IRENA
International Renewable Energy Agency

THE RENEWABLE ROUTE TO SUSTAINABLE TRANSPORT

A WORKING PAPER BASED ON REMAP

AUGUST 2016

WORKING PAPER

ISBN 978-92-95111-68-4 (Print)
ISBN 978-92-95111-67-7 (PDF)

About IRENA

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

Acknowledgements

This working paper has benefited from the valuable engagement of the REmap Transport Action Team and the authors thank all of those involved. Additionally, valuable comments and feedback was provided by Kerstin Geppert (FU-Berlin), Marc Londo (ECN), Gerard Ostheimer (Novozymes), Jacob Teter (IEA), Tali Trigg (GIZ) and Martijn van Walwijk (HAN). IRENA colleagues Maria Ayuso, Francisco Boshell, Laura Gutierrez, Ruud Kempener, Paul Komor, Jasper Rigter and Jeffrey Skeer also provided valuable feedback. This paper also benefited from insights gathered from the Transport Action Team webinars held in 2014 and 2015 and the authors thank the presenters: Carolina Anzola (UPME), Lewis Fulton (UC Davis), Jian Liu (CNREC), Marc Londo (ECN), Gereon Meyer (VDI/VDE), Jack Saddler (UBC) and Gerald Weber (Bioenergy 2020+).

This REmap working paper, the IRENA Transport Action Team, and IRENA's ability to engage with countries benefited greatly from voluntary contributions provided by Germany and Japan.

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Citation: IRENA (2016), The Renewable Route to Sustainable Transport: A Working Paper based on REmap. International Renewable Energy Agency, Abu Dhabi, **www.irena.org/remap**

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The transport sector makes up 30% of global final energy consumption and has the lowest renewable energy share of any sector. In view of the transport sector's importance for a global transition to a sustainable energy system, the International Renewable Energy Agency (IRENA) put together a team of more than two hundred experts from the private sector, academia, government and relevant international organisations to explore pathways for transforming the sector's energy use.

This working paper draws on IRENA's engagement with these experts and expands on the transport findings published in IRENA's report *REmap: Roadmap for a Renewable Energy Future, 2016 Edition* (IRENA, 2016a). REmap is a global renewable energy roadmap that explores the possibility of significantly increasing the share of renewables in the global energy system by 2030. The paper also proposes an action agenda that can contribute to increasing renewable energy use and the sustainability of the transport sector.

KEY FINDINGS

- Demand for energy in the transport sector is growing rapidly. According to business as usual of the government plans (known in this paper as the Reference Case), energy use in transport will grow from 106 exajoules (EJ) in 2013 to 128 EJ globally by 2030 – an annual growth rate of about 1%. While the transport sector today accounts for around a quarter of all energy-related global carbon dioxide (CO_2) emissions, the results show that emissions growth in the transport sector is the highest of all sectors, and is expected to increase by over one-third by 2030.
- In addition to climate change, the need to reduce air pollution in cities will remain a major driver for renewables in the sector. Cities and their surroundings consume approximately 75% of global primary energy supply. Transport's share of all energy used is 30% globally, but it differs in countries and regions depending on factors such as population density, income level, and weather. In many middle-income and fast-growing cities the transport sector makes up 50% or more of the energy demand for the city, with road transport the largest component. Therefore, the largest contributor to local air pollution in many cities is the transport sector.
- Energy security is another driver of the shift to renewables in the sector, as oil products make up a significant share of transport's total energy demand, and many countries rely on imports of crude oil or oil products.
- The road and rail segment will account for 70% of the transport sector's total final energy consumption (TFEC) by 2030. The remainder is fossil fuels used largely in shipping and aviation. Liquid biofuel use will more than double in the Reference Case and the share of electricity in the sector's TFEC will increase from 1.2% to 2.4%. Therefore, in the Reference Case, the share of renewables in the sector will increase from 3% in 2010 to 5% by 2030, but it will remain overwhelmingly fossil-fuel based.
- REmap explores the potential of accelerating renewable energy uptake in all energy sectors, including transport, and shows that the sector could increase its share in 2030 from 5% in the Reference Case to as much as 11% with the REmap Options and 15% with the Doubling Options.
- The renewable energy share in the sector in REmap would differ by transport mode. It would make up just 1% of the aviation sector, while comprising 3% of railway and road freight. Passenger transport would have 18% – the largest share of all transport modes.
- The growth of liquid biofuel use in the Reference Case is significant, according to government plans. The Reference Case anticipates a rise in biofuel use of 2.5 times today's level of 129 billion litres, reaching 320 billion litres by 2030. In REmap, this would increase by even more, to around 500 billion litres, but the majority of this additional gain would come from advanced liquid biofuels. Total growth in both cases is ambitious, given recent market trends and oil price developments, but it is technically feasible.

- Total electricity demand would reach approximately 860 terawatt-hours (TWh) in the sector by 2030 in the Reference Case, just short of tripling today's level. The sector could significantly increase its share of electricity use to about 4.3% of total demand, or around 1500 TWh in REmap – almost a doubling over the Reference Case. This would require electrifying various transport modes.

- However, describing the share of renewables used by electric vehicles (EVs) in terms of passenger kilometres would boost the share of service EVs provide to as high as 14% of total passenger road activity in REmap. For electric two- to three-wheelers, which will number 900 million worldwide by 2030, the share would be much higher. The share of renewables represented by activity is higher than the share described in energy terms because electric automobiles are much more efficient than those using internal combustion engines. Therefore, they require less energy to run.

- In REmap, the total number of EVs would reach 160 million, around 10% of the passenger car fleet, amounting to average annual sales of 10 million vehicles to 2030.

- Total investment needed to realise the renewable energy potential for transport in REmap on average USD 339 billion per year between today and 2030. This would be an additional total annual investment in renewable energy technology and related infrastructure of USD 212 billion per year compared to the Reference Case. The incremental investment required for the REmap Options would be lower, at only USD 40 billion per year, meaning a significant portion of investment would be redirected from fossil fuel technologies to renewables.

- Investment in technology in REmap would include USD 23 billion per year in biofuel plant production capacity. Of this, USD 10 billion per year would be for advanced biofuels. Between 2010 and 2015, the average annual investment for all types of liquid biofuels was USD 4.5 billion, so a fivefold increase would be needed.

- Based on the analysis of the REmap countries, the weighted average substitution cost of the REmap Options for the transport sector is estimated at USD 7.4 per gigajoule (GJ) of final renewable energy consumed. At a system level, these incremental costs would be equivalent to USD 63 billion per year in 2030 – a negligible fraction of the total transport sector expenditures on energy.

- Fuel combustion emissions from transport result in significant external costs in terms of their impact on human health and agricultural crops. Worldwide, the external costs of air pollution related to the use of fuels in the transport sector were in the range of USD 460 billion-2 400 billion per year in 2010, and this is expected to increase by 40% by 2030 to as high as USD 3 300 billion annually.

- The REmap Options would reduce external costs by between USD 40 billion-210 billion per year, when taking into account lower costs related to the reduced health impact from air pollution. Much of these costs come from urban areas, where the cost of damage from air pollution is at least four times higher than in rural areas.

- Air pollution is not the only source of external costs from fossil fuels. Carbon dioxide (CO_2) emissions also result in costs. In 2010, the transport sector's energy-related CO_2 emissions were around 7 gigatonnes (Gt). According to the Reference Case, these emissions could increase to 9.5 Gt by 2030 – rising by one-third. Implementing renewable energy technologies identified in this study would reduce these emissions by 1.1-1.6 Gt, or by 12%-17%, to 7.9-8.4 Gt per year in 2030. These savings would imply a reduction in CO_2 emissions-related external costs of USD 17-130 billion per year in 2030, depending on the assumption of the social cost of carbon.

This paper identifies three areas that require action in order to realize the REmap findings and provides ten suggestions for policy makers and other relevant stakeholders.

The three action areas are:

- Increase electric mobility in combination with renewable electricity generation and apply a system strategies approach that interlinks energy sectors.
- Develop sustainable and affordable advanced biofuel pathways for all transport modes including non-car modes such as freight, aviation and shipping.
- Explore emerging technology solutions and innovation for emerging transport modes such as aviation, shipping and military applications.

The ten policy recommendations to address the most prominent emerging issues in these areas are:

- Accelerate EV uptake by incentivising EV sales. A city and urban-area approach should promote car-sharing schemes and electric two- to three-wheelers, and support non-passenger modes such as fleet vehicles, buses and light-duty trucks.
- Accelerate investment in charging infrastructure and plan for infrastructure by taking into account the specific needs of cities and long-distance transport.
- Capture the synergies between transport and the power sector by using renewables to meet the new electricity demand from transport and by using electric mobility as a key flexibility measure to ease electricity system integration of wind and solar photovoltaic (PV).
- Ensure the availability and supply of affordable and sustainable feedstocks for biofuels by improving agricultural yields, increasing the use of degraded and marginal land, using feedstocks that do not compete with food production, and reducing losses in the food supply chain.
- Develop biofuel targets by considering life-cycle greenhouse gas (GHG) performance to support advanced production pathways, to prioritise the use and development of low-carbon bioenergy pathways, and to reduce non-sustainable bioenergy use.
- Implement regulations and provide support to level the playing field of advanced liquid biofuels and non-renewable energy sources, by considering their GHG-emission benefits.
- Establish or expand registers of origin to ensure sustainable feedstocks and promote the development of cross-border bioenergy trade.
- Streamline bioenergy policy making by better integrating energy, infrastructure, agriculture, resource, forestry, environment, food and innovation policies.
- Tap the potential of niche markets in the more difficult sectors of shipping and aviation, such as electric ferries, hybrid drives for short sea shipping, and drop-in biofuels in aviation.
- Recognise emerging and potential breakthrough technologies for which mass production would reduce costs and boost market prospects, and provide related manufacturing support and R&D funding.

1 INTRODUCTION TO REmap

1.1 IRENA's REmap programme

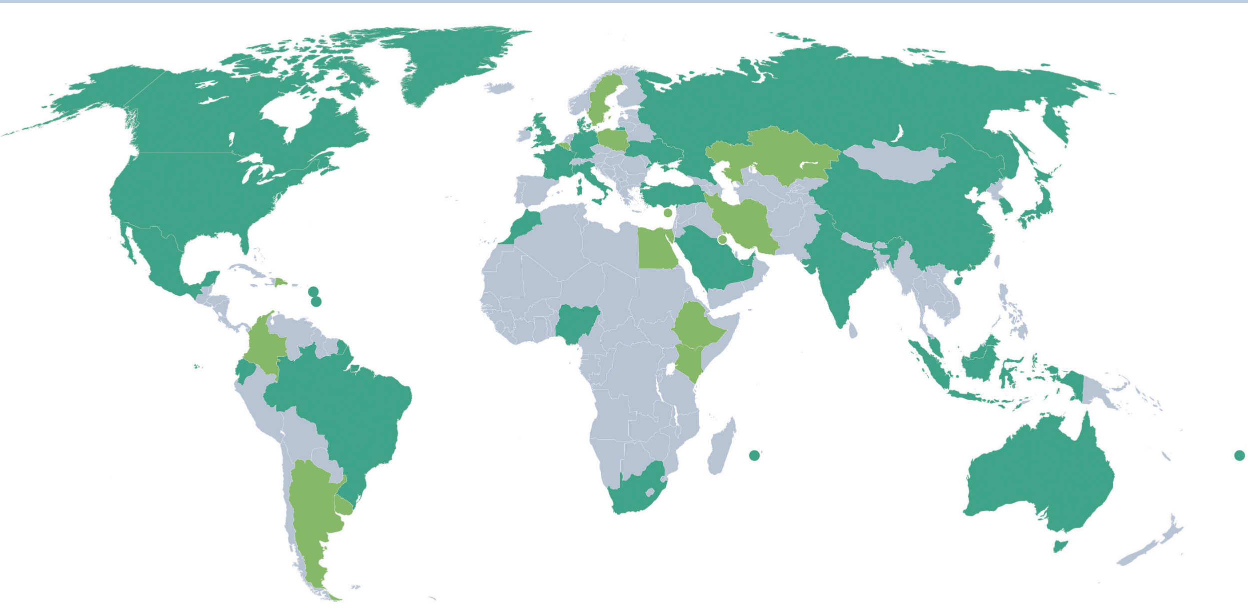
REmap is the International Renewable Energy Agency's (IRENA) global roadmap to significantly increase the share of renewable energy in the world's energy mix by 2030. REmap is a global study of renewable energy potential built from the bottom up, analysing 40 countries that represent over 80% of global energy use, and working closely with them to determine the potential of renewables. In addition to the power sector, the report looks at the end-use sectors of agriculture, buildings (residential, commercial, public, and services), industry and transport.

IRENA's approach in REmap follows two parallel tracks: (i) A country-based analysis to identify actions on technology deployment, investment and policies in collaboration with REmap countries and other key entities; and (ii) A series of technology roadmaps to identify cross-country insights on the actions required to significantly increase the share of renewables in the global energy mix.

The 2016 edition of the global REmap report, titled *Roadmap for a Renewable Energy Future,* shows that increasing the renewable energy share from 18% in 2010 (or around 18.4% in 2014) to 36% by 2030 is technically feasible and affordable – and that doubling the share of renewables will set the world on a trajectory to limit the global temperature rise to 2 degrees Celsius or below, as called for in the Paris Agreement (IRENA 2014a; 2016a). The report also shows how renewables can be much cheaper than fossil fuels when taking into account the savings from externalities, with these savings up to 15 times higher than the incremental cost of renewables.

For policy makers, the global REmap report identifies five action areas in which renewable energy technologies would play an important role. One of these areas is transport. The plan calls for promoting renewable power and biofuels in this sector to raise the share of renewable energy in our overall energy system. This paper goes into more detail about the transport sector related findings from REmap, and proposes an action agenda in order to achieve more renewable energy in the sector.

Figure 1: Map of countries participating in IRENA's REmap programme



Note: 26 countries participated in 2013 (dark green), 14 countries joined in 2014/2015 (light green)

1.2 Transport's role in REmap and what this working paper examines

The REmap programme has expanded to include in-depth analyses of countries' renewables potential, sector technology trends, and cost-savings analyses. These analyses have revealed a striking lack of systemic plans for expanding renewables in the transport sector.

Today, the transport sector has the lowest share of renewable energy use of any sector, and this will remain so under the Reference Case (also known as business as usual) to the year 2030 and beyond, based on current government plans. However, as REmap shows, there is emerging potential to significantly scale up renewables in transport. Considerable efforts are required to transform the sector.

IRENA has established a Transport Action Team to create a framework for cooperation with the IRENA Secretariat under the umbrella of the REmap programme. Member countries and a diverse group of experts in the transport field drive action in specific areas for a transformative impact on the deployment of renewables in the sector. This team complements REmap's country-based analysis approach and brings in experts from industry, academia and other organisations to provide valuable input.

