector decrease to 10% of 2020 levels by 2050.

The differences between these scenarios show the breadth of different visions for the future of sustainable transport and the relative importance of demand management, efficiency and the principal low GHG fuel options.

OTHER SCENARIOS

The key elements of some other specific scenarios compatible with a net zero or 1.5°C temperature rise objective are compared in Chapter 2.

Overall energy sector scenarios

IEA's Net Zero Emissions Scenario:[272] The Net Zero Emissions (NZE) by 2050 scenario relies on the deployment of a wide portfolio of low-emissions technologies and emissions reduction options to reach net zero CO_2 from the energy sector by 2050. The scenario achieves this without offsets from land-use measures but does utilise DACS and BECCS. The scenario combines ambitious energy efficiency measures with a rapid increase in renewable energy through the deployment of more than 550 clean energy technologies. The scenario is underpinned by detailed analysis of project lead times for minerals supplies and clean energy technologies as part of efforts to ensure the feasibility of the deployment.

IRENA 1.5°C Scenario:[273] The focus of this scenario is on the rapid deployment of renewable energy in all end-use sectors. The largest GHG reductions come from the use of renewables in power generation and for direct uses in heat and transport, combined with energy conservation and efficiency. In all, 19% of total abatement by 2050 comes from the direct electrification of end-use sectors. Another 19% comes from carbon removal measures, including carbon capture and storage (CCS), BECCS and other measures.

Bloomberg's Net Zero Scenario:[274] This scenario combines faster and greater deployment of renewables, nuclear and other low-carbon dispatchable technologies in power with the uptake of cleaner fuels in end-use sectors, most notably hydrogen and bioenergy. CCS accounts for 11% of all emissions abated over the scenario period.

Transport sector scenarios

TUMI 1.5° Scenario:[275] The TUMI Transport Outlook 1.5°C aims for a clearly defined carbon budget of 110 gigatonnes (Gt) of CO_2 until 2050 for the global transport sector, representing 26% of the total carbon budget of 400 Gt of CO_2 as estimated by the IPCC. The modelling is based on the One Earth Climate Model (OECM), an energy model that was expanded to increase accuracy and resolution for transport demand projection and in the regional and global transport energy demand calculation. Removals in the scenario come exclusively from natural carbon sinks, without the utilisation of technical carbon removal technologies such as CCS or BECCS.

ITF High Ambition Scenario:[276] This scenario is based on a set of bottom-up transport modelling tools that form a framework to test the impacts of policies and technology trends on transport activity and GHG emissions. The scenario provides detailed projections for transport demand for passengers and freight, with a slight reduction in passenger-km by 2050, but a 20% drop in tonne-km. Most GHG emission reductions come from shifts to cleaner modes of transport and the rapid adoption of zero emission vehicles (ZEVs).

ICCT 1.5°C Pathway Scenario:[277] This "ambitious yet feasible" decarbonisation scenario combines measures that are technologically feasible while also considering practical matters such as cost, time required to achieve large-scale production and deployment, and differences in advertised versus real-world emissions. Emissions reductions come mainly from efficiency improvements of vehicles and operations, the adoption of ZEVs, electrification, and renewable fuel use for the remaining ICE vehicles.

i IPCC scenarios are divided into eight different "climate categories" based on 21st century warming outcomes – labelled C1 through to C8. The C1 scenario aims to keep global temperatures below 1.5C with no or limited overshoot.

ENDNOTES

1 Renewable Energy Policy Network for the 21st Century (REN21), 2023, "Global Status Report 2023: Renewables in Energy Demand", https://www.ren21.net/gsr-2023/modules/energy_demand.

2 REN21, 2023, "Global Status Report 2023: Renewables in Energy Demand", https://www.ren21.net/gsr-2023/modules/energy_demand.

3 UNFCCC, 'The Paris Agreement', United Nations Climate Change, accessed 28 March 2024, https://unfccc.int/process-and-meetings/the-paris-agreement.

4 UNFCCC, 'The Paris Agreement', United Nations Climate Change, accessed 28 March 2024, https://unfccc.int/process-and-meetings/the-paris-agreement.

5 UNFCCC, 'Global Stocktake', United Nations Climate Change, accessed 28 March 2024, https://unfccc.int/topics/global-stocktake.

6 REN21, 2024, "Global Status Report 2024: Global Overview", https://www.ren21.net/gsr2024_GO_report/.

7 International Energy Agency (IEA), 2022, Transport, https://www.iea.org/reports/transport

8 IEA, 2022, "Transport", https://www.iea.org/reports/transport

9 IEA, 2022, Transport", https://www.iea.org/reports/transport

10 REN21 Policy Database. See GSR 2024 Data Pack, available at www.ren21.net/gsr2024-data-pack/go; International Energy Agency, "World Energy Balances 2023", 2023, https://www.iea.org/data-and-statistics/data-product/world-energy-balances#overview

11 IEA, 2022, "Transport", https://www.iea.org/reports/transport

12 REN21 & FIA Foundation, 2020, "Renewable Energy Pathways in Road Transport", https://www.ren21.net/wp-content/uploads/2019/05/REN21_FIA-Fdn_Renewable-Energy-Pathways_FINAL.pdf.

13 REN21 & FIA Foundation, 2020, "Renewable Energy Pathways in Road Transport", https://www.ren21.net/wp-content/uploads/2019/05/REN21_FIA-Fdn_Renewable-Energy-Pathways_FINAL.pdf; SLOCAT, 2021, "Tracking Trends in a Time of Change: The need for Radical Action Towards Sustainable Transport Decarbonisation, Transport and Climate Change Global Status Report – 2nd edition", https://tcc-gsr.com/wp-content/uploads/2021/06/1.1-Global-Transport-and-Climate-Change.pdf.

14 REN21 & FIA Foundation, 2020, "Renewable Energy Pathways in Road Transport", https://www.ren21.net/wp-content/uploads/2019/05/REN21_FIA-Fdn_Renewable-Energy-Pathways_FINAL.pdf.

15 Council for Decarbonising Transport in Asia, 2022, "The Path to Zero: A Vision for Decarbonised Transport in Asia –Overcoming Blind Spots and Enabling Change", https://councilreport.ndctransportinitiativeforasia.org/.

16 REN21 & FIA Foundation, 2020, "Renewable Energy Pathways in Road Transport", https://www.ren21.net/wp-content/uploads/2019/05/REN21_FIA-Fdn_Renewable-Energy-Pathways_FINAL.pdf; Abhijit Dutta, "Process Considerations for the Production of Hydrogen via Steam Reforming of Oxygenated Gases from Biomass Pyrolysis and Other Conversion Processes", Advanced Sustainable Systems, https://doi.org/10.1002/adsu.202300241.

17 Jaramillo, P., S. Kahn Ribeiro, P. Newman, S. Dhar, O.E. Diemuodeke, T. Kajino, D.S. Lee, S.B. Nugroho, X. Ou, A.Hammer Strømman, J. Whitehead, 2022: Transport. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, https://www.ipcc.ch/report/ar6/wg3/chapter/chapter-10/.

18 IEA, 2021, "Net Zero by 2050: A Roadmap for the Global Energy Sector", https://www.iea.org/reports/net-zero-by-2050; IEA, 2023, Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach: 2023 update, https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach; IRENA, 2023, World Energy Transitions: Outlook 2023. 1.5°C Pathway, Volume 1, https://www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023; Bloomberg New Energy Outlook 2022, 2022 https://about.bnef.com/new-energy-outlook/; TUMI, Transport Outlook 1.5°, https://www.transformative-mobility.org/assets/publications/TUMI-Transport-Outlook.pdf; The International Council on Clean Transportation, 2020, "Vision 2050", https://theicct.org/vision-2050/.

19 IRENA, 2022, "Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and Way Forward", https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Global_hydrogen_trade_part_1_2022_.pdf?rev=f70cfbdcf3d34b40bc256383f54dbe73.

20 IEA, 2023, "Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach", https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach.

21 REN21 & FIA Foundation, 2020, "Renewable Energy Pathways in Road Transport", https://www.ren21.net/wp-content/uploads/2019/05/REN21_FIA-Fdn_Renewable-Energy-Pathways_FINAL.pdf

22 Global Subsidies Initiative (GSI) & International Institute for Sustainable Development (IISD), 2023, *Fanning the Flames: G20 provides record financial support for fossil fuels*, https://www.energypolicytracker.org/G20-fossil-fuel-support/.