This working paper explores pathways for renewable energy and proposes an action agenda to inform national policy makers and technology experts of the areas requiring further work to increase the uptake of renewables in transport sector. It builds on the important inputs of the Transport Action Team members and a growing body of work at IRENA beyond REmap, including: technology briefs that include the latest technology and cost information for emerging renewable energy and transport technologies (IEA-ETSAP and IRENA, 2013a,b; IRENA 2015e, IRENA 2016d,e,f); IRENA's Renewable Energy Innovation Outlook for Advanced Liquid Biofuels for Transport (IRENA, 2016c), and biofuel feedstock and greenhouse gas emissions (IRENA, 2016b,c; PBL, 2016).

This working paper is the result of these broad engagements. It is based on quantitative, country-based studies and multiple stakeholder webinars focused on technology solutions, such as emerging biofuel technologies and electric mobility (IRENA 2015a,b). It also benefited from feedback from industry stakeholders at meetings held at the IRENA Council Meetings in November 2014 and 2015, and a sector workshop in Berlin in September 2015 held by the German Renewable Energy Agency (DENA).

Approach

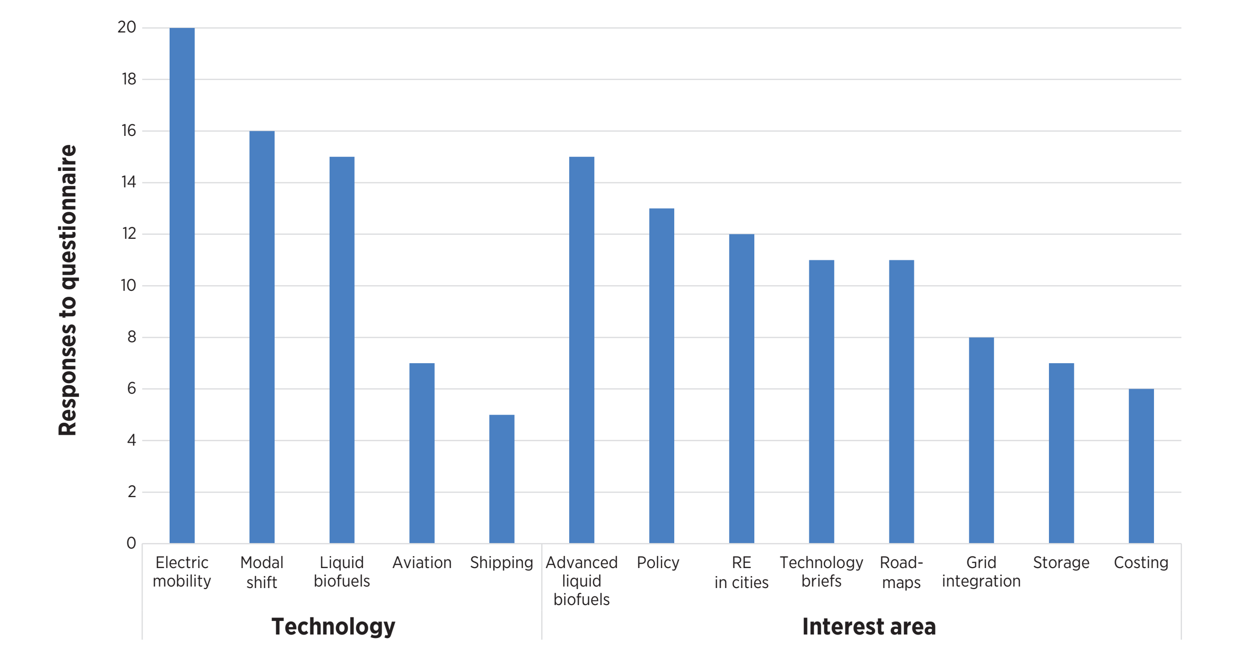
This working paper is based on three activities undertaken by the IRENA REmap programme and its Transport Action Team.

- The findings come from a quantitative, techno-economic analysis of renewable energy options for the transport sector, based largely on IRENA's REmap programme and the in-depth analyses of 40 countries.
- Additionally, stakeholder workshops and webinars were held to identify and prioritise tasks for stakeholders within action areas.
- Finally, a qualitative assessment was conducted to evaluate how actions could be turned into reality, drawing in part on other IRENA projects that touch on the transport sector.

IRENA's Transport Action Team consists of members from the IRENA Secretariat (under the umbrella of the REmap programme), countries taking part in REmap, and a diverse group of transport experts. The team was established in response to findings from the first REmap report in 2014, which showed both the slow rate of growth in renewable energy in the sector and the potential to accelerate this rate fourfold (IRENA, 2014a). Members asked IRENA to examine renewable energy options in transport in more detail and advise them on how to enhance and strengthen their policies. IRENA expanded its work on sustainable transport between 2014 and 2016. The team has emerged as an important source of coordinating efforts internally within IRENA, engaging countries in dialogue and convening a wide range of stakeholders from governments, organisations, industry and academia to gather information on the latest developments and discuss how to galvanise action.

This expert network addresses key topics on renewable energy in transport by sharing and coordinating

Figure 2: Transport Action Team interests



ongoing work, best practices, policies and technology developments. Besides networking, the team also aligns the efforts of IRENA and other initiatives towards a common goal of creating a more sustainable and renewable energy-friendly transportation sector. IRENA brings value to the transport debate through its strong relationships with its member countries (numbering 149 as of June 2016), and its close relationships with the 40 REmap countries. In addition to the strong country relationships, the team builds on broad technical and political expertise in renewable energy at IRENA.

The Transport Action Team has expanded to include over 200 experts from over 25 countries and around 100 organisations. Experts identified three main transport themes to explore (see Figure 2): electric mobility, advanced biofuels, and the role of emerging technologies and sectors. A discussion was organised around each theme, and team members were engaged over the period of over a year to discuss the topic and REmap findings. The results of this discussion are found in Sections 3-5 of this paper and tied in with findings from other studies and IRENA efforts.

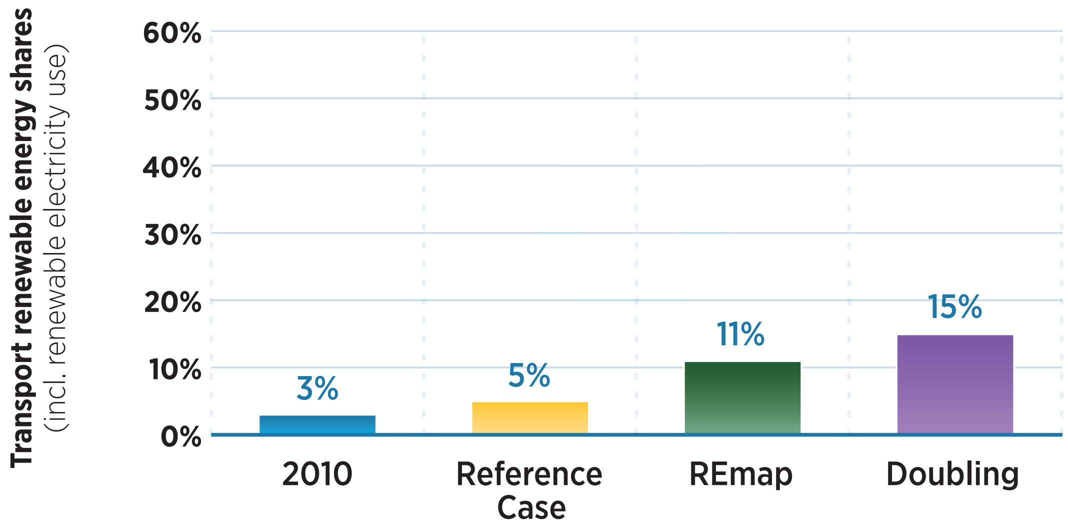
The REmap Action Team is a living effort, and will continue over the coming years to share data, best-practice and information. The aim will be to develop an action agenda focused on advancing renewable energy and the overall sustainability of the transport sector. Therefore this paper is just a starting point, and lays out the key focus areas off which the team and IRENA can pursue future research, analysis and policy efforts.

1.3 Brief overview of REmap transport sector findings

The transport sector is where renewable energy has made the least progress in recent years. It is also a sector in which liquid biofuels can quickly reach the limits of sustainable production. Therefore, to raise its renewables share, the sector must shift to electric-based technologies. These can include individual mobility technologies like battery electric vehicles (BEV), plug-in hybrid vehicles (PHEV), and electric vehicles (EVs) for freight and public transit.

Stemming the increase in the sector's energy demand will also require a shift from individual, fossil-fuelled vehicles to more efficient modes of transportation that can consume renewable power, such as electrified public transport and longer range rail. A shift to renewables in transport thus depends not only on technological advances, but also on behavioural and societal changes.

Figure 3: Share of renewable energy in global transport final energy demand, 2010-2030



The advantage for the public is that these changes enable more environmentally friendly energy and an improvement in the standard of living with cleaner and more liveable urban environments.

The REmap approach is based on a country-by-country analysis of renewable energy options between today and 2030. The roadmap consists of several parts: a Reference Case that reflects renewable energy deployment in governments' existing or planned national energy plans (business as usual); and the REmap Options, which are renewable energy options on top of the Reference Case, which IRENA has identified in collaboration with governments, and which are deployable by 2030. In total, around 600 realisable REmap Options were identified for the 40 countries, approximately 100 of these in the transport sector.

Additionally IRENA has conducted analysis that looks into how the transport sector could see significantly higher renewable energy uptake and decarbonisation beyond the REmap Options. This analysis is known as the Doubling, and the technologies and methods identified as the Doubling Options, which see higher deployment of electrification, emerging technologies in aviation, shipping and heavy freight transport, and structural change known as modal shifts. The Doubling Options are aligned with the aim of doubling the share of renewable energy in the global energy mix by 2030 however they have longer term implications. Importantly these options are necessary if the world is to set itself on a pathway towards total energy system decarbonisation early in the 2nd half of this century. If this is to occur, the overlooked sectors and technologies will need to take on a bigger role and renewable options will need to be deployed.

The results show that the share of renewable energy in the transport sector today is just above 3.1%, but will increase to just above 5% in 2030 in the Reference Case.[1] This would consist of 4.5% liquid biofuels and 0.6% renewable electricity. If the countries were to implement the REmap Options, the renewable energy share would increase to 11% (IRENA, 2015a). Scaled up to a global level, this would be equivalent to a total renewable energy demand of 14.1 exajoules (EJ) in the sector.[2]

1 Unless specifically indicated in the text, the renewable energy shares refer to the use of energy carriers to generate energy required to transport passengers and freight. It is estimated by the total renewable energy use from all energy carriers (*e.g.* biomass, solar thermal) and the share of renewable electricity consumed by all forms of electric mobility.

2 1 EJ is 10^{18} joules, and is equivalent to the total energy consumption of a mid-size country.

Further action can increase this share to as high as 15% if the Doubling Options are deployed.

The 11% share would include a more than quadrupling of the annual liquid biofuel demand to approximately 500 billion litres by 2030, of which around one-quarter would be advanced biofuels[3]. The total number of electric vehicles in the car stock would reach 160 million, or around 10% of the vehicle stock by 2030. This excludes small two- and three-wheelers, which would reach about 900 million by 2030 (including e-bikes).

Expanding renewable transit technologies will alter expenditures for the types of fuels and technologies used in the sector. Since many of these are investments in technological learning (including R&D), their costs are higher than conventional fossil technologies that have already experienced decades of investment and capacity development. Therefore, a shift to the new and clean technologies identified in REmap would cost up to USD 63 billion more annually in 2030 than the Reference Case if comparing the system cost of the transport sector. Additional investment would also be required, with around USD 40 billion annually more invested in infrastructure and technologies in REmap than in the Reference Case. Annual transport sector-related investment would total USD 339 billion to 2030.

A switch to these technologies would have important benefits to the macro-economy. External cost savings of USD 40 billion-210 billion annually result when air pollution is taken into account (the impact on human health and agriculture are considered in the analysis), resulting in net savings of up to USD 147 billion annually by 2030. A large part of this savings is found in cities and urban areas, where approximately 75% of global energy is used. Some cities see over 50% of their energy demand come from the transport sector, and the sector is often the largest contributor to local air pollution.

Increasing renewables in REmap would also result in 1.1-1.6 gigatonnes (Gt) less CO_2 emissions by 2030 than in the Reference Case. If these avoided emissions were valued with a carbon price ranging from USD 17-80 per tonne, total savings would be USD 19 billion-130 billion per year. Therefore, accounting for the low end of air pollution and CO_2 benefits, total costs would be USD 4 billion annually, while the high end would result in substantial savings of up to USD 227 billion annually. Taking a holistic approach to valuing the costs of technology options that also includes savings from reduced externalities, helps to understand the larger economic costs and benefits of expanding renewables in the transport system.

IRENA has also done its own assessment to identify technology options for increasing renewables even beyond what was identified in the REmap Options. These are called the Doubling Options, and are necessary to reach even greater renewable shares, with the goal of doubling this share in total final energy consumption. While this assessment was not based on a collaborative process with countries as the REmap Options were, it has provided important insights into the types of actions and technologies that could increase the renewable energy share beyond 11% in transport. If these Doubling Options were implemented, the sector's renewable energy share would reach as much as 15% (making up 17 EJ per year of renewable energy use). This would represent a fivefold increase in share, or nearly a sixfold increase in renewable energy use, over today's levels. Nearly all of this increase would be related to further electrification of the sector, including modal shift (getting people to switch to different modes of transportation). IRENA's assessment for the Doubling Options is still ongoing, therefore the remainder of this paper details only the REmap Options in greater detail.

3 Biofuels for transport are commonly classified as conventional or advanced. There are a number of approaches to defining this classification, including the use of characteristics such as technology maturity, feedstock, product quality, and greenhouse gas (GHG) emissions. Advanced biofuels produced from feedstocks that do not compete with food crops and require less land are seen as a more sustainable option to substitute fossil fuels in the future.

2 SUMMARY OF KEY FINDINGS FROM REmap

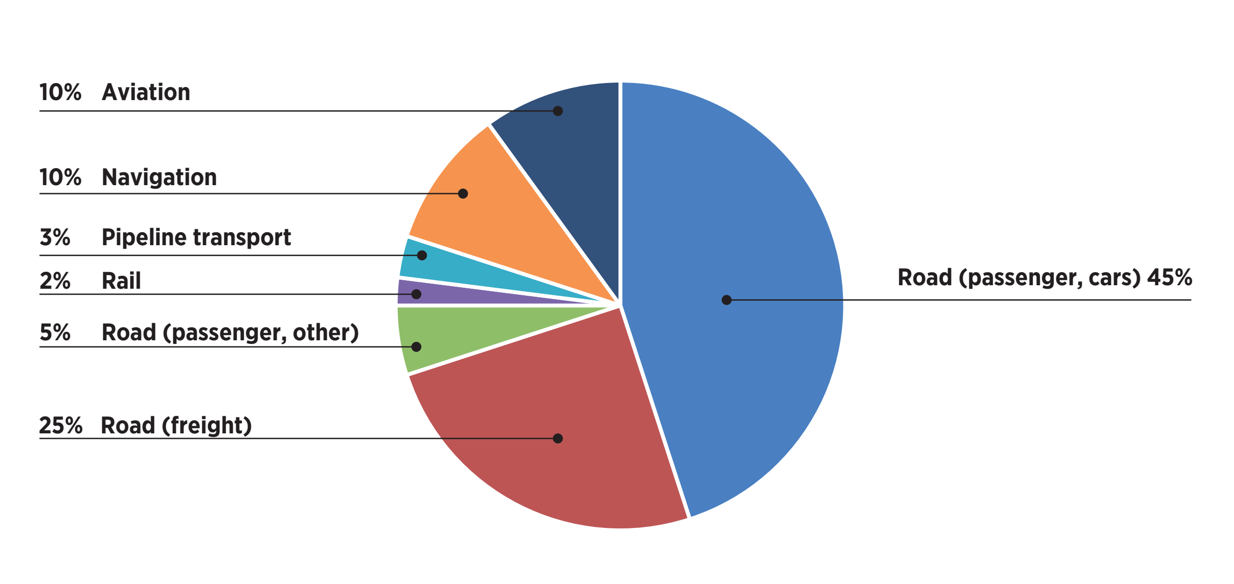
2.1 Current situation

Transport represented approximately 28% of total global final energy consumption in 2013. Demand for energy in transport in the same year was 107 EJ. More than 90% of the sector's energy use comes from petroleum products. The share of renewables in its total energy mix was only 2.5% in 2013, the lowest of all sectors in the global energy system – and even lower than the 2010 level of 3%. The total renewable energy share in 2013 is broken down into: 1.4% ethanol 0.8% diesel, 0.01% biomethane, and 0.3% other liquid biofuels. Electricity makes up just 1% of the transport sector's total final energy consumption (TFEC) in 2013 (IEA, 2015a).

The transport sector's TFEC increased by more than 60%, from 66 EJ in 1990 to 107 EJ in 2013. The fuel mix still account for about 93% of the sector's TFEC, mainly for road transportation. The share of electricity (1%) and other fuels (*e.g.* natural gas) (3%) remained the same in the entire period. Only liquid biofuels have gained a market share of 3% as of 2010, up from almost no use in 1990. These biofuels have substituted for gasoline and diesel produced from crude oil. The vast majority of the growth in electricity consumption in transport came from the rail sector (IEA, 2015a).

The transport sector deals with the energy use of all transport modes: road, rail, aviation and navigation (including shipping). Road transportation (passenger cars and freight transport) dominates the sector's total energy demand, accounting for three-quarters of its TFEC in 2013 (Figure 4). Total light vehicle production in 2014 is estimated to have reached 88 million (Roland

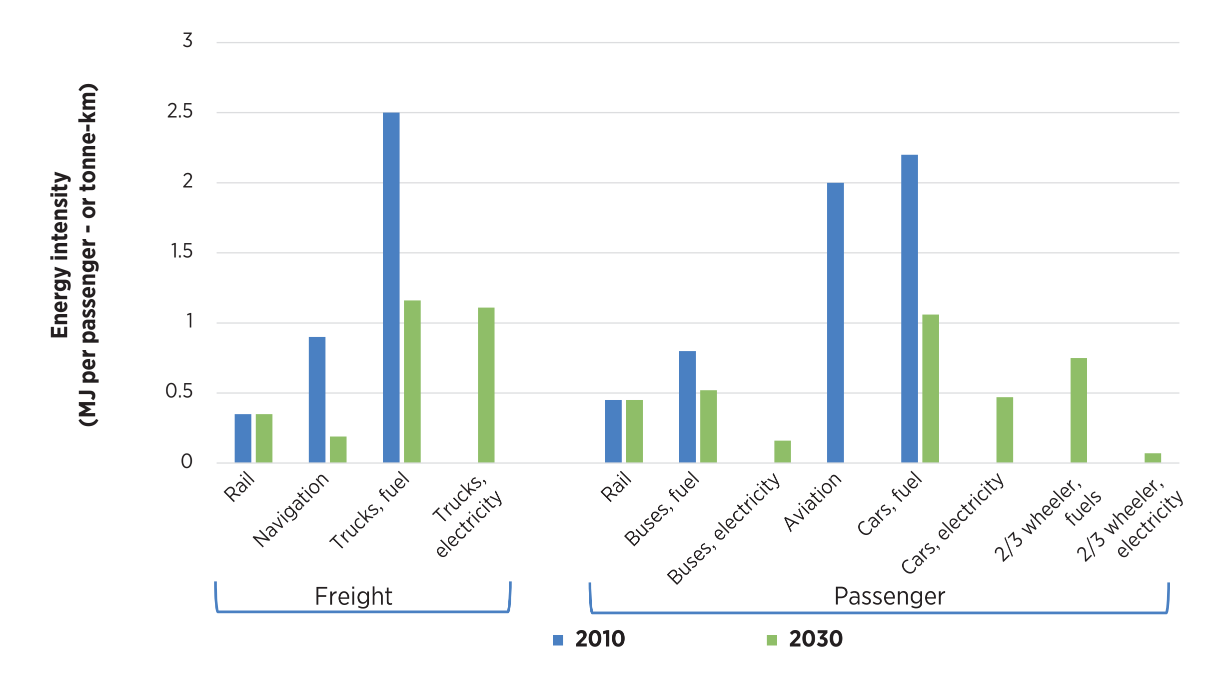
Figure 4: Breakdown of global energy use by mode in transport, 2013



Based on IEA (2015a)
Note: aviation and navigation include bunkers.

4 Throughout this paper, the term ethanol or ethanol is used, as it is the most comment name for alcohol based liquid biofuels; however, in energy statistics the term "biogasoline" is often used.

Figure 5: Energy intensity by transport mode, 2010 and 2030



Source: IRENA assessment based on country statistics and estimates

Berger/Lazard, 2014), of which around 80% were passenger cars; the remainder, primarily light trucks. Aviation accounted for 10% of TFEC in the transport sector in 2013, with sea transport accounting for around 10%. They together represent about 3-4% of the total global CO_2 emissions (Cames, 2015) (with around 70% of these aviation and sea emissions occurring internationally, hence excluded from the domestic emission accounting frameworks).

Energy intensity varies depending on transport mode and whether the vehicle combusts a fuel to produce mechanical energy or uses electricity. Figure 5 shows the amount of energy needed in various modes to move a tonne of freight or a passenger-kilometre (km). The largest use of energy today are in passenger modes such as aviation and automobiles (typically around 2 megajoule (MJ) per passenger-km), and freight transport by trucks (which is as high as 2.5 MJ per tonne-km). The most energy efficient means of transport for freight are rail, pipelines and shipping (navigation); however, all three are limited by the availability of the transportation network. For passenger travel, rail and bus offer the greatest energy efficiency, but also lack network flexibility.

Electricity offers 2-3 times more efficiency over internal combustion engines, when viewed in final energy terms. However, viewed in terms of primary energy, overall efficiency can differ depending on the electricity generation mix. When electricity is sourced from coal power, more primary energy is consumed to produce electricity than is necessary for an efficient internal combustion engine. If electricity is sourced from solar, wind, or hydropower, then no energy is lost during conversion and electric mobility results in significant energy savings on a primary energy level.

Besides improving efficiency through the use of electricity in transport, countries have paid a lot of attention to improving the fuel efficiency of transport modes themselves. Between 2005 and 2013, average fuel efficiency has improved by about 20% in the OECD countries. To put this in perspective, the fuel savings related to this efficiency increase during the period is equivalent to the total size of Italy's transport sector energy demand, at 1.5 EJ. There is significant further potential to improve efficiency worldwide, particularly in the transport sector. Between 2005 and 2013, average fuel efficiency improvement reached 2% per year worldwide. The voluntary target set by the Global Fuel

Economy Initiative (GFEI) is 3.1% per year (GFEI, 2015). More than 80% of the global transport market is carrying out some kind of fuel economy initiative. Countries that lag behind are in largely in Southeast Asia, Latin America and Africa. This is significant because in recent years vehicle sales have shifted mainly to these developing countries.

It is equally important to consider the energy density of liquid fuels. Some transport modes require high levels of energy density, meaning high levels of energy in a unit of volume. Diesel, biodiesel and gasoline have an energy density of around 32-35 MJ per litre of fuel (based on lower heating value). Ethanol has significantly less density of around 18-21 MJ per litre. In modes where high energy density is required, such as aviation and shipping, the energy density of fuel is an important consideration due to space and weight limitations, and a prime reason why electricity cannot be considered with existing technologies, because with current electricity storage options the size requirement for batteries would be too large.

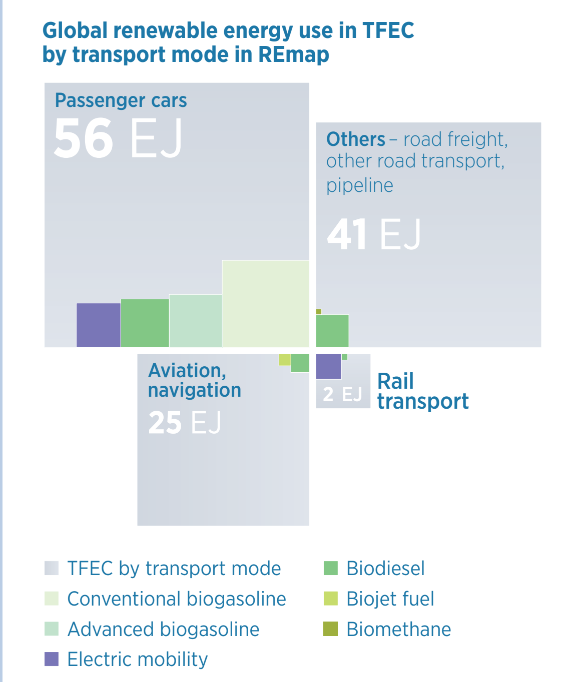
2.2 Role of renewables

There are many transportation modes and vehicle types, using a wide variety of fuel types and qualities for different applications. The sector's energy needs are therefore complex compared to other sectors, requiring renewable energy solutions tailored to each application. However renewables can play a role in all different modes of transport.

Today, passenger cars account for around half of transport sector energy demand. But road freight transport, aviation and shipping are all growing at faster rates than passenger cars. Renewable alternatives must be sought in all modes in order to increase the sector's overall renewables share. Alternatives to petroleum-based fuels include liquid biofuels, electric road transport, and modal shifts that consume electricity. As the world moves towards lower-carbon electricity, increasingly based on renewable power generation, these electricity-based systems will become more sustainable.

The differentiated network and energy density needs point to some likely trends for a sustainable transport sector, and in the areas of biofuels and electricity.

Figure 6: Final energy use by transport mode and consumption of renewables in 2030



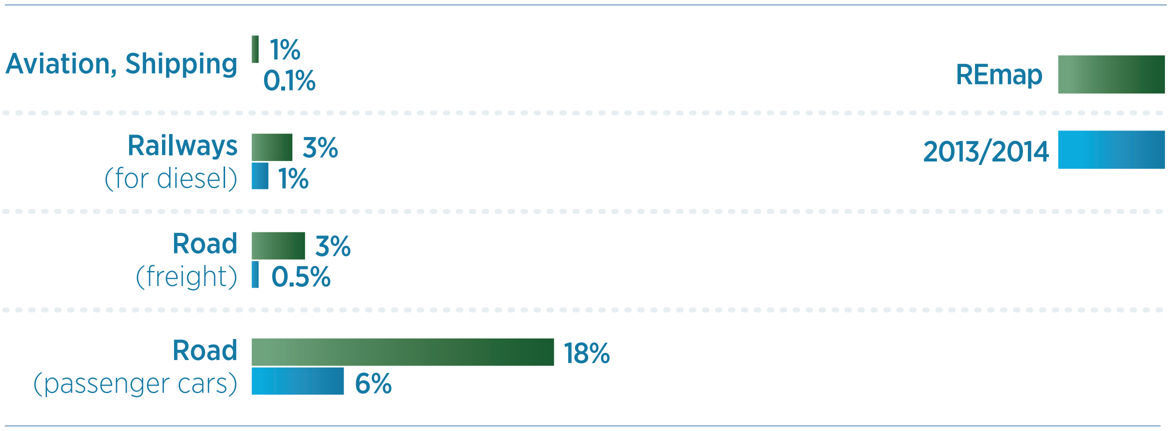
Biofuels are in limited supply. For that reason, these could be used in aviation and shipping, which require higher energy density, while modes such as passenger transport in cars, buses, and two- to three-wheelers, and freight in trucks or fleet vehicles, could instead benefit from the increased efficiency of electric drives and hydrogen (*e.g.* notably in Japan).

Different modes use renewable energy to varying degrees, reflecting the use of different fuels (Figure 6). Road transport, particularly passenger vehicles that can use ethanol, has the largest renewable energy use, followed by road freight, which largely uses biodiesel. The rail, aviation and shipping segments have substantially lower use.

2.3 Renewable energy use in the sector today

Currently around 129 billion litres of biofuels are produced each year, equivalent to about 2.7 EJ of final renewable energy use. Their production has stabilised over the past few years. Biomethane, or biogas, is another option that is catching on in several European countries such as Germany or Sweden, but its contribution remains very low.

Figure 7: Renewable energy share by transport mode in 2013/2014 and in 2030 according to REmap



Electric vehicles are alternatives to internal combustion engines. Out of a car stock of around 800 million units and 70 million cars sold per year, roughly 500 000 EVs were sold in 2015 – under 1% of new car sales. By the end of 2015 there were 1.25 million electric vehicles were on the road (this includes all forms such as passenger cars, delivery vans, buses, etc.) (IEA, 2016). In addition, small electric two- to three-wheelers are gaining significant ground in the market, particularly in China.

Total electricity demand for EVs represents approximately 3 terawatt-hours (TWh) per year (1% of the sector's total electricity demand of 300 TWh per year). Assuming 23% of this is sourced from renewable power (equivalent to the global share of renewables-based electricity generation), electric vehicles consume 0.7 TWh per year of renewable electricity. Other forms of electric mobility contribute another 0.2 TWh per year of renewable electricity consumption.

In cities, where the majority of passenger miles are driven, EVs have a particularly high potential to help transform energy use and improve the environment. Transport accounts for more than half of the global emissions of nitrogen oxides (NO_x) and 20-30% of all other air pollutants (*i.e.* non-methane volatile organic compounds, sulphur oxide (SO_x), carbon dioxide (CO_2), and particulate matter ($PM_{2.5}$ and PM_{10})). In addition, electric mobility provides complementary services to the electricity grid and helps promote decentralised power (also known as vehicle-to-grid, or V2G).