23 Black, Simon, Antung Liu, Ian Parry, and Nate Vernon, 2023, "IMF Fossil Fuel Subsidies Data: 2023 Update," Working paper, https://www.imf.org/-/media/Files/Publications/WP/2023/English/wpiea2023169-print-pdf.ashx

24 BloombergNEF, 2023, "Cost of Clean Energy Technologies Drop as Expensive Debt Offset by Cooling Commodity Prices", https://about.bnef.com/blog/cost-of-clean-energy-technologies-drop-as-expensive-debt-offset-by-cooling-commodity-prices/.

25 IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.

26 IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.

27 IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.

28 MIT Climate Portal, 2023, "Why Have Electric Vehicles Won Out Over Hydrogen Cars (so far)?", https://climate.mit.edu/ask-mit/why-have-electric-vehicles-won-out-over-hydrogen-cars-so-far.

29 REN21, 2023, "Global Status Report 2023: Renewables in Energy Demand", https://www.ren21.net/gsr-2023/modules/energy_demand; IEA, 2023, "Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach", https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach.

30 IRENA, 2019, "Advanced biofuels: What holds them back?", https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Advanced-biofuels_2019.pdf.

31 IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.

32 International Transport Forum (ITF), 2023, "ITF Transport Outlook 2023", https://www.oecd-ilibrary.org/transport/itf-transport-outlook-2023_5fc66b10-en.

33 ITF, 2023, "ITF Transport Outlook 2023", https://www.oecd-ilibrary.org/transport/itf-transport-outlook-2023_5fc66b10-en.

34 J. Cooper, 2020, "Genuine technology neutrality in transport benefits 2050 climate targets", Politico, https://www.politico.eu/sponsored-content/genuine-technology-neutrality-in-transport-benefits-2050-climate-targets/

35 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.

36 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.

37 IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.

38 H2Stations.Org (blog), "Statistics: Hydrogen Infrastructure", accessed 27 March 2024, https://www.h2stations.org/statistics/.

39 IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.

40 Piet Andries, "Denmark Shuts down All of Its Hydrogen Fuel Stations", Newmobility.News (blog), 2023, https://newmobility.news/2023/09/18/denmark-shuts-down-all-of-its-hydrogen-fuel-stations/.

41 Sustainable Mobility for All, 2022, "Electromobility and Renewable Electricity: Developing Infrastructure for Synergies", https://www.sum4all.org/data/files/electromobility_and_renewable_electricity-developing_infrastructure_for_synergies.pdf.

42 Global Sustainability Initiative (GSI) & International Institute for Sustainable Development (IISD), 2023, "Fanning the Flames: G20 provides record financial support for fossil fuels", https://www.energypolicytracker.org/G20-fossil-fuel-support/.

43 BloombergNEF, 2023, "Cost of Clean Energy Technologies Drop as Expensive Debt Offset by Cooling Commodity Prices", https://about.bnef.com/blog/cost-of-clean-energy-technologies-drop-as-expensive-debt-offset-by-cooling-commodity-prices/.

44 IRENA, 2019, "Advanced biofuels: What holds them back?", https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Advanced-biofuels_2019.pdf; IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.

45 ITF, 2023, “ITF Transport Outlook 2023”, https://www.itf-oecd.org/itf-transport-outlook-2023.
46 ITF, 2023, “ITF Transport Outlook 2023”, https://www.oecd-ilibrary.org/transport/itf-transport-outlook-2023_5fc66b10-en; SLOCAT, 2023, “Transport, Climate and Sustainability Global Status Report, 3rd Edition”, https://tcc-gsr.com/.
47 ITF, 2023, “ITF Transport Outlook 2023”, https://www.itf-oecd.org/itf-transport-outlook-2023; SLOCAT, 2023, “Transport, Climate and Sustainability Global Status Report. 3rd Edition”, https://tcc-gsr.com/.
48 IEA, 2023, “Global Hydrogen Review 2023”, https://www.iea.org/reports/global-hydrogen-review-2023.
49 CALSTART, 2023, “Drive to Zero’s Zero-Emission Technology Inventory Data Explorer”, Version 1.0, https://globaldrivetozero.org/zeti-data-explorer/.
50 IEA, Global EV Outlook 2023: Catching up with climate ambitions, https://iea.blob.core.windows.net/assets/dacf14d2-eabc-498a-8263-9f97fd5dc327/GEVO2023.pdf.
51 US Department of Energy, ‘All-Electric Vehicles’, US Department of Energy, accessed 27 March 2024, http://www.fueleconomy.gov/feg/evtech.shtml.
52 REN21, ‘Global Status Report 2023: Renewables in Energy Demand’.; IEA, https://www.iea.org/reports/transport Energy consumption in transport by fuel in the Net Zero Scenario, 2000-2030
53 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.
54 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.
55 IEA, “Rail”, accessed September 2023, https://www.iea.org/energy-system/transport/rail.
56 IEA, 2021, "Trends and Developments in Electric Vehicle Markets", https://www.iea.org/reports/global-ev-outlook-2021/trends-and-developments-in-electric-vehicle-markets.
57 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.
58 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.
59 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.
60 MIT Energy Initiative, 2019, "Insights into Future Mobility", http://energy.mit.edu/insightsintofuturemobility.
61 ICCT, 2021, “A Global Comparison of the Life-cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars”, https://theicct.org/wp-content/uploads/2021/07/Global-Vehicle-LCA-White-Paper-A4-revised-v2.pdf
62 Georg Bieker, 2021, "A Global Comparison of the Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars", International Council on Clean Transportation (blog), https://theicct.org/publication/a-global-comparison-of-the-life-cycle-greenhouse-gas-emissions-of-combustion-engine-and-electric-passenger-cars/.
63 Zeke Hausfather, "Factcheck: How Electric Vehicles Help to Tackle Climate Change", Carbon Brief, 2019, https://www.carbonbrief.org/factcheck-how-electric-vehicles-help-to-tackle-climate-change/.
64 IEA, 2023, "Global EV Outlook 2023", https://iea.blob.core.windows.net/assets/dacf14d2-eabc-498a-8263-9f97fd5dc327/GEVO2023.pdf.
65 IRENA, “IRENASTAT Online Data Query Tool”, accessed January 2024, https://pxweb.irena.org/pxweb/en/IRENASTAT/IRENASTAT__Power%20Capacity%20and%20Generation/Country_ELECSTAT_2024_H1.px/.
66 REN21, 2023, "Global Status Report 2023: Renewables in Energy Demand",https://www.ren21.net/gsr-2023/modules/energy_demand
67 IRENA, 2023, “World Energy Transitions Outlook”, https://www.irena.org/Energy-Transition/Outlook.
68 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.
69 REN21, 2023, "Global Status Report 2023: Renewables in Energy Demand", https://www.ren21.net/gsr-2023/modules/energy_demand.
70 IEA, 2022, "Grid Integration of Electric Vehicles", https://www.iea.org/reports/grid-integration-of-electric-vehicles.
71 REN21, 2023, "Global Status Report 2023: Renewables in Energy Demand", https://www.ren21.net/gsr-2023/modules/energy_demand.
72 Kristen Brown and Chris Teague, "Upcoming Electric Cars: 2024-2030", US News & World Report, 2024, https://cars.usnews.com/cars-trucks/advice/future-electric-cars.
73 Paul Lienert and Tina Bellon, "Exclusive: Global Carmakers Now Target $515 Billion for EVs, Batteries", *Reuters*, 2021, sec. Disrupted, https://www.reuters.com/business/autos-transportation/exclusive-global-carmakers-now-target-515-billion-evs-batteries-2021-11-10/.
74 National Automobile Dealers Association, 2023, ”Beyond the Sticker Price: The Cost of Ownership of EVs V. ICE Vehicles”, https://www.nada.org/nada/nada-headlines/beyond-sticker-price-cost-ownership-evs-v-ice-vehicles
75 M. Bryla, ”To EV or not to EV? A clear cost analysis between electric vehicles and ICE cars”, The Driven, 2023, https://thedriven.io/2023/02/02/to-ev-or-not-to-ev-a-clear-cost-analysis-between-electric-vehicles-and-ice-cars/.
76 Saral Chauhan, Malte Hans, Moritz Rittstieg and Saleem Zafar, "The Economics of Fleet Electrification", McKinsey, 2023, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/why-the-economics-of-electrification-make-this-decarbonization-transition-different; Michael Krail, "Electric versus Internal Combustion Engine (ICE) Cars - Cost Analysis Reveals Clear Advantage for Electric Vehicles", Fraunhofer Institute for Systems and Innovation Research, 2023, https://www.isi.fraunhofer.de/en/presse/2023/presseinfo-04-elektroauto-versus-Verbrenner-Kostenanalyse.html.
77 International Renewable Energy Agency, ‘Renewable Power Generation Costs in 2022’ (Abu Dhabi: IRENA, 2023), https://www.irena.org/Publications/2023/Aug/Renewable-Power-Generation-Costs-in-2022.
78 International Renewable Energy Agency, ‘Renewable Power Generation Costs in 2022’ (Abu Dhabi: IRENA, 2023), https://www.irena.org/Publications/2023/Aug/Renewable-Power-Generation-Costs-in-2022.
79 Humphrye Njogu, ‘Accelerating Adoption of Electric Vehicles for Sustainable Transport in Nairobi’, Brookings, 2023, https://www.brookings.edu/articles/accelerating-adoption-of-electric-vehicles-for-sustainable-transport-in-nairobi/.
80 Adekunle Agbetiloye, ‘Kenya Making Great Strides to Become Africa’s Electric Vehicle Hub’, ESI-Africa.Com (blog), 2023, https://www.esi-africa.com/features-analysis/kenya-making-great-strides-to-become-africas-electric-vehicle-hub/.
81 James Fox, ‘What Is Vietnam’s Mining Capacity for EV Batteries?’, Vietnam Briefing, 2022, https://www.vietnam-briefing.com/news/what-is-vietnams-mining-capacity-for-ev-batteries.html/.
82 Huong Le, Francisco Posada, and Zifei Yang, ‘Electric Two-Wheeler Market Growth in Vietnam: An Overview’, *International Council on Clean Transportation*, 2022, https://theicct.org/wp-content/uploads/2022/10/asia-pacific-lvs-NDC-TIA-E2W-mkt-growth-Vietnam-nov22.pdf.
83 US Energy Information Administration, ‘What Is U.S. Electricity Generation by Energy Source?’, 2024, https://www.eia.gov/tools/faqs/faq.php; Clarion Energy Content Directors, ‘Solar and Wind Will Trim Fossil Generation’s Market Share through ’24, EIA Says’, *Power Engineering* (blog), 2023, https://www.power-eng.com/renewables/electric-power/; Changying Zhao et al., ‘China’s Energy Transitions for Carbon Neutrality: Challenges and Opportunities’, *Carbon Neutrality* 1, no. 1 (2022): 7, https://doi.org/10.1007/s43979-022-00010-y.
84 IEA, 2022, “World Energy Outlook”, https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf.
85 IEA, 2023, “Critical Minerals Market Review 2023”, https://iea.blob.core.windows.net/assets/afc35261-41b2-47d4-86d6-d5d77fc259be/CriticalMineralsMarketReview2023.pdf.
86 IEA, 2023, “Critical Minerals Market Review 2023”, https://iea.blob.core.windows.net/assets/afc35261-41b2-47d4-86d6-d5d77fc259be/CriticalMineralsMarketReview2023.pdf.
87 IEA, 2022, “World Energy Outlook Special Report, The Role of Critical Minerals in Clean Energy Transitions”, https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf.
88 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023; T. Lipman & P. Maier, 2022, “Advanced materials supply considerations for electric vehicle applications”, MRS Bulletin, https://link.springer.com/article/10.1557/s43577-022-00263-z.
89 Scott Gorman, "6 Ways Solid-State Batteries Are Better than Lithium-Ion Ones", CPI, 2023, https://www.uk-cpi.com/blog/6-ways-solid-state-batteries-are-better-than-lithium-ion-alternatives-in-electric-vehicles.
90 Reuters, 2022, "Taiwan Battery Maker ProLogium Signs Investment Deal with Mercedes-Benz", https://www.reuters.com/markets/deals/taiwan-battery-maker-prologium-signs-investment-deal-with-mercedes-benz-2022-01-27/.
91 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.
92 T. Lipman & P. Maier, 2022, “Advanced materials supply considerations for electric vehicle applications”, MRS Bulletin, https://link.springer.com/article/10.1557/s43577-022-00263-z.
93 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.
94 T. Lipman & P. Maier, 2022, “Advanced materials supply considerations for electric vehicle applications”, MRS Bulletin, https://link.springer.com/article/10.1557/s43577-022-00263-z.
95 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.
96 N. Mughees, 2020, “Switched reluctance motors for electric vehicles”, https://insights.globalspec.com/article/14597/switched-reluctance-motors-for-electric-vehicles; T. Lipman & P. Maier, 2022, “Advanced materials supply considerations for electric vehicle applications”, MRS Bulletin, https://link.springer.com/article/10.1557/s43577-022-00263-z.