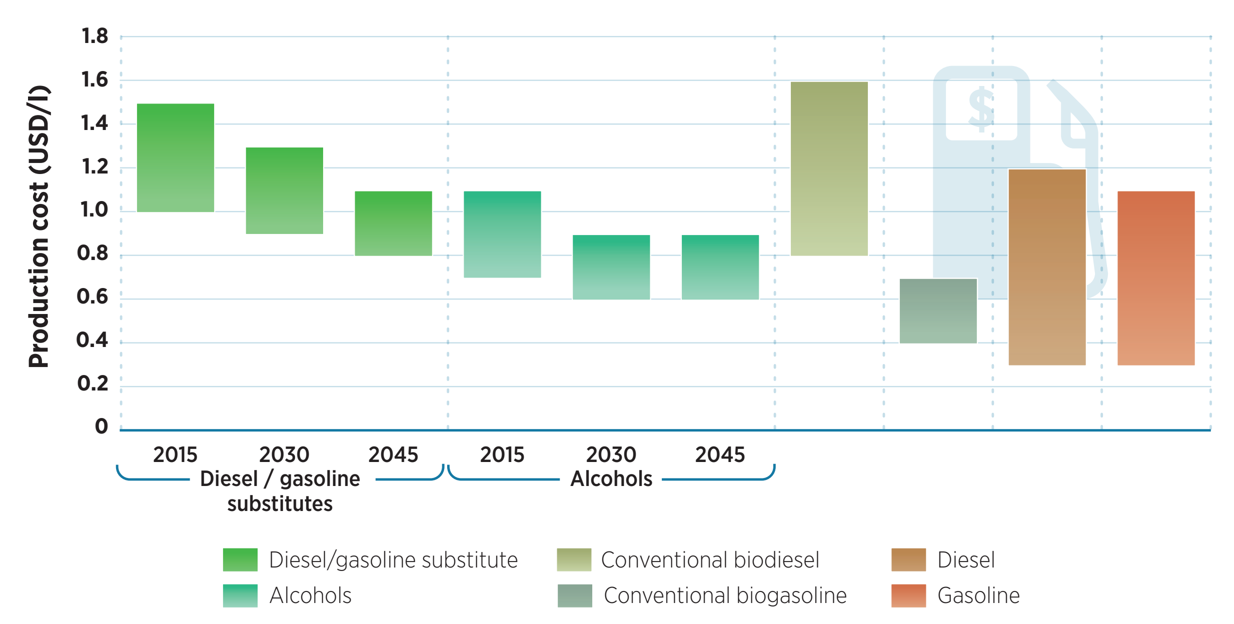
2.4 Global potential of renewable energy in 2030

In the Reference Case, energy use in the transport sector would continue to grow from 107 EJ in 2013 to 128 EJ by 2030, an annual growth rate of about 1%. The total liquid fuel market (gasoline, diesel, biofuels, and others) would reach more than 3 500 billion litres in 2030, the sector's highest energy demand. Oil products for road and rail transportation would then account for 70% of the sector's TFEC by 2030, with the remainder used largely in shipping and aviation.

The share of liquid biofuels would more than double to 5.2% by 2030 to a total demand of 6.4 EJ. Likewise, the share of electricity consumption in the sector's TFEC would increase from 1.2% to 2.4% in the same period. Liquid biofuels and electric vehicles (including electrified railway systems and road transportation) would be the main substitute for oil products in road and rail transport. Thus, the share of renewables in the sector would increase from just 3% in 2010 to 5% by 2030 in the Reference Case.

Figure 7 shows the development of the renewable energy if all REmap Options were deployed. With REmap Options, the sector could increase its share of renewable energy to as much as 11% overall. The share would differ by transport mode, from as low as 1% for aviation, 3% for railways and road freight transport, to as much as 18% for passenger transport. However, REmap

Figure 8: Production cost of advanced liquid biofuels, 2015-2045



Based on IRENA (2016c)

Note: All data has been converted from GJ to litres based on lower heating values.
Diesel/gasoline bars indicate the range based on a USD 40-140/bbl crude oil price. Ranges for biodiesel and ethanol refer to a USD 700-1500/tonne vegetable oil price and a USD 150-300/tonne corn price, respectively.

shows there is significant potential to increase the share of renewables in all modes, between 3 and 10 times today's shares.

In REmap, biofuels use would quadruple from today's level of 129 billion litres to around 500 billion litres (or about 12 EJ). Worldwide, about 5.5 EJ (about 200 billion litres) of additional biofuels could be added by 2030 with the REmap Options, bringing total biofuel demand to approximately 12 EJ. About 6 EJ (283 billion litres) of ethanol demand would be conventional; another 2 EJ would be considered advanced (94 billion litres). Biodiesel use is projected to reach 4 EJ. This can be split into 1 EJ of advanced (30 billion litres) and 3 EJ of conventional (90 billion litres). Biomethane demand would grow roughly tenfold to 0.035 petajoules (PJ) (or 0.9 billion m^3) (see Table 1).

If the size of the average biofuel plant were to increase to meet this demand, producing around 200 million litres per year, then 30-40 advanced biofuel plants and around 90 conventional plants would need to be built each year from 2014 to 2030. Given recent market trends and the oil price development, this is an ambitious level of growth.

Total transport electricity demand would reach 3.1 EJ in the sector by 2030 in the Reference Case, a little under three times today's level. The Reference Case already takes into account most structural changes for electrification, such as high-speed trains instead of buses, or trams in cities. The REmap Options would significantly increase the share of electricity used in the sector to about 4.3%, or around 5.3 EJ, driven largely by more liquid biofuels and electric vehicles.

In the REmap Options, the various forms of electric mobility use 630 TWh of additional electricity. This demand comes from plug-in hybrids, battery-electric cars and two- to three-wheelers. To put this in perspective, this is about the same amount of electricity produced in Germany in 2010. The 630 TWh can be split into 480 TWh per year for electric vehicle passenger cars, 55 TWh per year for two- to three- wheelers and 95 TWh per year for modal shifts.

Worldwide, the total number of electric vehicles (including both battery-electric and plug-in hybrid) on the road surpassed 1 million in 2015 – an important milestone – with an estimated 1.25 million on the roads (IEA, 2016). REmap analysis shows that this

Table 1: Overview of key technology developments in transport

	Units	2013/ 2014	Reference Case	REmap
Electric Vehicles	million vehicles	0.8	60	160
- Passenger vehicles	million vehicles	*0.8*	*59*	*158*
- Buses	million vehicles	*0.01*	*0.5*	*1.4*
- Light duty vehicles	million vehicles	*0.004*	*0.3*	*0.9*
2/3 wheelers	million vehicles	200	500	900
Bioliquids	billion litres	129	250	500
- Conventional ethanol	billion litres	*93*	*185*	*283*
- Advanced ethanol	billion litres	*1.0*	*10*	*94*
- Conventional biodiesel	billion litres	*35*	*55*	*93*
- Advanced biodiesel (incl. bio jet kerosene, drop-in)	billion litres	*0.01*	*0.3*	*30*
Biomethane	billion m^3	0.01	0.3	0.9

1.25 million can increase to 160 million by 2030, or approximately 10% of total passenger car stock of about 1.5 billion-1.6 billion cars in that year. On average, sales would need to reach 10 million electric vehicles per year between now and 2030, significantly more than the 0.4 million vehicles sold in 2014, which was only about one half of 1% of the estimated 70 million passenger cars sold in that year (BNDES, 2015). By comparison, the Reference Case assumes average annual sales of 3 million electric vehicles per year.

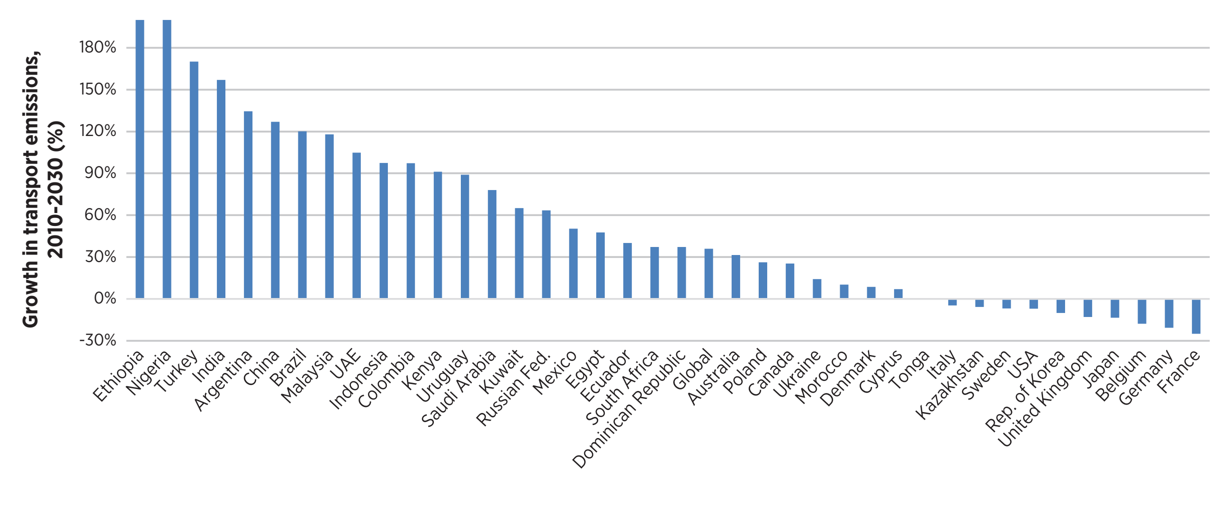
In REmap in 2030 renewable electricity consumed by electric vehicles would make up 1.6% of the sector's total final energy demand, and total electricity 3.5% (around 45% of electricity in 2030 is renewable in REmap). If electric vehicles were represented by passenger kilometres, the share of vehicle service they provide would be much higher at 10-14%. Besides helping raise the share of renewables in the sector, electric mobility is so efficient that its related energy savings would be equal to the sector's total final energy demand of 4.4% in 2030. Liquid biofuels do not offer such efficiency improvements.

Although transport today accounts for less than a quarter of the energy-related global CO_2 emissions, the sector's emissions are growing by more than any sector of the global economy. Transport sector CO_2 emissions from fossil fuels will increase by over one-third by 2030, with large differences in emissions growth by country. Figure 9 shows most countries with the fastest growing transport emissions are in Africa, Asia and Latin America, while Europe and the United States should see emissions decline.

Higher shares of renewables and less fossil fuel use have multiple benefits for the transport sector. Lower fossil fuel demand reduces the emissions of air pollutants and CO_2. Up to 1.6 Gt of CO_2 emissions from fossil fuel use can be avoided in REmap compared to the Reference Case. Potential emission reductions in the transport sector comprise over 10% of total potential emission reductions from renewables (7.6-8.6 Gt CO_2) (IRENA, 2016a).

Countries increasingly understand this potential, as shown in the Intended Nationally Determined Contributions (INDCs), the pledges to reduce greenhouse gas emissions submitted ahead of the 21st Conference of the Parties to the United Nations Framework Convention Climate Change (COP21) in Paris. Among the 120 INDCs submitted in October 2015, three-quarters explicitly identify the transport sector as a source for mitigating climate change, and more than 60% of INDCs propose transport sector-specific mitigation measures. In addition, 11% of INDCs include a transport-sector emission-reduction target, and 15% include assessments of country-level transport mitigation potential. Transport-related actions in the INDCs are heavily skewed towards passenger transport, which is included in 88% of INDCs identifying specific transport modes. Among these, urban transport measures are mentioned in 85% of INDCs, while strategies such as high-speed rail (2%), and walking

Figure 9: Growth in transport emissions from fossil fuels between 2010 and 2030 in the Reference Case



and cycling (13%) received less attention (PPMC, 2015; Gota, 2015).

REmap shows that there is significant potential for reducing CO_2 emissions in the sector. Figure 10 shows the difference between REmap and the Reference Case in how far the transport sector's CO_2 emissions from fossil fuels can be reduced in 2030. Globally, the sector could cut CO_2 emissions by around 11%, with a range of 5-20%, depending on the country.

A number of initiatives were announced during the COP21 in December 2015. The common aim of these initiatives is to reduce the sector's CO_2 emissions by 50% by 2050 compared to 1990, if the global transport sector follows the Reference Case. REmap shows the importance of acting sooner, as even with the high level of renewables deployed in REmap, very significant additional reductions will be necessary after 2030 if the 2050 goal is to be met. Efforts will need to continue in improving fuel efficiency, reducing emissions in the

Figure 10: Reduction of energy related CO_2 emissions in the transport sector in 2030, REmap vs. Reference Case

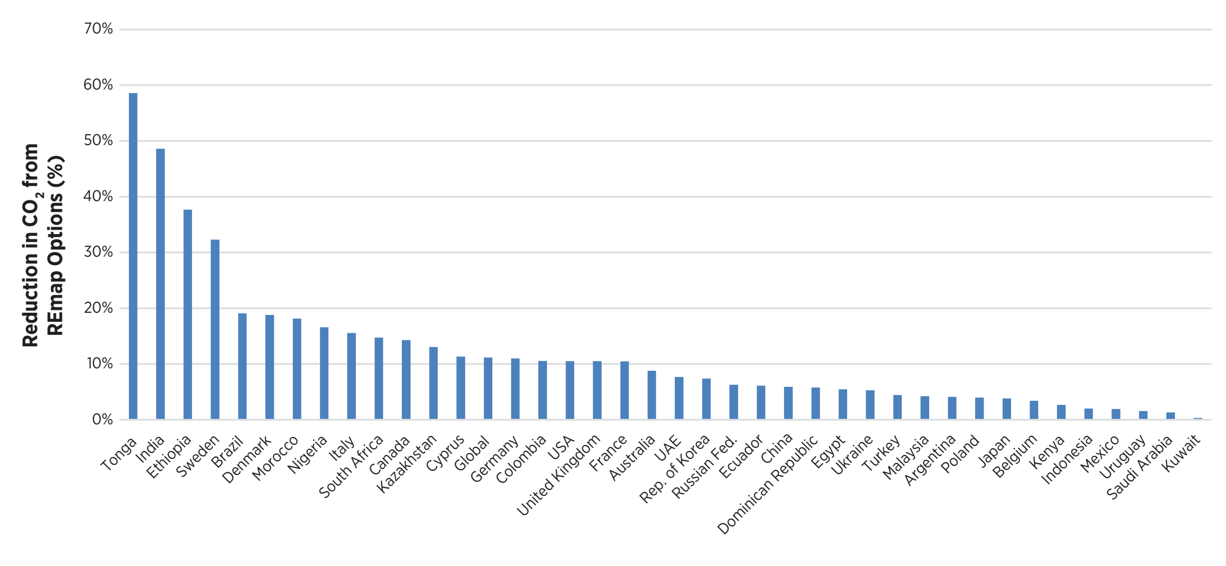


Figure 11: Change in air pollutant emissions between 2010 and 2030

Note: Abbreviations stand for – $PM_{2.5}$: fine particulate matter; NO_x: mono-nitrogen oxides; SO_2: sulphur dioxide; VOC: volatile organic compounds; NH_3: ammonia. The values at the top of the bars show the total transport sector emissions in 2010 of the pollutant in kilotonnes.

freight sector, implementing sustainable urban plans for major cities and emerging economies, implementing mitigation measures to reduce emissions in the aviation sector, and in several electrification-focused areas. Recent studies also show that halving the sector's total CO_2 emissions by mid-century would be possible if both urban transport mitigation options and cost-effective EVs are fully utilised (Creutzig, 2015).

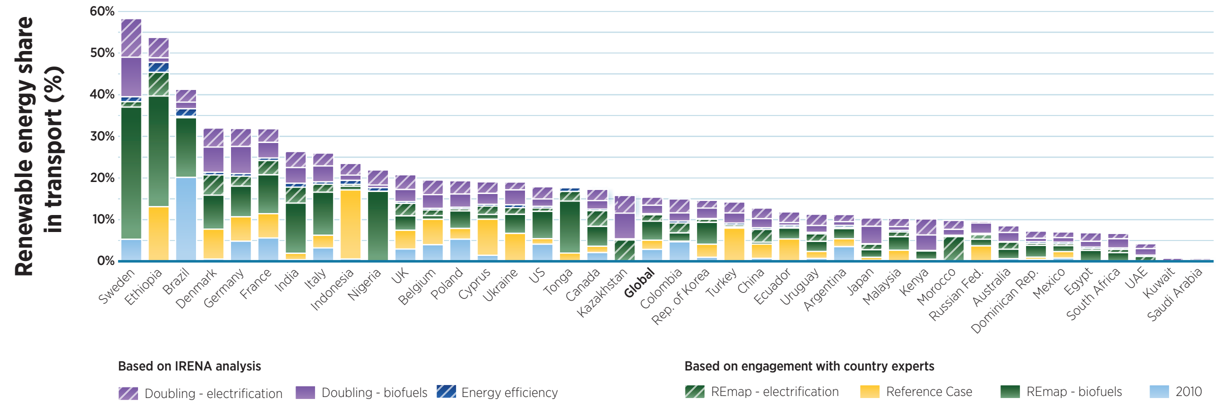
Figure 11 shows how emissions of five air pollutants develop between 2010 and 2030, comparing the Reference Case and REmap Options. Already in the Reference Case, there are significant reductions in emissions of air pollutants. The greatest reduction from 2010 levels is in ammonia (NH_3), NO_x and $PM_{2.5}$ emissions, while the smallest reduction is in SO_2. The REmap Options result in continued reduction in emissions from all sources. Total reduction of pollutants in REmap compared to 2010 levels range from 16% to as high as 38%.

2.5 Country findings

Implementing the REmap Options on top of the Reference Case will increase the share of renewable energy in the transport sector from 3% to 11% by 2030, exceeding 20% in a number of countries. The share in countries varies significantly, from around 0-1% in Middle Eastern countries, to as high at 35% in Brazil and Sweden. However, most countries fall into the 5-20% range (see Figure 12).

The breakdown of renewable energy use differs considerably from country to country. In 2010, the renewables contribution came either from conventional ethanol or forms of electric mobility other than electric vehicles (largely train and tram networks). In countries where electrified railways and public transportation are common (*e.g.* former Soviet Union countries and several European countries), electric mobility accounted for the largest share of renewables in the

Figure 12: Share of renewable energy in the transport sector in REmap countries, 2010 and 2030



Note: Renewable energy in transport includes the total of liquid and gaseous biofuels and renewable electricity.

transport sector (if electricity was produced from renewables). In Brazil and the US, ethanol dominated the mix. The share of ethanol and diesel in most European countries was relatively equal. Indonesia and Malaysia used mainly biodiesel. In 2030, the mix will expand to include more electric vehicles and advanced biofuels.

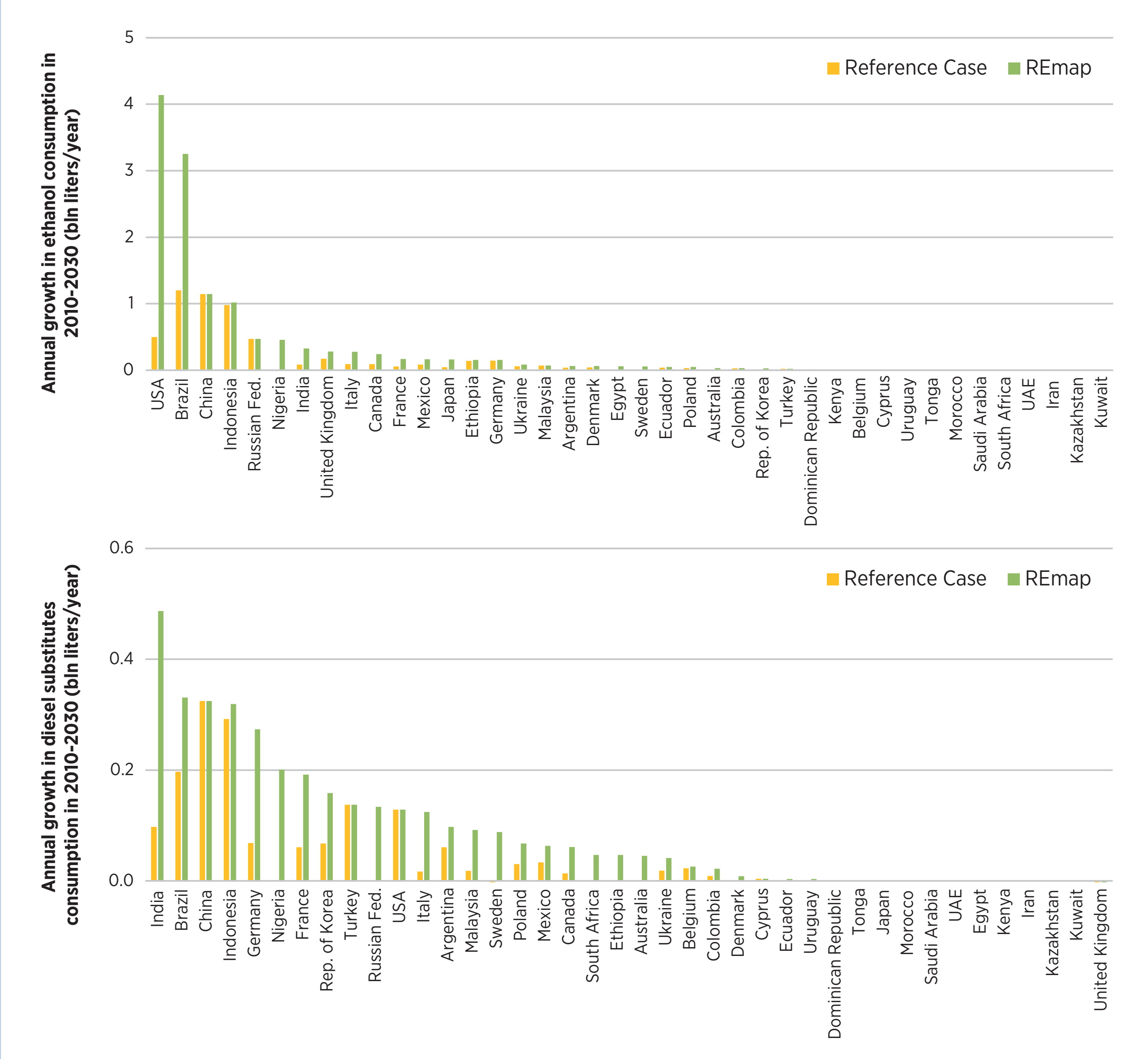
Sweden is a good case study. The country already has a large bio-based economy, but lacks vision for harnessing its strong renewables potential in the sector up to 2030. Renewables make up around 6% of the sector today, and according to the Reference Case, this share is not projected to grow by 2030. However, implementing REmap could ramp up the renewables share to more than 30% in that period. This potential comes from a mix of advanced biofuels from forestry feedstocks as well as advanced biodiesel and biomethane for use in freight transport and other passenger road vehicles. The country has even further potential than what has been identified in the REmap Options through country consultations. The assessment encompassed in IRENA's Doubling Options shows an additional potential to take the country's renewable energy share from over 30% to as high as 60%. The Doubling Options put much more emphasis on getting people to abandon individual transport and use instead public and electric transit (which boosts the share of renewables use because Sweden produces a lot of renewable power). The plan puts more electrified buses and light-duty vehicles on the road, as well as trams. It also foresees greater use of bioenergy, such as biogas in road transport, and drop-in liquid biofuels in aviation and shipping.

Brazil, the world's large biofuel producer, has the potential to increase its renewable energy share to about 34% by 2030 with the REmap Options. This potential requires further production of conventional ethanol from sugar cane, and advanced ethanol from bagasse, and other agricultural residues and woody biomass.

In both China and Denmark, the share of electric vehicles will increase significantly, but the catalysts for electric mobility differ. In China, the key drivers are cheap electricity and the need to reduce emissions in cities to improve air quality. In Denmark, the main driver is government policy, which aims to create a storage option for the growing share of variable renewable power.

In other countries, like Turkey and South Africa, growth comes from biofuels. In Germany, liquid biofuels are increasingly used in the form of biodiesel for road vehicles, followed by advanced biofuels, including large growth in biokerosene for the aviation sector.

Figure 13: Annual growth in ethanol and diesel substitutes consumption in 40 REmap countries, 2010-2030



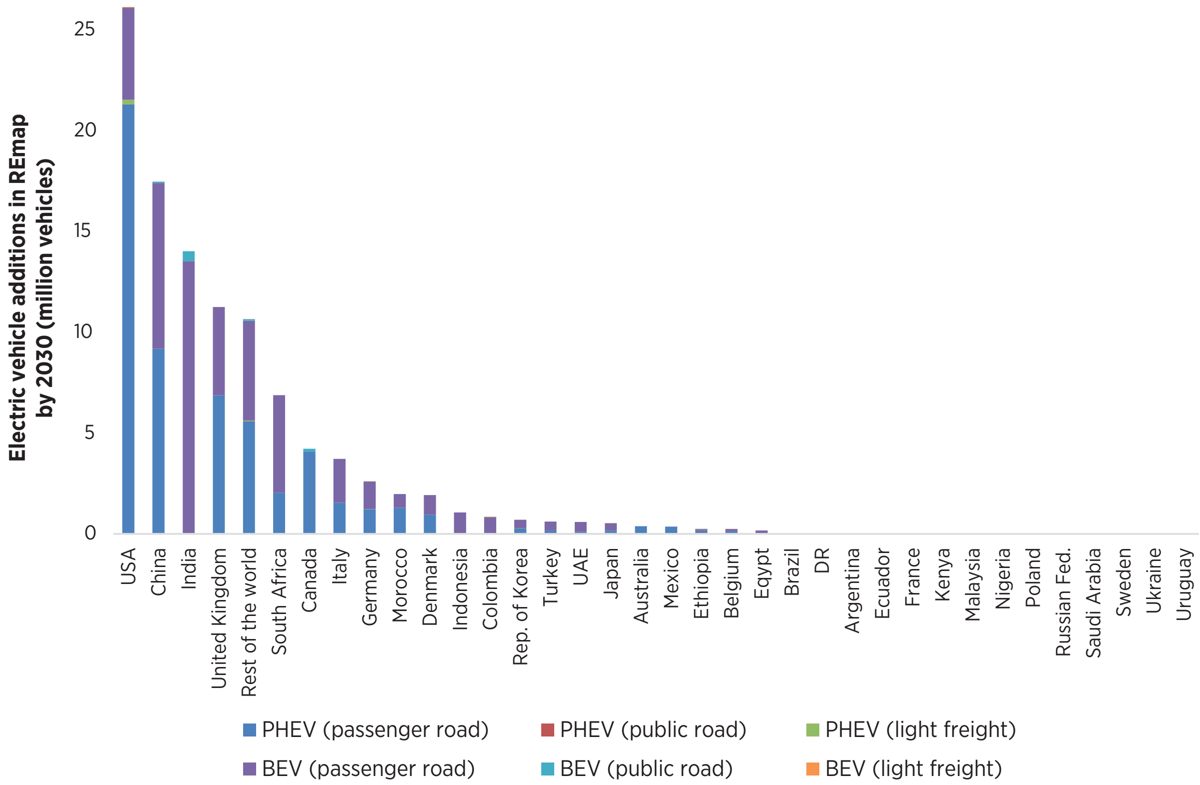
Conventional ethanol is not growing, due to the sustainability constraints of this fuel in the region.

Similar developments are taking place around the world, depending on resource availability and national energy and transport sector policies. Despite growth in biofuel use and renewable power consumption in all countries, the renewable energy share is growing very little. This is because demand for energy in the sector is growing as fast as the use of renewables.

Scenarios estimated by different organisations have projected demand of 5-19 EJ for liquid biofuels in 2030. REmap shows biofuel demand will be 12 EJ. This is technically feasible, but will require significant growth. The demand for liquid biofuels worldwide in REmap would need to grow by 8% annually between today and 2030 to reach this level. This rate may be slower than the 2000 to 2012 rate of about 19% per year, but it is still considerable, especially given the slowdown in biofuels production and lower investment in the past few years, as well as the recent decline in the price of oil.

At the country level, annual consumption of ethanol and biodiesel is seen growing at very different rates under REmap. In China and Indonesia, ethanol consumption would grow by more than 1 billion litres per year between 2010 and 2030. Growth is even higher in Brazil and the United States at 3 billion and 4 billion litres per year, respectively. This would mean increasing annual growth

Figure 14: Electric vehicle REmap Options in 2030



in ethanol consumption by three and eight times that of their current national plans. Diesel consumption would grow by between 0.2 billion and 0.5 billion litres in the top seven countries, meaning these countries would see growth of two to four times the amount diesel consumption in REmap compared to the Reference Case.

Raising the share of renewable energy from liquid biofuels in the transport sector will require special attention from policy makers and the energy industry to develop cost-competitive and sustainable advanced biofuels in the coming years. Importantly, governments will need a longer-term perspective and they must view the technology development as an investment in technological learning. All countries will demand more liquid biofuels; however, since feedstock availability is distributed unevenly, trade in liquid biofuels will increase. Likewise, innovation will play a key role in developing more efficient technologies that use primary biomass for biofuels, as resources are constrained.

Regarding electric vehicles, a country-by-country analysis projects around 60 million electric vehicles and 500 million two- to three-wheelers (including e-bikes) in the global vehicle stock by 2030 in the Reference Case. Roughly four-fifths of the two- to three-wheelers would be in China. Electric vehicle sales would reach around 3 million per year.

Tapping the potential beyond national plans, the REmap Case would result in 160 million electric vehicles in the global stock by 2030. In addition, two- to three-wheelers would reach 900 million. Figure 14 shows a breakdown of electric four-wheeler additions by type of vehicle and country. Additions in the US are by far the largest, exceeding 25 million in 2030. The US is followed by China, India and the United Kingdom.