97 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023; Trading Economics, "Commodity", accessed March 2023, https://tradingeconomics.com/commodity/.

98 IEA, 2023, 'Trends in Batteries – Global EV Outlook 2023 – Analysis', https://www.iea.org/reports/global-ev-outlook-2023/trends-in-batteries.

99 IEA, 2023, 'Trends in Batteries – Global EV Outlook 2023 – Analysis', https://www.iea.org/reports/global-ev-outlook-2023/trends-in-batteries.

100 Dustin Hawley, 'How Much Do EV Batteries Cost?', J.D. Power, 2023, https://www.jdpower.com/cars/shopping-guides/how-much-do-ev-batteries-cost.

101 McKinsey & Company, 'Battery Recycling Takes the Driver's Seat', McKinsey & Company, 2023, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-recycling-takes-the-drivers-seat.

102 Marie McNamara, 'How Policy Can Advance a Circular Battery Economy', RMI, 2023, https://rmi.org/how-policy-can-advance-a-circular-battery-economy/.

103 United States Department of Energy, 2023, "Department of Energy Announces $2 million to Enhance Domestic Advancements in Lithium-Ion Battery Recycling and Remanufacturing", https://www.energy.gov/eere/ammto/articles/department-energy-announces-2-million-enhance-domestic-advancements-lithium-ion#:~:text=The%20U.S.%20Department%20of%20Energy's,administered%20through%20the%20ReCell%20Center.

104 ICCT, 2023, "Will the U.S. EV battery recycling industry be ready for millions of end-of-life batteries?", https://theicct.org/us-ev-battery-recycling-end-of-life-batteries-sept23/.

105 Zi-Hoon Lee and Hyung-Kyu Kim, "Seoul Pushes for Battery Recycling to Bypass US Bill", The Korea Economic Daily, 2022, https://www.kedglobal.com/batteries/newsView/ked202209160009.

106 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.

107 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.

108 Dave Nichols, "Environmental Impact of EV Batteries", GreenCars, 2023, https://www.greencars.com/greencars-101/environmental-impact-of-ev-batteries.

109 Ivan Penn, Eric Lipton, and Gabriella Angotti-Jones, "The Lithium Gold Rush: Inside the Race to Power Electric Vehicles", *The New York Times*, 2021, https://www.nytimes.com/2021/05/06/business/lithium-mining-race.html; RT.com, "The Green Scam: How Electric Vehicles Harm the Environment That They're Supposed to Save", Big News Network, 2023, https://www.bignewsnetwork.com/news/274044226/the-green-scam-how-electric-vehicles-harm-the-environment-that-theyre-supposed-to-save.

110 International Battery Metals, 2021, "What are the sources for lithium?", 28 July, https://www.ibatterymetals.com/insights/what-are-the-sources-for-lithium.

111 M. Vera, W. Torres, C. Galli, Al Chagnes & V. Flexer, 2023, Environmental impact of direct lithium extraction from brines, Nature Reviews Earth & Environment, Volume 4, March, https://www.nature.com/articles/s43017-022-00387-5; Parker SS, Franklin BS, Williams A, Cohen BS, Clifford, MJ, Rohde MM, 2022, *Potential Lithium Extraction in the United States: Environmental, Economic, and Policy Implications*, https://www.scienceforconservation.org/products/lithium.

112 Parker SS, Franklin BS, Williams A, Cohen BS, Clifford, MJ, Rohde MM, 2022, Potential Lithium Extraction in the *United States: Environmental, Economic, and Policy Implications*, https://www.scienceforconservation.org/products/lithium.

113 Parker SS, Franklin BS, Williams A, Cohen BS, Clifford, MJ, Rohde MM, 2022, *Potential Lithium Extraction in the United States: Environmental, Economic, and Policy Implications*, https://www.scienceforconservation.org/products/lithium

114 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.

115 IEA, 2023, "Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach", https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach.