The majority of the electric vehicle market would be passenger cars. The number of vehicle additions in REmap would result in around 50% PHEV vehicles and 45% BEV vehicles. Some countries, such as the

Figure 15: Carbon emission intensity of electric vehicles by country in REmap in 2030

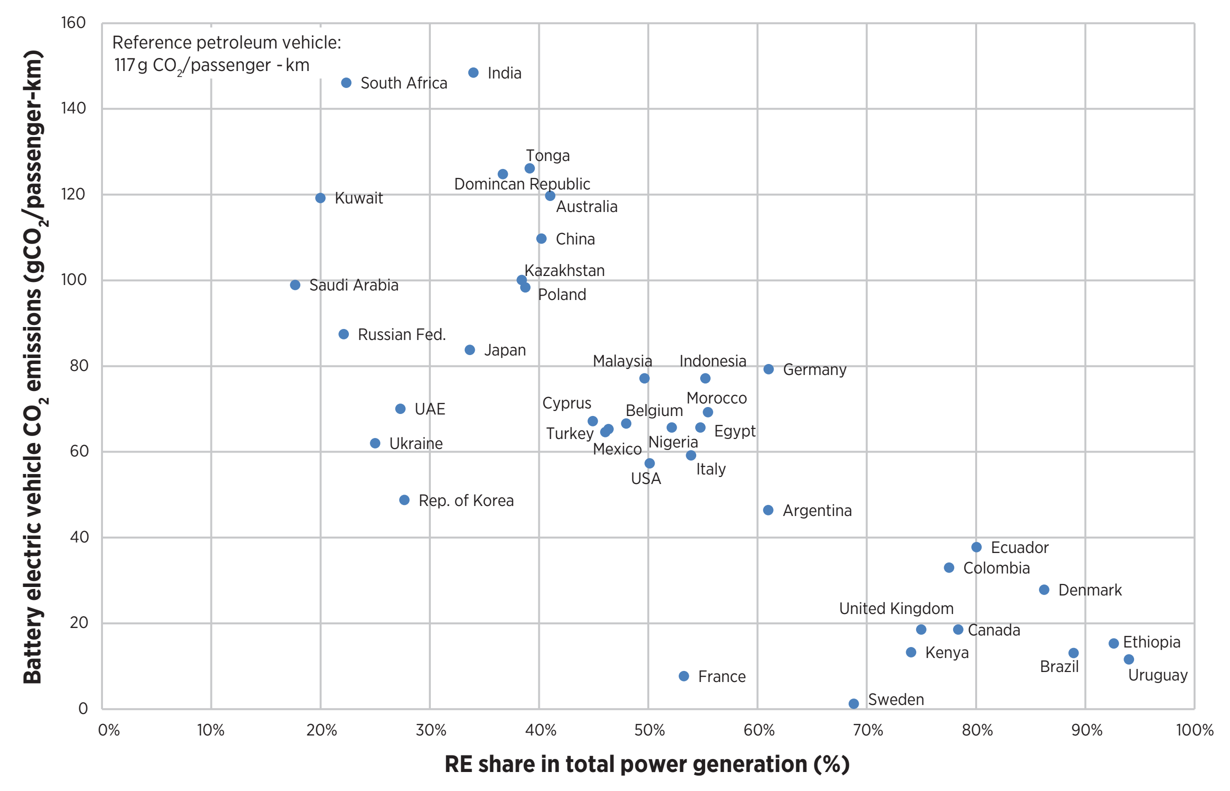
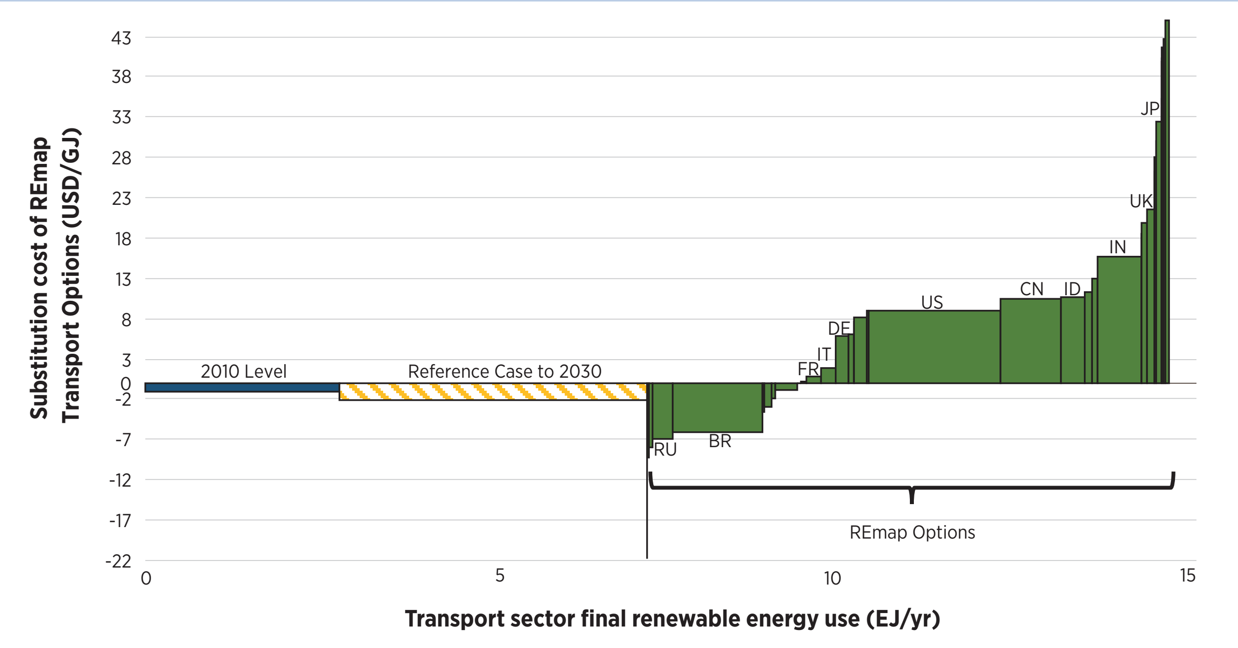


Figure 16: Cost-supply curve of renewable energy technologies identified in REmap in the transport sector by country



Note: costs have been estimated based on international energy prices that exclude the effect of any tax and subsidies, as well as a discount rate of 7.5% for OECD and 10% for non-OECD countries (the perspective is also known in REmap as the "Government perspective"). The abbreviations shown in the figure include – RU: Russian Federation; BR: Brazil; FR: France; IT: Italy; DE: Germany; US: United States; CN: China; ID: Indonesia; IN: India; UK: United Kingdom; JP: Japan.

US and Germany, would also increase the number of light freight vehicles and electric buses, which would make up around 5% of the additions. Not shown in the figure are significant additional electric two- to three-wheelers, which are found primarily in Asian countries such as India and China.

The carbon emission intensity of vehicles varies widely in the REmap Case, depending on countries' power mix in 2030. In countries with significant renewable electricity, such as Brazil, Denmark or Sweden, emissions from BEVs will range from 0-20 g CO_2 per km, whereas some countries will have emissions over 120 g CO_2, per km, close to the CO_2 emissions intensity of a comparable petroleum-based passenger car.

2.6 Costs and benefits of renewable energy technologies

Figure 16 compares the substitution costs of renewable energy options in the transport sector of 40 REmap countries. The costs are compared from a government perspective for the year 2030, assuming a USD 105 per barrel crude oil price – a little over two times higher than in mid-2016, but consistent with the latest IEA projections for the year 2030 (IEA, 2015c). The government perspective excludes taxes and subsidies for all energy prices (for both fossil fuels and renewables, representing international prices). The weighted average cost of the options is estimated at USD 7.4 per GJ of final renewable energy. A positive cost of substitution indicates additional costs associated with providing the same level of energy service with the REmap renewables options in the sector. If this cost were expressed relative to a barrel of crude oil, renewables would cost on average USD 45 more than the average price of crude oil in 2030. At a system level, these costs are equivalent to USD 63 billion per year in 2030. While this metric gives an idea of energy system costs, it does not provide a larger economic perspective that would take into account cost-savings from lower levels of air pollution or CO_2 emissions.

A number of countries have options with negative substitution costs, such as Brazil, Ethiopia, Nigeria, Poland, Russian Federation, and Sweden. The range of costs, from USD 0-20 per GJ, covers a larger number of

Figure 17: Costs and savings from reduced externalities with the REmap Options by sector

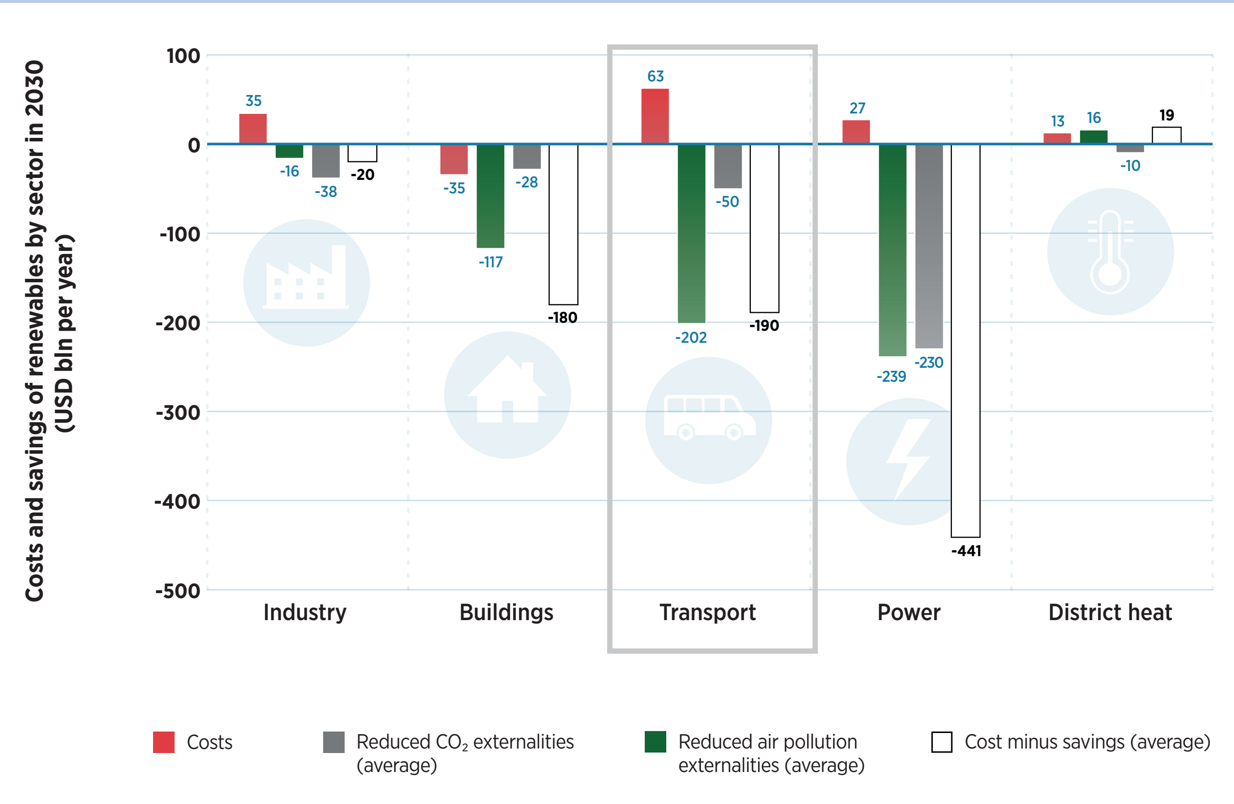
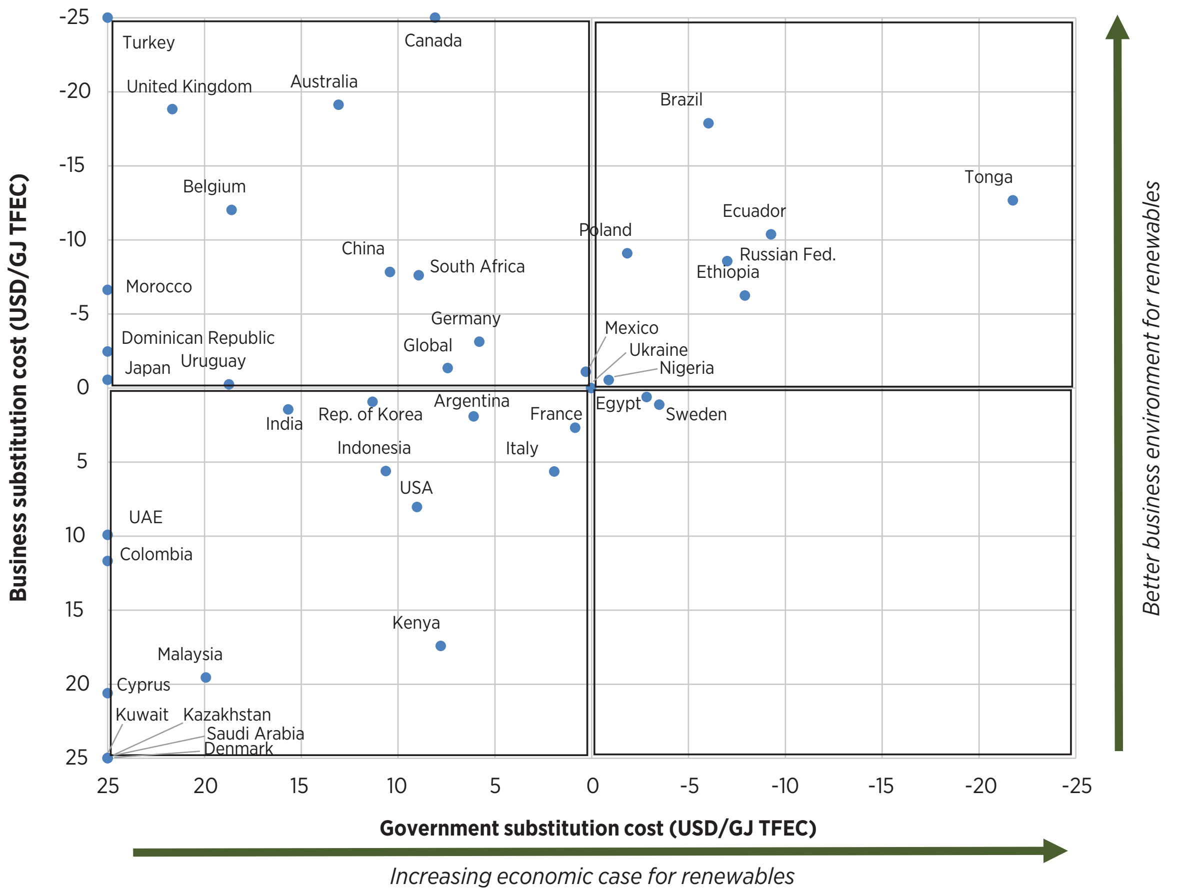


Figure 18: Comparison of substitution costs from government and business perspectives by country for REmap Options in transport



Note: Countries that fall on the outer axes have substitution costs that are outside the graph area. Cost reductions associated with lower external costs that result from the REmap Options are not included in the substitution costs displayed in the figure.