116 ITF, 2023, "ITF Transport Outlook 2023", https://www.oecd-ilibrary.org/transport/itf-transport-outlook-2023_5fc66b10-en.

117 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.

118 Catherine Ledna et al., "Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis", 7 March 2022, https://doi.org/10.2172/1854583.

119 The White House, 2022, "Fact Sheet: Vice President Harris Announces Actions to Accelerate Clean Transit Buses, School Buses, and Trucks", https://www.whitehouse.gov/briefing-room/statements-releases/2022/03/07/fact-sheet-vice-president-harris-announces-actions-to-accelerate-clean-transit-buses-school-buses-and-trucks/.

120 Niels Anner, "How to Cut Europe's Ferry Emissions in Half", Siemens Energy, 2022, https://www.siemens-energy.com/global/en/home/stories/the-electrification-of-europes-ferry-fleet.html, https://www.siemens-energy.com/global/en/home/stories/the-electrification-of-europes-ferry-fleet.html.

121 ITF, 2023, "Decarbonisation, Coastal Shipping and Multimodal Transport", Roundtable summary, https://www.itf-oecd.org/sites/default/files/docs/decarbonisation-coastal-shipping-multimodal-transport.pdf.

122 Infineon, 2021, "Why ships of the future will run on electricity", https://www.infineon.com/cms/en/discoveries/electrified-ships/.

123 Yara, 2021, "Yara to start operating the world's first fully emission-free container ship", Press release, https://www.yara.com/corporate-releases/yara-to-start-operating-the-worlds-first-fully-emission-free-container-ship/?_gl=1*op44m4*_up*MQ..*_ga*NzI1Njg3ODA3LjE3MDE5NDg1NTk.*_ga_W5MJZ2GTWV*MTcwMTk0ODU1OS4xLjAuMTcwMTk0ODU1OS4wLjAuMA.

124 Sustainable Ships, 2023, *"COSCO 700 TEU Full Electric Container Ship"*, https://www.sustainable-ships.org/stories/2023/cosco-700-teu-full-electric-container-ship; ITF, 2023, "Decarbonisation, Coastal Shipping and Multimodal Transport", Roundtable summary, https://www.itf-oecd.org/sites/default/files/docs/decarbonisation-coastal-shipping-multimodal-transport.pdf.

125 Volvo, "Our Electric Truck Range", Volvo Trucks, 2024, https://www.volvotrucks.com/en-en/trucks/electric.html.

126 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023; Hongyang Cui, Yihao Xie and Tianlin Niu, "China Is Propelling Its Electric Truck Market by Embracing Battery Swapping", *International Council on Clean Transportation* (blog), 2023, https://theicct.org/china-is-propelling-its-electric-truck-market-aug23/.

127 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.

128 CALSTART, "ZETI Data Explorer", Global Commercial Vehicle Drive to Zero, accessed 28 March 2024, https://globaldrivetozero.org/tools/zeti-data-explorer/.

129 Steve Hanley, 'Scania & Northvolt Announce New Battery For Heavy-Duty Trucks', CleanTechnica, 2023, https://cleantechnica.com/2023/04/23/scania-northvolt-announce-new-battery-for-heavy-duty-trucks/; Scania, 'Scania and Northvolt Unveil Green Battery Capable of Powering Trucks for 1.5 Million Kilometers', Scania Group, 2023, https://www.scania.com/group/en/home/newsroom/press-releases/press-release-detail-page.html/4518788-scania-and-northvolt-unveil-green-battery-capable-of-powering-trucks-for-1-5-million-kilometers.

130 Volvo, "Our Electric Truck Range", Volvo Trucks, 2024, https://www.volvotrucks.com/en-en/trucks/electric.html.

131 Stan Lee, "Samsung SDI to supply batteries for Volvo's electric trucks launching in 2022", THE ELEC, 2021, http://thelec.net/news/articleView.html?idxno=2227.

132 Glenn Research Center, "Electrified Aircraft Propulsion (EAP)", NASA, 2024, https://www1.grc.nasa.gov/aeronautics/eap/.

133 IATA, "Our Commitment to Fly Net Zero by 2050", accessed 28 March 2024, https://www.iata.org/en/programs/environment/flynetzero/.

134 Jayant Mukhopadhaya, "What to Expect When Expecting Electric Airplanes", *International Council on Clean Transportation* (blog), 2022, https://theicct.org/aviation-global-expecting-electric-jul22/.

135 ITF, 2023, "ITF Transport Outlook 2023", https://www.oecd-ilibrary.org/transport/itf-transport-outlook-2023_5fc66b10-en.

136 Casey Crownhart, 'The Runway for Futuristic Electric Planes Is Still a Long One', MIT Technology Review, 2023, https://www.technologyreview.com/2023/03/14/1069724/futuristic-electric-planes-evtols/.

137 DHL, "Electricity Is in the Air as E-Cargo Planes Take Flight", accessed 28 March 2024, https://www.dhl.com/global-en/delivered/sustainability/electric-aircraft-sustainable-logistics.html; Dayna Fedy-Macdonald, "Orders for Eviation Alice All-Electric Aircraft Now Valued at over US$4 Billion", Skies Mag (blog), 2023, https://skiesmag.com/news/orders-eviation-alice-all-electric-aircraft-valued-over-4-billion/.

138 Airbus, 2021, "Towards the World's First Hydrogen-Powered Commercial Aircraft", https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe.

139 SLOCAT, 2023, "Transport, Climate and Sustainability Global Status Report. 3rd Edition", https://tcc-gsr.com/.

140 Marie Rajon Bernard et al., "Charging Solutions for Battery Electric Trucks", The International Council on Clean Transport, 2022, https://theicct.org/wp-content/uploads/2022/12/charging-infrastructure-trucks-zeva-dec22.pdf.

141 Marie Rajon Bernard et al., "Charging Solutions for Battery Electric Trucks", The International Council on Clean Transport, 2022, https://theicct.org/wp-content/uploads/2022/12/charging-infrastructure-trucks-zeva-dec22.pdf

142 IEA, 2023, "Trends in Charging Infrastructure – Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023/trends-in-charging-infrastructure.

143 Marie Rajon Bernard et al., "Charging Solutions for Battery Electric Trucks", The International Council on Clean Transport, 2022, https://theicct.org/wp-content/uploads/2022/12/charging-infrastructure-trucks-zeva-dec22.pdf

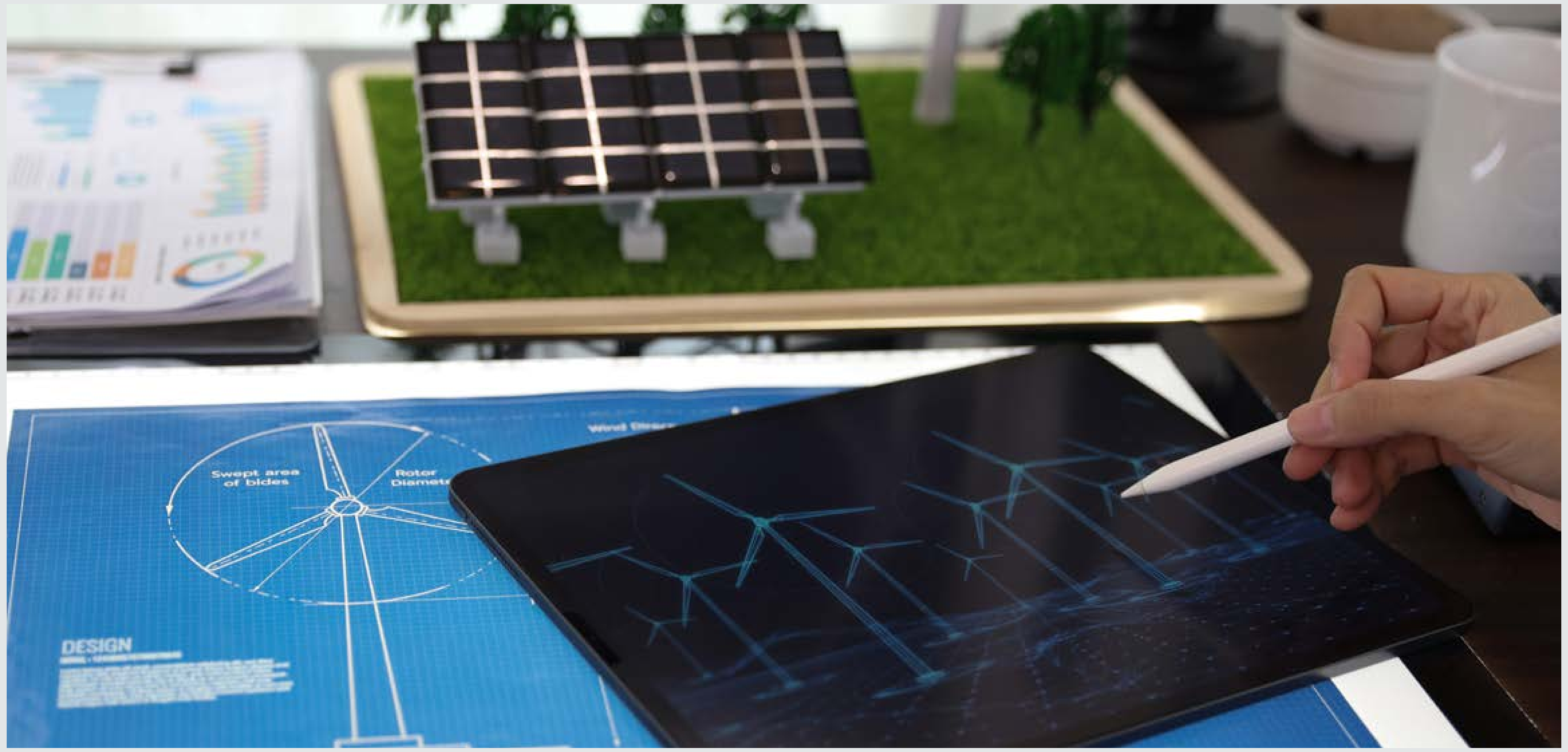
144 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.
145 Janus Electric, "Electrifying Australia's Road Transport Fleet with Tomorrows Technology, Today", accessed 28 March 2024, https://www.januselectric.com.au.
146 Carrie Hampel, "Mitsubishi Fuso & Ample Trial Truck Battery Swapping", electrive, 2023, https://www.electrive.com/2023/07/26/mitsubishi-fuso-ample-trial-truck-battery-swapping/.
147 IEA, 2023, "Global EV Outlook 2023", https://www.iea.org/reports/global-ev-outlook-2023.
148 Bernard et al., 'Charging Solutions for Battery Electric Trucks'.
149 REN21 & FIA Foundation, 2020, "Renewable Energy Pathways in Road Transport", https://www.ren21.net/wp-content/uploads/2019/05/REN21_FIA-Fdn_Renewable-Energy-Pathways_FINAL.pdf.
150 IRENA, 2020, "Green Hydrogen: A Guide to Policy Making",https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_hydrogen_policy_2020.pdf?rev=c0cf115d8c724e4381343cc93e03e9e0.
151 Energy Efficiency & Renewable Energy, "Hydrogen Delivery", Energy.gov, accessed 28 March 2024, https://www.energy.gov/eere/fuelcells/hydrogen-delivery.
152 IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.
153 REN21, 2023, "Global Status Report 2023: Renewables in Energy Demand", https://www.ren21.net/gsr-2023/modules/energy_demand.
154 IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.
155 IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.
156 IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.
157 IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.
158 IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.
159 IEA, 2023, "Trends in Electric Light-Duty Vehicles", https://www.iea.org/reports/global-ev-outlook-2023/trends-in-electric-light-duty-vehicles.
160 IEA, 2023, "Trends in Electric Light-Duty Vehicles", https://www.iea.org/reports/global-ev-outlook-2023/trends-in-electric-light-duty-vehicles.
161 IEA, 2023, "Trends in Electric Light-Duty Vehicles", https://www.iea.org/reports/global-ev-outlook-2023/trends-in-electric-light-duty-vehicles.
162 IEA, 2023, "Trends in Electric Light-Duty Vehicles", https://www.iea.org/reports/global-ev-outlook-2023/trends-in-electric-light-duty-vehicles.
163 IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.
164 Michael Liebreich, "Hydrogen Ladder Version 5.0", LinkedIn, 2023, https://www.linkedin.com/pulse/hydrogen-ladder-version-50-michael-liebreich/?trackingId=oNrEljRCQ%2FCBCcqZ3kb6Hg%3D%3D.
165 SLOCAT, 2023, "Transport, Climate and Sustainability Global Status Report, 3rd Edition", https://tcc-gsr.com/.
166 Sam Wilson, "Hydrogen-Powered Heavy-Duty Trucks: A Review of the Environmental and Economic Implications of Hydrogen Fuel for on-Road Freight", Union of Concerned Scientists, 2023, https://doi.org/10.47923/2023.15274.
167 IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.
168 Einride, 2023 "Electric vs Hydrogen Trucks: "The Gap Will Widen", https://www.einride.tech/insights/prof-david-cebon-on-electric-vs-hydrogen-the-gap-will-widen; CNET, "Cheapest Electric Cars for 2024", accessed 28 March 2024, https://www.cnet.com/roadshow/news/the-most-affordable-electric-cars/.
169 Leigh Collins, "Global Sales of Hydrogen-Powered Vehicles Fall by 11.5% in First Four Months of 2023", Hydrogen Insight, 2023, https://www.hydrogeninsight.com/transport/global-sales-of-hydrogen-powered-vehicles-fall-by-11-5-in-first-four-months-of-2023/2-1-1466755.
170 Rachel Parkes, "South Korea Set to Double Hydrogen Bus Subsidy Budget in 2024 to Finance up to 1,500 Vehicles", Hydrogen news and intelligence | Hydrogen Insight, 2023, https://www.hydrogeninsight.com/transport/south-korea-set-to-double-hydrogen-bus-subsidy-budget-in-2024-to-finance-up-to-1-500-vehicles/2-1-1495868.
171 Leigh Collins, "Netherlands Unveils €150m Plan to Subsidise Hydrogen Trucks, Vans, Buses and Filling Stations", Hydrogen Insight, 2023, https://www.hydrogeninsight.com/transport/netherlands-unveils-150m-plan-to-subsidise-hydrogen-trucks-vans-buses-and-filling-stations/2-1-1526684.
172 IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.
173 H2Stations.Org (blog), "Statistics: Hydrogen Infrastructure", accessed 27 March 2024, https://www.h2stations.org/statistics/.
174 Thomas Oberst, "Press Release: Europe Is Increasingly Adapting Its Growing Hydrogen Refuelling Infrastructure to Include Heavy-Duty Vehicle Refuelling" (LBST, 2024), https://www.h2stations.org/wp-content/uploads/2024-01-24-LBST-HRS-2023-en.pdf.
175 Polly Martin, "Shell to Permanently Close All of Its Hydrogen Refuelling Stations for Cars in California", Hydrogen Insight, 2024, https://www.hydrogeninsight.com/transport/shell-to-permanently-close-all-of-its-hydrogen-refuelling-stations-for-cars-in-california/2-1-1596104.
176 Innovation Origin, "First Shell, Now Motive, Hydrogen Fuel Station Clusures Continue in the UK", IO, 2023, https://innovationorigins.com/en/first-shell-now-motive-hydrogen-fuel-station-closures-continue-in-the-uk/.
177 Daryl Wilson, 'Toward a Cross-Border, Global Hydrogen Trade Market', *Hydrogen Council* (blog), 2022, https://hydrogencouncil.com/en/toward-a-cross-border-global-hydrogen-trade-market/.
178 IRENA, 2021, "World Energy Transitions Outlook: 1.5°C Pathway", https://www.irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook.
179 IEA, 2023, "Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach", https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach.
180 BloombergNEF, 2023, "Cost of New Renewables Temporarily Rises as Inflation Starts to Bite", https://about.bnef.com/blog/cost-of-new-renewables-temporarily-rises-as-inflation-starts-to-bite/.
181 BloombergNEF, 2023, "Cost of New Renewables Temporarily Rises as Inflation Starts to Bite", https://about.bnef.com/blog/cost-of-new-renewables-temporarily-rises-as-inflation-starts-to-bite/.
182 REN21, 2023, Renewables 2023 Global Status Report: Economic and Social Value Creation, https://www.ren21.net/wp-content/uploads/2019/05/GSR2023_EconSocialValueCreation_Full_Report_with_endnotes_web.pdf
183 IEA, 2023, "Declining Electricity Consumption in Advanced Economies Is Weighing on Global Demand Growth This Year", https://www.iea.org/news/declining-electricity-consumption-in-advanced-economies-is-weighing-on-global-demand-growth-this-year.
184 IEA, 2023, "Declining Electricity Consumption in Advanced Economies Is Weighing on Global Demand Growth This Year", https://www.iea.org/news/declining-electricity-consumption-in-advanced-economies-is-weighing-on-global-demand-growth-this-year.
185 IEA et al., 2021, "Tracking SDG 7: The Energy Progress Report", https://www.iea.org/reports/tracking-sdg7-the-energy-progress-report-2021.
186 IRENA, 2022, "Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and Way Forward", https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Global_hydrogen_trade_part_1_2022_.pdf.
187 IEA, 2023, "Global Hydrogen Review 2023", https://www.iea.org/reports/global-hydrogen-review-2023.
188 IRENA, 2022, "Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and Way Forward", https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Global_hydrogen_trade_part_1_2022_.pdf.
189 IEA, 2023, "Energy Technology Perspectives 2023", https://iea.blob.core.windows.net/assets/d1ec36e9-fb41-466b-b265-45b0e7a4af36/EnergyTechnologyPerspectives2023.pdf.
190 BloombergNEF, 2023, "Clean Hydrogen's Missing Trillions", https://about.bnef.com/blog/liebreich-clean-hydrogens-missing-trillions/.
191 Agora Verkehrswende, Agora Energiewende and Frontier Economics, 2018, "The Future Cost of Electricity-Based Synthetic Fuels", https://www.agora-energiewende.de/fileadmin/Projekte/2017/SynKost_2050/Agora_SynKost_Study_EN_WEB.pdf.
192 Green Hydrogen Organisation, "Morocco | Green Hydrogen Vision", accessed 28 March 2024, http://gh2.org/countries/morocco.
193 Gobierno de Chile, "National Green Hydrogen Strategy", Ministerio de Energia, 2020, https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf.
194 Directorate-General for Energy, "Renewable Hydrogen Production: New Rules Formally Adopted", European Commission, 2023, https://energy.ec.europa.eu/news/renewable-hydrogen-production-new-rules-formally-adopted-2023-06-20_en.
195 Government of Australia, Department of Climate Change, Energy, the Environment and Water, "State of Hydrogen 2022", 2022, https://www.dcceew.gov.au/energy/publications/ state-of-hydrogen-2022.
196 J. Nakano, "China's Hydrogen Industrial Strategy", Center for Strategic and International Studies, February 3, 2022, https://www.csis.org/analysis/chinas-hydrogen-industrial-strategy.
197 National Development and Reform Commission, "China Hydrogen National Strategy", March 23, 2022, https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/t20220323_1320038.html; Y. Yu, "China's National Hydrogen Development Plan", Energy Iceberg, April 6, 2022, https://energyiceberg.com/national-hydrogen-development-plan.
198 IRENA, 2022, "Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and Way Forward", https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Global_hydrogen_trade_part_1_2022_.pdf.
199 TWI, 'What Is Hydrogen Storage and How Does It Work?', TWI, 2024, https://www.twi-global.com/technical-knowledge/faqs/what-is-hydrogen-storage.aspx.