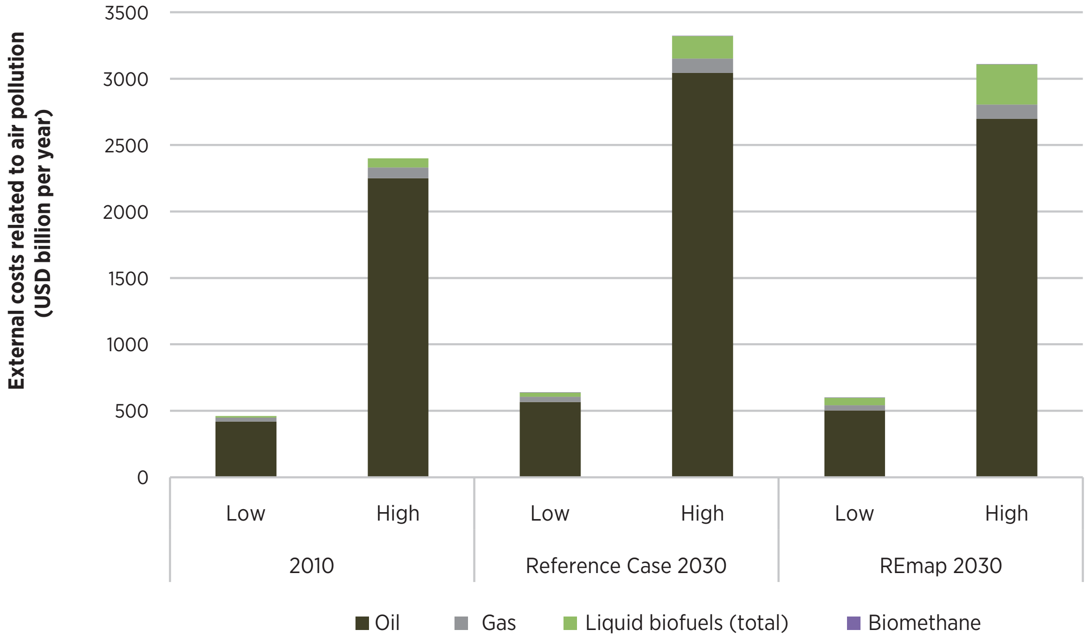
countries and all the large consumers, such as European countries, the US, China and India. The upper level (above USD 20 per GJ) includes countries such as the UK, Japan and Turkey.

Figure 18 compares the cost of substitution from business and government perspectives. The government perspective excludes any taxes and subsidies from energy prices and assumes a standard discount rate. The business perspective accounts for any taxes and subsidies and assumes country-specific discount rates for technologies based on 30-year government bond yields. This provides insight as to whether government policies and the business environment are aligned with the economic case for renewables.

Separating the figure into quadrants helps to understand this further. If a country falls in the right two quadrants, there is a strong economic case for the REmap renewables options. If a country falls in the upper two quadrants, it also has a favourable business case. This would mean that government policies and the marketplace are supportive of the types of renewable energy options identified in REmap.

The figure shows that over half of the countries have supportive business environments for renewables, while the remainder largely have neither a supportive business environment nor a directly compelling economic one (those falling into the lower-left quadrant). However, it is important to note that even in countries with a less compelling economic case, the results change if external costs are factored into the substitution cost. The effect would be the same for all countries – a shift right in the graph – though in differing magnitude based on local factors. When externalities are factored in, the economic

Figure 19: External costs of air pollution in the transport sector



case for renewables is significantly improved, and many countries that fall in the bottom-left quadrant would find themselves in the bottom right. If government policies reflected these external costs, the countries would move to the upper-right quadrant where their business case reflects the economic appeal of the renewable energy options.

A few countries in particular can provide some insights. Two countries with both compelling economic and business cases are Brazil and Tonga, although for different reasons. Brazil has an ample supply of both cheap electricity and biofuels, whereas Tonga has to pay very high prices for imported oil products. The result is that renewables in both countries are attractive both to the markets and governments. Other countries, such as China and Germany, have decided to incentivise renewables-based technologies, such as biofuels or electric vehicles. This has resulted in an attractive marketplace for these technologies. The US and oil-producing countries have neither a very supportive marketplace nor a compelling economic case due to lower-priced oil and tax environments. A country's placement in the figure does not mean all technologies cannot compete. Indeed, there are areas where some do. The country placement just reflects the portfolio of technologies identified in REmap. However, if countries in the left quadrants were to factor into their markets a mechanism that would internalise the external costs associated with fossil fuels, they would move up and to the right, improving the marketplace and aligning government policies with the economic case for renewables.

To understand this shift, REmap assesses how deploying renewables affects externalities. Cities are a main source of costs associated with externalities in the transport sector. They consume 75% of global primary energy, and in many cities over half of the energy use is related to the transport sector. Higher shares of renewables result in the substitution of fossil fuels and significant external benefits. Fossil fuels create air pollution by emitting $PM_{2.5}$, NO_X, SO_2, volatile organic compounds (VOCs) or NH_3. If these emissions were valued by considering their worldwide impact on human health and agricultural crops, external costs related to use of fuels in the transport sector would be USD 460 billion-2 400 billion per year, based on 2010. More than 95% of this total is related to the use of gasoline and diesel. As the demand for fuels increases, this cost is expected to grow by about 40% between 2010 and 2030 in the Reference Case. As a result, external costs related to the transport sector would increase to USD 640 billion-3 300 billion per year in 2030.

External costs of oil products would follow the same growth rate as all energy carriers put together. By comparison, costs related to the use of biofuels would increase by a factor of two, given that their consumption increases significantly in 2010-2030. External costs could be reduced by up to 6% with the implementation of all Remap Options, resulting in total external costs of USD 600 billion-3 110 billion per year in 2030. This is equivalent to a savings of USD 40 billion-210 billion per year in 2030. External cost savings related to fossil fuels are about 10% compared to the Reference Case in 2030. These savings are to some extent offset by the increase in external costs related to the biofuels, an increase of about 85% between the Reference Case and REmap.

External costs of fossil fuels are not limited to air pollution. Costs arise from CO_2 emissions as well. In 2010, the transport sector's energy-related CO_2 emissions were around 7 Gt. According to the Reference Case, these emissions can increase to 9.5 Gt by 2030, a rise of around 35%. With the implementation of REmap Options, these emissions can be reduced by 12-17% to 7.9-8.4 Gt. Assuming a carbon price of USD 17-80 per tonne of CO_2, there are additional savings in external costs of USD 19 billion-130 billion per year. Renewables can result in total savings of USD 55 billion-340 billion per year in 2030.

Realising the potential of renewable energy identified in REmap will also require a significant acceleration of investment in technology and infrastructure. Investment needs are estimated to be USD 347 billion per year between now and 2030. Of this total, USD 130 billion of annual investment would occur in the Reference Case, with the additional USD 217 billion of annual investment resulting from the REmap Options. The incremental investment need of the REmap Options would be lower, at only USD 40 billion per year, meaning USD 177 billion would be investment redirected from fossil fuel technologies to renewables. These investment costs, however, do not include costs associated with modal shift, which can include public tramlines, and electrified roads and rail.

Investment in technology includes USD 23 billion per year in biofuel plant production capacity. Of the total for biofuels, USD 1o billion per year is for advanced biofuels. The average annual investment for all types of liquid biofuels was USD 4.5 billion per year between 2010 and 2015, so a fivefold increase would be needed.

Infrastructure for electric vehicles will also be required, including a combination of home charging units, public charging units and high-voltage fast charging for longer distance travel. REmap would require investment of around USD 8 billion per year in charging infrastructure, with over half of this investment in home or place-of-residence charging units.

Costs associated with large infrastructure investments for modal shifts are usually significant, but are hard to quantify. The costs associated with different types of modal shifts also vary significantly. One study compared the deployment for different types of modal shifts (buses vs. trains) based on how much time it takes passengers to get from one point to another – called travel time budget. This quantifies the investment needed per travel time unit. While the study did not provide investment numbers, as they vary by country, it did show that most commuters have a limited travel time budget. The study found that faster options, such as train travel, require significantly higher investment costs (Giannakidis *et al.,* 2015). Therefore the relative mix of modal shift options as well as regional costs will have an effect on investment totals.

2.7 Key indicators and mapping progress

In REmap, total final renewable energy use in the global transport sector is expected to be 14 EJ. This potential is significantly beyond the level projected by government plans (Reference Case) and today's levels. Deploying these 14 EJ of final renewable energy in the global transport sector would result in a renewable energy share of 11% by 2030, nearly four times that of today. About 85% of this would be from biofuels and 15% from renewable electricity. But because electricity is much more efficient, electric forms of transport would provide around half of all passenger-kilometres.

This roadmap has identified three priority areas for deploying this potential: 1) Increasing electric mobility with a system strategy approach that interlinks energy sectors; 2) Develop sustainable and affordable advanced biofuels pathways, and; 3) Expore emerging technology solutions and innovation for transport modes such as aviation and shipping. In order to track progress in these priority areas and in realising the quantified REmap potential, this roadmap proposes a number of indicators as shown in Table 2.

Table 2: Progress indicators for renewable energy technologies in the transport sector

	Units	2014	2030 Reference Case	REmap
Renewable energy share				
Including electricity	% of transport sector energy use	3.0	5.7	11.4
Excluding electricity		2.8	5.1	10.0
Electricity use share		1.3	2.4	4.3
Bioenergy use				
Total liquid biofuels consumption	bln litres/yr	129	250	500
Conventional ethanol	bln litres/yr	93	185	283
Advanced ethanol	bln litres/yr	1	10	94
Biodiesel (conventional and advanced)	bln litres/yr	35	56	120
Kerosene	bln litres/yr	0	0	2
Hydrogen	bln litres/yr	0	0	1
Biomethane	bln m^3	0.15	0.32	0.98
Additional biofuel plants (compared to today)				
Conventional ethanol plants			500-750	750-1000
Advanced ethanol plants			40-75	400-500
Biodiesel plants (conventional and advanced)			220-300	340-480
Electric Mobility				
Total number of EVs (4-wheeler)	Million	1	60	160
EVs (passenger cars)	Million	1	59	158
Other EVs	Million	<0.1	1	2
Two- to three-wheeler EVs	Million	200	500	900
Share of EVs in total stock	%	<0.1	4	10
Biofuel and battery prices				
Biofuel prices (excl. taxes)				
Conventional ethanol	USD/l	0.45	0.40	
Advanced ethanol	USD/l	1.70	0.55	
Biodiesel	USD/l	1.01	0.75	
Battery pack prices	USD/kWh	250	80-120	50-100
Total investment needs in renewable technology and infrastructure	bln USD/yr	23	130	347
Investment needs in biofuel production (between today and 2030)	bln USD/yr	3	7	23
Investment needs in EV charging infrastructure	bln USD/yr	1	3	8
Investment needs in EVs	bln USD/yr	20	120	316
of which is incremental investment in EVs	bln USD/yr	6	12	31
Fuel expenditures				
Gasoline/diesel expenditure (in 2030) (excluding tax/subsidy)	bln USD/yr	1400	2750	2430
Biofuel expenditure (in 2030) (excluding tax/subsidy)	bln USD/yr	55	219	390

2.8 Deeper structural change and aggressive technology adoption with the Doubling Options

The Doubling Options are IRENA's own exploratory assessment to identify technology options that would increase renewables even beyond what has been identified in the REmap Options. These options imply more structural change and greater electrification. They are necessary to reach even higher renewable shares and to achieve the goal of doubling the renewable energy share in total final energy consumption.

The technologies identified include biomethane and hydrogen, especially in trucks. Some countries are considering different options to use excess renewable electricity in production processes, such as in power-to-gas to produce hydrogen. This hydrogen can be stored and used subsequently in fuel-cell vehicles. A number of automobile manufacturers have been considering such opportunities. Aviation and shipping would adopt liquid biofuels, and electrified public transport would substitute passenger cars to a higher degree than in the REmap Options. The renewable energy share in the transport sector's total energy demand would be 15%, a fivefold increase over today's level.

2.9 Priority areas for action

In addition to quantifying the potential of options for raising the share of renewables, REmap also tells us about the challenges to realising them. There is still very little production of advanced biofuels from lignocellulosic biomass (wood, grasses or inedible parts of plants), agricultural residues or waste. EVs are promising, but infrastructure that enables their use – like charging stations – must be developed in parallel to expanding capacity. Finally, much more innovation, research, development and deployment is required in the aviation and shipping sectors. We therefore need to create more knowledge to support these emerging options, including a better understanding of their costs and economic viability. This calls for sharing knowledge on state-of-the-art renewable technology options, coordinating research efforts, and aligning policies, standards, and advocacy efforts. Global action to realise the potential estimated in REmap can only occur with the engagement of global experts. To catalyse action, IRENA has identified three priority areas for both policy makers and industrial stakeholders:

1) **Electric mobility and the role of systems thinking:** Electric vehicle sales are expected to grow in the coming decade. REmap suggests at least 10% of all passenger cars on the road could be electric by 2030. Along with the growing demand for public transport and modal shifts, railway use will more than double between now and 2030 worldwide. Increasingly, future energy systems will not view sectors independently; the interplay between and coupling of sectors will start to emerge. As power systems become cleaner with higher shares of renewable electricity, the potential to store and convert this power into heat or mechanical energy will be important in a world that relies more and more on electric mobility.
2) **Advanced liquid biofuels:** Advanced biofuels will be key if the share of renewables in transport is to increase. Additionally, they have potential to be used in modes such as freight, shipping and aviation, and in drop-in applications with existing infrastructure. However, production volumes and costs remain a challenge, and investments are needed to drive down costs.
3) **Emerging sectors and technologies:** Technologies such as biomethane, hydrogen fuel cells, and sail power for shipping all have tremendous potential. The key drivers for these technologies may not be cost, but important local environmental and security benefits.

The following sections go into detail about these three action areas. For each area, the sections provide an overview of the current status of technology and markets, developments to 2030 and ten policy suggestions for a transition to a sustainable transport system by 2030.

3 ELECTRIC MOBILITY

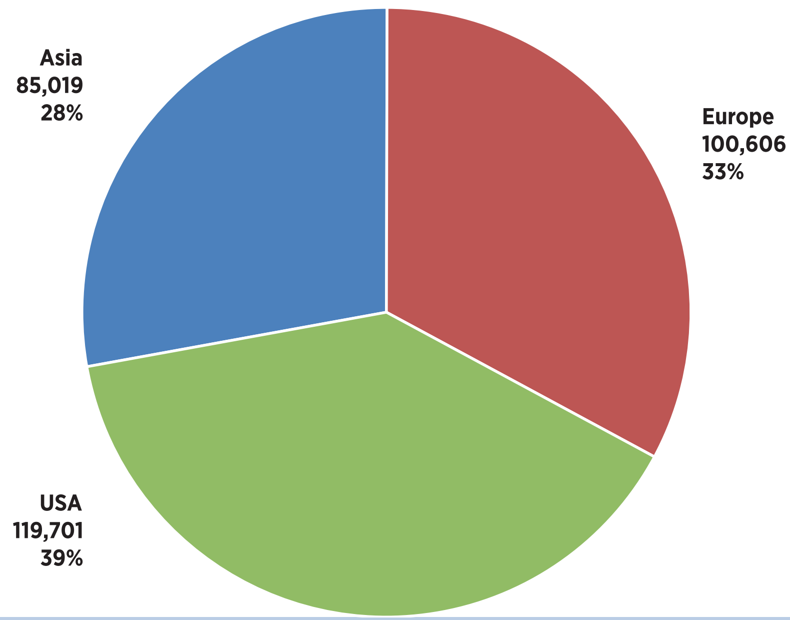
Renewables-based electric mobility will represent an important share of transport sector's total renewable energy demand in 2030. As electric mobility expands, it creates new demand for electricity that can be sourced with renewables. The potential identified in REmap requires total electric vehicle sales to reach an average of 10 million per year between now and 2030, a significant increase from under 1 million today. Nearly half of the total demand for electricity for these vehicles would be sourced with renewable power, as that sector is seeing a significant shift to power sources such as solar and wind. Electric mobility is promising because it is an efficient mode of transport that does not create local air pollution and CO_2 emissions; however, costs must fall and enabling infrastructure (charging stations, railways) needs to be developed in parallel to capacity growth. Another major challenge is the security of material supply, especially lithium, which will be increasingly critical as demand for new batteries grows. Measures to improve life-cycle efficiency will be key. Overall, the transition to sustainable energy in transport by accelerating electric mobility requires a more holistic approach that creates synergies with the rest of the energy supply sector and economy.