200 Fadwa Eljack and Monzure-Khoda Kazi, 'Prospects and Challenges of Green Hydrogen Economy via Multi-Sector Global Symbiosis in Qatar', *Frontiers in Sustainability* 1 (2021), https://doi.org/10.3389/frsus.2020.612762.
201 Fuyuan Yang et al., 'Review on Hydrogen Safety Issues: Incident Statistics, Hydrogen Diffusion, and Detonation Process', *International Journal of Hydrogen Energy* 46, no. 61 (2021): 31467–88, https://doi.org/10.1016/j.ijhydene.2021.07.005.
202 Hao Li et al., 'Safety of Hydrogen Storage and Transportation: An Overview on Mechanisms, Techniques, and Challenges', *Energy Reports* 8 (1 November 2022): 6258–69, https://doi.org/10.1016/j.egyr.2022.04.067.
203 Eljack and Kazi, 'Prospects and Challenges of Green Hydrogen Economy via Multi-Sector Global Symbiosis in Qatar', Frontiers in Sustainability, 21 January, 2021, https://www.frontiersin.org/articles/10.3389/frsus.2020.612762/full; International Energy Agency (IEA), 'Global Hydrogen Review 2023', IEA, 2023, https://www.iea.org/reports/global-hydrogen-review-2023.
204 Maria Sand et al., 'A Multi-Model Assessment of the Global Warming Potential of Hydrogen', *Communications Earth & Environment* 4, no. 1 (2023): 1–12, https://doi.org/10.1038/s43247-023-00857-8.
205 Nikolaus Kurmayer, 'Scientists Reiterate Concerns about Climate-Warming Hydrogen Leaks', EURACTIV, 2023, https://www.euractiv.com/section/energy-environment/news/scientists-reiterate-concerns-about-climate-warming-hydrogen-leaks/.
206 Viviana Negro, Michel Noussan, and David Chiaramonti, 'The Potential Role of Ammonia for Hydrogen Storage and Transport: A Critical Review of Challenges and Opportunities', *Energies* 16, no. 17 (January 2023): 6192, https://doi.org/10.3390/en16176192.
207 Martin Cames, Nora Wissner, and Jürgen Sutter, 'Ammonia as a Marine Fuel Risks and Perspectives' (Berlin: Institute for Applied Ecology, 2021), https://en.nabu.de/imperia/md/content/nabude/verkehr/210622-nabu-study-ammonia-marine-fuel.pdf.
208 Negro, Noussan, and Chiaramonti, 'The Potential Role of Ammonia for Hydrogen Storage and Transport', Energies 2023, https://doi.org/10.3390/en16176192.
209 Phan Anh Duong et al., 'Safety Assessment of the Ammonia Bunkering Process in the Maritime Sector: A Review', *Energies* 16, no. 10 (2023): 4019, https://doi.org/10.3390/en16104019.
210 Rachel Parkes, 'SPECIAL REPORT | Burns, Blindness and Agonising Deaths: Is It Safe to Ship Hydrogen-Derived Ammonia around the World?', Hydrogen Insight, 2022, https://www.hydrogeninsight.com/transport/special-report-burns-blindness-and-agonising-deaths-is-it-safe-to-ship-hydrogen-derived-ammonia-around-the-world-/2-1-1327957.
211 Demaco, 'Hydrogen Transportation: Three Well-Known Energy Carriers Compared', *Demaco Cryogenics* (blog), 2024, https://demaco-cryogenics.com/blog/hydrogen-transportation-three-energy-carriers/.
212 Negro, Noussan, and Chiaramonti, 'The Potential Role of Ammonia for Hydrogen Storage and Transport', Energies 2023, https://doi.org/10.3390/en16176192.
213 Parkes, "Burns, blindness and agonising deaths: is it safe to ship hydrogen-derived ammonia around the world?", Recharge News, July 2022, https://www.rechargenews.com/energy-transition/special-report-burns-blindness-and-agonising-deaths-is-it-safe-to-ship-hydrogen-derived-ammonia-around-the-world-/2-1-1267513; Samie Parkar, 'The Maritime Decarbonisation Hub', 2023, https://www.ammoniaenergy.org/wp-content/uploads/2023/02/Maritime-Insights-speaker-slides-Feb-2023.pdf.
214 REN21, 2023, "Global Status Report 2023: Renewables in Energy Demand", https://www.ren21.net/gsr2023-demand-modules.
215 IEA, 2022, "Renewables 2022", https://iea.blob.core.windows.net/assets/ada7af90-e280-46c4-a577-df2e4fb44254/Renewables2022.pdf
216 Motola et.al., "Clean Energy Technology Observatory: Advanced biofuels in the European Union - 2023 Status Report on Technology Development, Trends, Value Chains and Markets", Publications Office of the European Union, https://publications.jrc.ec.europa.eu/repository/handle/JRC135082.
217 Motola et.al., "Clean Energy Technology Observatory: Advanced biofuels in the European Union - 2023 Status Report on Technology Development, Trends, Value Chains and Markets", Publications Office of the European Union, https://publications.jrc.ec.europa.eu/repository/handle/JRC135082.
218 Jeswani et.al., 2020, "Environmental sustainability of biofuels: a review", https://royalsocietypublishing.org/doi/10.1098/rspa.2020.0351#d1e3146; Pereira et.al., 2019, "Comparison of biofuel life-cycle GHG emissions assessment tools: The case studies of ethanol produced from sugarcane, corn, and wheat", Renewable and Sustainable Energy Reviews, https://www.sciencedirect.com/science/article/abs/pii/S1364032119302552.
219 Elshout et.al., 2022, "Comparing greenhouse gas footprints and payback times of crop-based biofuel production worldwide", BIOFUELS-UK, https://www.tandfonline.com/doi/epub/10.1080/17597269.2019.1630056/.
220 Jeswani et.al., 2020, "Environmental sustainability of biofuels: a review", https://royalsocietypublishing.org/doi/10.1098/rspa.2020.0351#d1e3146;
221 Jeswani et.al., 2020, "Environmental sustainability of biofuels: a review", https://royalsocietypublishing.org/doi/10.1098/rspa.2020.0351#d1e3146;
222 IEA Bioenergy, 2023, "Assessment of Successes and Lessons Learned for Biofuels Deployment", https://www.ieabioenergy.com/wp-content/uploads/2022/08/IEABio_LLBF_WP4-Report_final.pdf.
223 European Parliament, 2024, "Revision of the Renewable Energy Directive | Legislative Train Schedule", https://www.europarl.europa.eu/legislative-train/package-fit-for-55/file-revision-of-the-renewable-energy-directive.
224 European Union, 2024, "Official Journal of the European Union", https://eur-lex.europa.eu/TodayOJ/.
225 European Union, 2024, "Official Journal of the European Union", https://eur-lex.europa.eu/TodayOJ/.
226 European Union, 2024, "Official Journal of the European Union", https://eur-lex.europa.eu/TodayOJ/.
227 IEA, 2022, "Improvement Opportunities for Policies and Certification Schemes Promoting Sustainable Biofuels with Low GHG Emissions Part 1: A Review of Policy Frameworks", https://task39.ieabioenergy.com/wp-content/uploads/sites/37/2022/12/Improvement-opportunities-for-low-carbon-sustainable-biofuel-policies-and-certification-schemes.pdf.
228 Agora Verkehrswende, 2023, "Towards Decarbonising Transport 2023. A Stocktake on Sectoral Ambition in the G20", https://www.agora-verkehrswende.de/en/publications/towards-decarbonising-transport-2023/.
229 Subchefia para Assuntos Jurídicos, 'Decreto No 7172' Presidência da República Casa Civil Subchefia para Assuntos Jurídicos, 2010, https://www.planalto.gov.br/ccivil_03/_Ato2007-2010/2010/Decreto/D7172.htm.
230 Monica Prestes, 2022, "Palm Oil for Biodiesel in the Amazon: Sustainable Fuel or Deforestation Risk?", https://www.globalissues.org/news/2022/04/04/30517.
231 IEA, 2017, "Technology Roadmap: Delivering Sustainable Bioenergy", https://www.ieabioenergy.com/blog/publications/technology-roadmap-delivering-sustainable-bioenergy/.
232 Food and Agriculture Organization of the United Nations (FAO), 2024, "The Bioenergy and Food Security (BEFS) Approach", https://www.fao.org/energy/befs/en/.
233 FAO, "GBEP Sustainability Indicators", Global Bioenergy Partnership, accessed 3 April 2024, https://www.fao.org/in-action/global-bioenergy-partnership/programme-of-work/working-areas/gbep-sustainability/en.
234 Glasgow Declaration in Sustainable Bioenergy, "Transparency, Trust and Best Practice of Responsible Biomass Use", accessed 14 November 2023, https://sustainablebioenergy.org/wp-content/uploads/GSBD_2023Report_Transparency-trustandbestpracticeofresponsiblebiomassuse.pdf.
235 ISO, 2015, Sustainability criteria for bioenergy, ISO 13065:2015 – Sustainability criteria for bioenergy
236 European Commission, 2021, "Commission Presents Renewable Energy Directive Revision", https://commission.europa.eu/news/commission-presents-renewable-energy-directive-revision-2021-07-14_en.
237 NDRC, 2014, "Biofuel Sustainability Performance Guidelines", https://www.nrdc.org/resources/sustainability-certification-biofuels.
238 European Comission, "Voluntary Schemes", accessed 3 April 2024, https://energy.ec.europa.eu/topics/renewable-energy/bioenergy/voluntary-schemes_en.
239 IRENA, 2022, Renewable Energy Employment by Technology in 2022, https://www.irena.org/Data/View-data-by-topic/Benefits/Renewable-Energy-Employment-by-Country.
240 IRENA, 2021, "World Energy Transitions Outlook: 1.5°C Pathway", https://www.irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook.
241 Md Mosleh Uddin and Mark Mba Wright, "Anaerobic Digestion Fundamentals, Challenges, and Technological Advances", *Physical Sciences Reviews* 8, no. 9 (1 September 2023): 2819–37, https://doi.org/10.1515/psr-2021-0068.
242 FAO, 2022, "Fuel Not Fire: From Burning Crop Waste to Bioenergy", http://www.fao.org/fao-stories/article/en/c/1303769/.
243 IEA, 2023, "Renewable Energy Market Update", https://www.iea.org/reports/renewable-energy-market-update-june-2023/will-energy-security-concerns-drive-biofuel-growth-in-2023-and-2024.
244 IEA, 2023, "Renewable Energy Market Update", https://www.iea.org/reports/renewable-energy-market-update-june-2023/will-energy-security-concerns-drive-biofuel-growth-in-2023-and-2024.
245 IRENA, 2021, "World Energy Transitions Outlook: 1.5°C Pathway", https://www.irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook.
246 Milton Bastos, "Brazil's Ethanol Program – An Insider's View", Energy Tribune, 2007, https://web.archive.org/web/20110710193215/http://www.energytribune.com/articles.cfm?aid=534.
247 Carlos Alexandre de Oliveira, "Brazil Has Over 34 million Licensed Vehicles, One of the Largest Flex-Fuel Fleets in the World", *Climate Scorecard* (blog), 2022, 34, https://www.climatescorecard.org/2022/11/brazil-has-over-34-million-licensed-vehicles-one-of-the-largest-flex-fuel-fleets-in-the-world/.
248 IEA, 2022, "Is the Biofuel Industry Approaching a Feedstock Crunch?", https://www.iea.org/reports/is-the-biofuel-industry-approaching-a-feedstock-crunch.

249 IEA, 2022, "Is the Biofuel Industry Approaching a Feedstock Crunch?", https://www.iea.org/reports/is-the-biofuel-industry-approaching-a-feedstock-crunch.
250 IRENA, 2022, "World Energy Transitions Outlook 2022", https://www.irena.org/Digital-Report/World-Energy-Transitions-Outlook-2022.
251 IEA, 2023, "Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach", https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach.
252 IRENA, 2023, "World Energy Transitions: Outlook 2023. 1.5°C Pathway", https://www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023.
253 IRENA, 2023, "World Energy Transitions: Outlook 2023. 1.5°C Pathway", https://www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023.
254 IEA, 2023, "Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach", https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach.
255 IEA, 2022, "Is the Biofuel Industry Approaching a Feedstock Crunch?", https://www.iea.org/reports/is-the-biofuel-industry-approaching-a-feedstock-crunch.
256 IEA, 2022, "Is the Biofuel Industry Approaching a Feedstock Crunch?", https://www.iea.org/reports/is-the-biofuel-industry-approaching-a-feedstock-crunch.
257 IPCC, WGIII, AR6, Chapter 7: Agriculture, Forestry and Other Land Uses (AFOLU) https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter07.pdf
258 IRENA, 2023, "Agricultural residue-based bioenergy: Regional potential and scale-up strategies", https://www.irena.org/Publications/2023/Nov/Agricultural-residue-based-bioenergy-Regional-potential-and-scale-up-strategies.
259 IEA Bioenergy, 2020, "Roles of bioenergy in energy system pathways towards a "well-below-2- degrees-Celsius (WB2) world", https://www.ieabioenergy.com/wp-content/uploads/2020/07/Roles-of-bioenergy-in-energy-system-pathways-towards-a-WB2-world-Workshop-Report.pdf.
260 IEA Bioenergy, 2020, "Roles of bioenergy in energy system pathways towards a "well-below-2- degrees-Celsius (WB2) world", https://www.ieabioenergy.com/wp-content/uploads/2020/07/Roles-of-bioenergy-in-energy-system-pathways-towards-a-WB2-world-Workshop-Report.pdf.
261 Babiker et.al., 2022, "Cross-sectoral perspectives", IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Section 12.4, https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter12.pdf.
262 FAO, 2023, "The State of Food Security and Nutrition around the World", https://www.fao.org/3/CC3017EN/online/state-food-security-and-nutrition-2023/executive-summary.html.
263 Action Against Hunger, 2020, "World Hunger Facts", https://www.actionagainsthunger.org.uk/why-hunger/world-hunger-facts.
264 UNEP, 2021, "UNEP Food Waste Index Report 2021", http://www.unep.org/resources/report/unep-food-waste-index-report-2021.
265 OECD-FAO Agricultural Outlook 2023-2032, https://read.oecd.org/10.1787/08801ab7-en?format=pdf.
266 Janet Ranganathan, "Sustainable Healthy Diets – Guiding Principles", World Resources Institute, 2019, https://www.researchgate.net/publication/337136307_FAO_and_WHO_2019_Sustainable_healthy_diets_-_Guiding_principles_Rome.
267 Babiker et.al., 2022, "Cross-sectoral perspectives", IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Section 12.4, https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter12.pdf.
268 IRENA, 2016, "Boosting Biofuels, Sustainable Paths to Greater Energy Security", www.irena.org/DocumentDownloads/Publications/IRENA_Boosting_Biofuels_2016.pdf.
269 FAO, Rapid Appraisal, https://www.fao.org/energy/bioenergy/bioenergy-and-food-security/assessment/befs-ra/en/.
270 World Bank Policy Research Working Paper 5371, Placing the 2006/08 Commodity Boom in Perspective, https://documents1.worldbank.org/curated/en/921521468326680723/pdf/WPS5371.pdf.
271 Jaramillo et.al., 2022, "Transport", IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter10.pdf.
272 IEA, 2021, "Net Zero by 2050: A Roadmap for the Global Energy Sector", https://www.iea.org/reports/net-zero-by-2050; IEA, 2023, "Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach: 2023 update", https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach.
273 IRENA, 2023, "World Energy Transitions: Outlook 2023. 1.5°C Pathway", https://www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023.
274 Bloomberg New Energy Finance, 2022, "New Energy Outlook 2022", https://about.bnef.com/new-energy-outlook/.
275 TUMI, "Transport Outlook 1.5°", https://www.transformative-mobility.org/assets/publications/TUMI-Transport-Outlook.pdf.
276 ITF, 2023, "ITF Transport Outlook 2023", https://www.itf-oecd.org/itf-transport-outlook-2023.
277 The International Council on Clean Transportation, 2020, "Vision 2050", https://theicct.org/vision-2050/.

PHOTO CREDITS

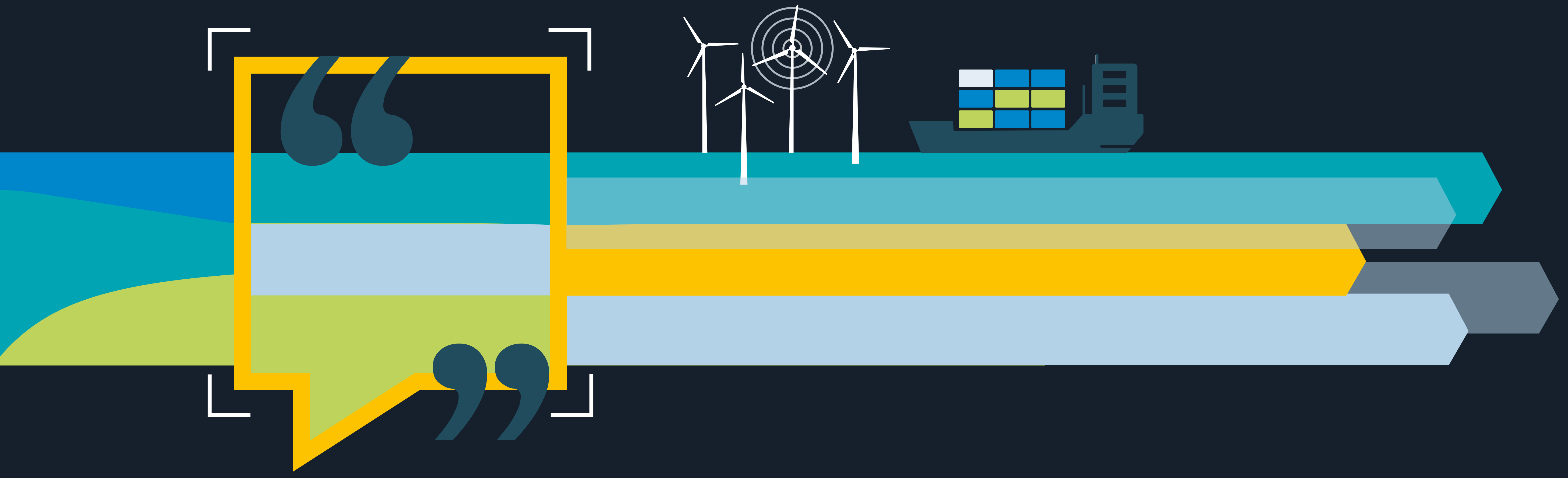
Page 12: ©UNIKYLUCKK; shutterstock.com
Page 12: ©BanksPhotos; iStock.com
Page 12: ©Halfpoint; shutterstock.com
Page 15: ©hirun; iStock.com
Page 16: ©BirdImages; iStock.com
Page 16: ©narvikk; iStock.com
Page 17: ©Bim; iStock.com
Page 17: ©querbeet; iStock.com
Page 18: ©LeoPatrizi; iStock.com
Page 20: ©onurdongel; iStock.com
Page 21: ©JGalione; iStock.com
Page 21: ©querbeet; iStock.com
Page 22: ©onurdongel; iStock.com
Page 23: ©swissmediavision; iStock.com
Page 23: ©adventtr; iStock.com
Page 24: ©VioletaStoimenova; iStock.com
Page 24: ©Axel Redder; shutterstock.com
Page 26: ©JessicaGirvan; shutterstock.com
Page 27: ©noomcpk; shutterstock.com
Page 27: ©Gorloff-KV; shutterstock.com
Page 28: ©Kletr; shutterstock.com
Page 28: ©Pandora Pictures; shutterstock.com
Page 28: ©hopsalka; iStock.com
Page 29: ©pmvfoto; shutterstock.com
Page 30: ©Wengen Ling; iStock.com
Page 31: ©megaflopp; iStock.com
Page 33: ©Audio und werbung; shutterstock.com
Page 33: ©Makhh; shutterstock.com
Page 34: ©LucVi; shutterstock.com
Page 35: ©Karl-Friedrich Hohl; iStock.com
Page 36: ©imagedepotpro; iStock.com
Page 36: ©Petair; shutterstock.com
Page 36: ©Scharfsinn; shutterstock.com
Page 37: © SimonSkafar; iStock.com
Page 38: ©Owlie Productions; iStock.com
Page 42: ©NicolasMcComber; iStock.com
Page 43: ©SweetBunFactory; iStock.com
Page 44: ©simonkr; iStock.com
Page 44: ©RiverRockPhotos; iStock.com
Page 45: ©SweetBunFactory; iStock.com
Page 45: ©leoaleks; iStock.com
Page 46: ©Wirestock; iStock.com
Page 47: ©imaginima; iStock.com
Page 48: ©Tramino; iStock.com
Page 49: ©Knut Brevik Andersen, Wilhelmsen Ship Service
Page 50: ©MasaoTaira; iStock.com
Page 52: ©Tramino; iStock.com
Page 54: ©angkhan; iStock.com
Page 55: ©gchutka; iStock.com
Page 55: ©onurdongel; iStock.com
Page 55: ©Scharfsinn86; iStock.com
Page 59: ©MihailDechev; iStock.com
Page 60: ©DarcyMaulsby; iStock.com
Page 60: ©Petmal; iStock.com
Page 63: ©santosha; iStock.com
Page 64: ©PhilAugustavo; iStock.com
Page 65: ©greenleaf123; iStock.com
Page 65: ©Pornsawan Baipakdee; iStock.com
Page 66: ©SimplyCreativePhotography; iStock.com
Page 69: ©Thirawatana Phaisalratana; iStock.com
Page 69: ©DEBOVE SOPHIE; iStock.com
Page 69: ©pixelfusion3d; iStock.com
Page 71: ©georgeclerk; iStock.com
Page 72: ©gremlin; iStock.com
Page 72: ©pixelfit; iStock.com
Page 82: ©onuma Inthapong; iStock.com



REN21

GLOBAL FUTURES REPORT

RENEWABLES FOR SUSTAINABLE TRANSPORT
BRIDGING PERSPECTIVES



ISBN 978-3-948393-16-8

REN21 Secretariat
158 Ter rue du Temple,
75003 Paris,
France

www.ren21.net