3.1 Current status and potential identified in REmap to 2030

Electric mobility sourced with renewable power is an efficient way to increase the share of renewables in the transport sector. As energy-consuming technologies, electric vehicles create new demand for electricity that can be supplied with renewable power. This will increase the share of renewables in both the power and transport sectors. In addition to the benefits of this shift, like reducing CO_2 emissions and air pollution, electric mobility also creates significant efficiency gains.

The energy demand to deliver the same amount of transport service is at least 2-3 times more efficient for an electric vehicle than for a vehicle with an internal combustion engine. Furthermore, losses in conversion from putting energy into the vehicle to the start of motion are about zero. Assuming solar and wind deliver electricity with no conversion losses, then system efficiency is very high. Such efficiency benefits are especially important for urban freight and logistic transport modes. These systems often operate below their optimal efficiency because they require frequent

Figure 20: Electric vehicle sales in Asia, Europe and the US in 2014



Source: Based on UC Davis (2015)

stopping and starting. Other benefits of electric mobility are less local air pollution and, depending on the power generation mix, lower CO_2 emissions.

By the end of 2015, the number of electric vehicles on the road was estimated to reach 1.25 million (IEA, 2016). REmap shows that this number can increase to 158 million four-wheel BEV and PHEV passenger vehicles and about 2 million freight vehicles and public buses by 2030. This is almost three times more EVs than in the Reference Case, which projects 60 million. REmap shows the additions would be largely split between BEV and PHEV, each with roughly half of the market, indicating the importance of both types of vehicles for more consumer choice.

The 160 million four-wheel EVs on the road would make up around 10% of the total vehicle stock. This estimate is close to what industry leaders have pledged to reach – a share of 15% by 2030 (UN, 2014). However, recent vehicle growth shows little sign of even starting to approach this high number, with BEVs comprising only 0.1% of the 1 billion vehicles registered in 2015. Annual sales of 4-wheel EVs in 2014 totalled 300 000, with around 500 000 expected in 2015 – far from the 10 million per year needed to reach the REmap totals. Therefore, a twentyfold increase is needed.

Additionally, over 900 million electric two- to three-wheelers are expected to be on the roads. Roughly half of these would be in China. Today, there are around 200 million such vehicles worldwide, meaning sales of electric two- to three-wheelers would have to average 45 million per year to meet the REmap totals. To put this effort in perspective, around 50 million two- to three-wheelers (mostly internal combustion engines) are sold worldwide every year. In 2015, expected sales of electric mid-size and large two-wheelers were about 4.3 million (Weiss *et al.*, 2015). Hence, 10 times more would have to be sold annually by 2030.

Assuming all these new vehicles were to consume 100% renewable electricity, then 480 TWh per year of additional renewable power would be required in 2030 (approximately 1.5% of the total global electricity generation). The share of electricity in transport's total energy demand would increase from 1% to 4% in 2013-2030. This would not only come from EVs, but other forms of electric mobility (*e.g.* trains, trams) would also growth significantly. These would represent about 60% of total electricity use in the sector compared to 40% consumed by electric vehicles. Today, around 3 100 billion passenger-km are used in railways worldwide. In REmap, this would more than double to approximately 7 500 billion passenger-km in 2030. This growth in demand is split between the increase that would occur anyway due to higher rates of urbanisation or population growth, but also from structural changes that increase demand at the expense of flights or long-distance buses.

3.2 Market developments in different countries and regions

Today the market for electric passenger vehicles is highly fragmented, with just a few countries making up the lion's share of sales. Sales have been sluggish and below expectations, although they have picked up in some countries such as Norway, the Netherlands (continental), France and China, which is the current world leader in sales. Electric vehicles have been successful where governments have provided tax incentives (Norway), given free access to restricted city centres (London), or otherwise mandated low emissions (California). A number of cities are also discussing banning internal combustion engines (*e.g.* a diesel ban is being considered for Paris by 2020, and Oslo is considering banning all cars by 2019 in the downtown area), or creating low emission zones (*e.g.* London) through banning heavy-duty vehicles or emission-intensive modes of transport in certain areas. The main driver of electric vehicle sales in India is city air pollution; today, thirteen of the twenty most-polluted cities in the world are in India (see also the section on modal shift).

Regional developments in electric vehicles differ greatly. For example, the Asian electric vehicle market is somewhat different than the rest of the world, and mainly composed of two- to three-wheelers. Today, Asia accounts for two-thirds of the total global market (Aia, 2014), where two- to three-wheelers are seen as a practical mode of transport due to the high density of cities and road infrastructure. Although various incentives exist in countries to support their uptake, a lack of clear policies to support the growth of supply, manufacture and battery recycling slow down market growth. Safety concerns and affordability are two other barriers to further growth.

Despite the uncertainty in the policy environment, the Asian two- to three-wheeler market increased by 9% in 2014 from the previous year. Of global annual sales of medium- and large-sized two-wheelers (scooters) and three-wheelers of between 20 and 30 million units, more than 90% were in China.

The small two-wheeler market is also growing quickly. In 2012 around 30 million electric bicycles were sold worldwide. This market is expected to grow to about 50 million vehicles per year in 2018 (Aia, 2014).

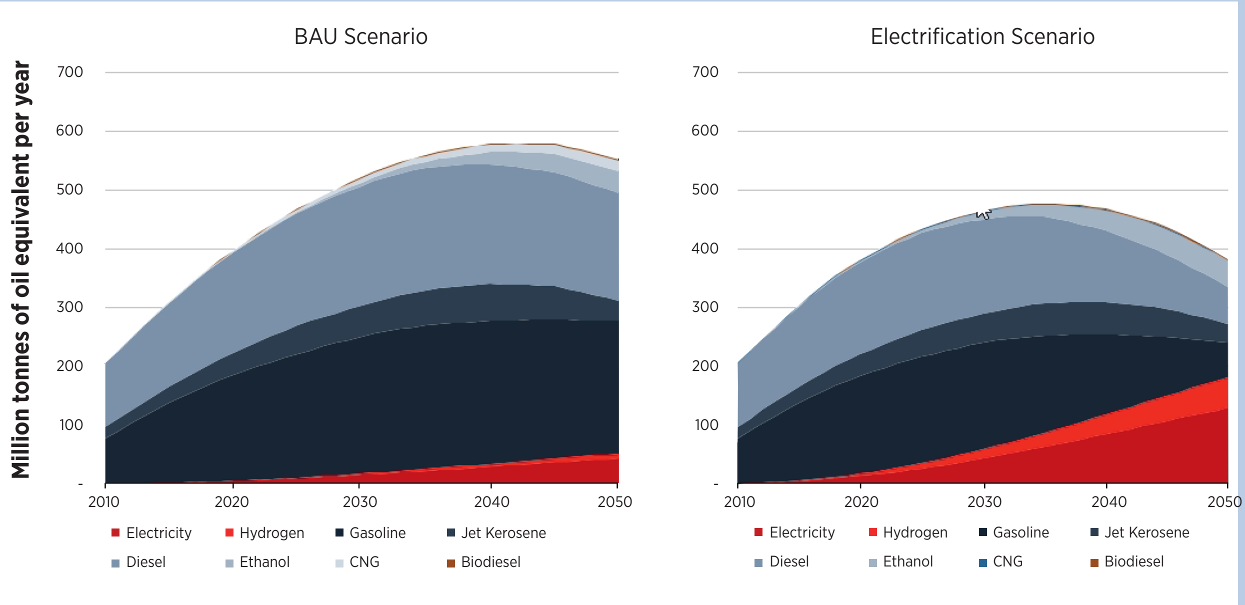
By 2018, cumulative sales of electric two- and three-wheelers in China alone will amount to 355 million (IRENA, 2014b). China is followed by India. There are more than 80 million vehicles in India, and the overall vehicle market is growing by around 10% per year. Unlike China, however, the Indian electric vehicle market shrank in 2015. The number of producers has fallen from 28 to 7 and total annual sales decreased between 2014 and 2015 (Pandit, 2015). However, a newly formed National Electric Mobility Mission aims to reverse this by increasing EVs to 6-7 million by 2020. The mission covers all vehicle segments, including passenger, freight and public vehicles. It will promote adoption of EVs through support for expanding charging infrastructure, and policy efforts focused on reducing regulatory barriers.

China also offers subsidies and tax incentives to promote deployment of four-wheelers. China has set a target of 5 million alternative energy vehicles by 2020, and annual sales of four-wheel electric vehicles increased markedly between 2014 and 2015. In 2014 only 36 000 vehicles were sold, but in 2015 this rose to 128 000. However, China is still not realising its targets.

China has a large range of incentives for both passenger and public electric vehicles. By 2020, it is expected to have 12 000 charging stations. The country is investing heavily in vehicle-to-grid (V2X) technology, and a recent study by the China National Renewable Energy Centre (CNREC/ERI, 2015) emphasised the storage benefits of significant electric vehicle deployment alongside China's plans to expand solar PV and wind power capacity. As Figure 21 shows, this electrification scenario has considerable potential to curb fossil fuel use in the transport sector.

The European Union (EU) has aggressive CO_2 emission reduction goals of 60% in the transport sector by 2050, which will greatly increase the appeal of zero-carbon

Figure 21: China's transport sector energy mix



Source: CNREC/ERI (2015)

Note: BAU stands for business as usual vehicles. When these standards become sufficiently strict, it will probably be more cost-efficient for an original equipment manufacturer (OEM) to partly sell zero-emission vehicles than to further reduce emissions from internal combustion engine (ICE) vehicle sales (ECN, 2015). CO_2 emission standards could provide an incentive for EV sales by the mid-2020s. Additionally, some cities are considering banning certain types of ICEs (EC, 2015), and this trend could accelerate.

France, Germany, Norway and the Netherlands (continental) have electric vehicle and charging point targets for 2020 and 2030 (as does the US). France aims to have seven million charging points by 2030, Germany 1 million EVs on the road by 2020, the Netherlands 200 000 by 2020. However, recent sales point to difficulty in reaching these goals and growth in the vehicle stock is slow. In Europe, BEV vehicle sales dominate the market, with vehicles on the road largely concentrated in Italy, Norway, Germany and France. PHEV vehicles have yet to take hold, making up just around one-quarter of registered electric vehicles. In 2014 in Europe, sales of all EVs were 96 000, and by 2015 that number increased to 182 000.

Norway is the EV leader in Europe. Almost one-fourth of its new cars registered in 2014 were electric. This high share is the result of subsidies that are scheduled to be phased out between 2018 and 2020 (Telegraph, 2015). Norway and the Netherlands, among others, have announced plans to allow sales of only electric passenger road vehicles as of the middle of the next decade, effectively banning sales of diesel and petrol vehicles (India also recently announced a similar goal, and is aiming to do the same by 2030). However, in all cases the plans are still under discussion and not yet enshrined in law (Renew Economy, 2016).

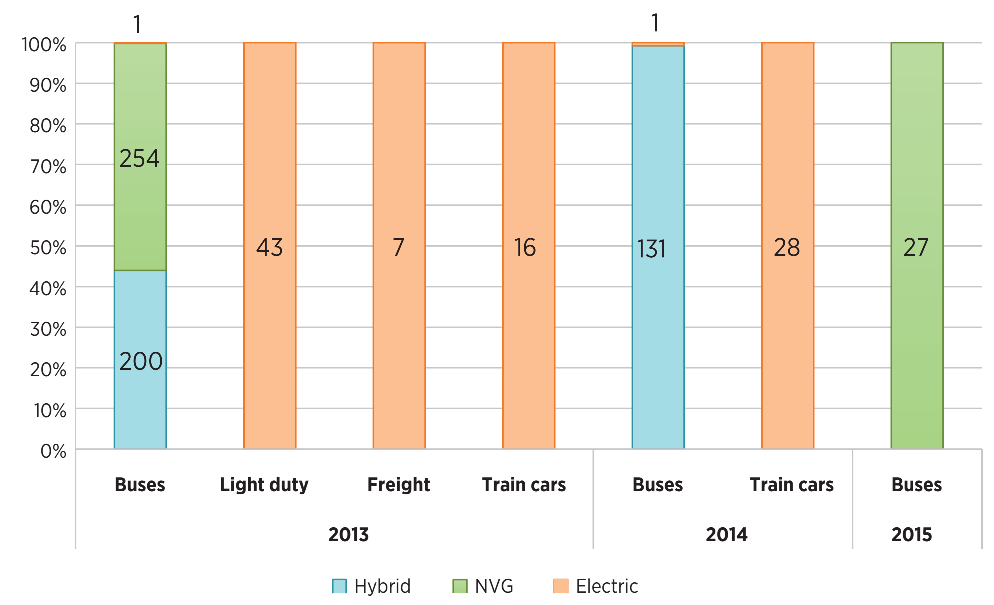
Germany has also stepped in to accelerate the adoption of electric vehicles. In April 2016, the country announced plans to provide subsidies to buyers of both BEV and PHEVs, as well as providing support for charging stations. The aim is to help reach the goal of one million EVs by 2020, which Germany is far from meeting, with

Table 3: Registered BEV and HEV in Europe in 2014

	2014									
	EV					PHEV				
Country	**Motor-bikes**	**Passenger Vehicles**	**Trucks**	**Buses**	**Total EV**	**Motor-bikes**	**Passenger Vehicles**	**Trucks**	**Buses**	**Total PHEV**
Austria	567	3386	820	131	4904	0	0	0	0	0
Belgium	254	2719	11	7	2991	0	1517	0	0	1517
Denmark	0	2700	296	14	3010	0	99	12	0	111
Finland	0	410	0	5	415	0	530	0	0	530
France	0	30121	0	0	30121	0	0	0	0	0
Germany	6566	18948	3517	116	29147	0	5058	0	0	5058
Ireland	0	447	70	0	517	0	32	1	0	33
Italy	38850	14502	0	1128	54480	0	1809	0	0	1809
Netherlands	196	6825	1304	72	8397	0	36937	0	0	36937
Spain	3086	2661	1152	8	6907	109	633	0	45	787
Sweden	0	3045	0	10	3055	0	5043	0	10	5053
Switzerland	9533	3741	390	52	13716	0	950	0	0	950
Norway	0	43170	0	0	43170	0	4145	0	0	4145
UK	1013	10565	4501	154	16233	0	6318	3	0	6321
Total Europe	**60065**	**143240**	**12061**	**1697**	**217063**	**109**	**63071**	**16**	**55**	**63251**

Source: VDI/VDE (2015)

Figure 22: Vehicle goals by segment and fuel type in Colombia



Source: UPME (2015)

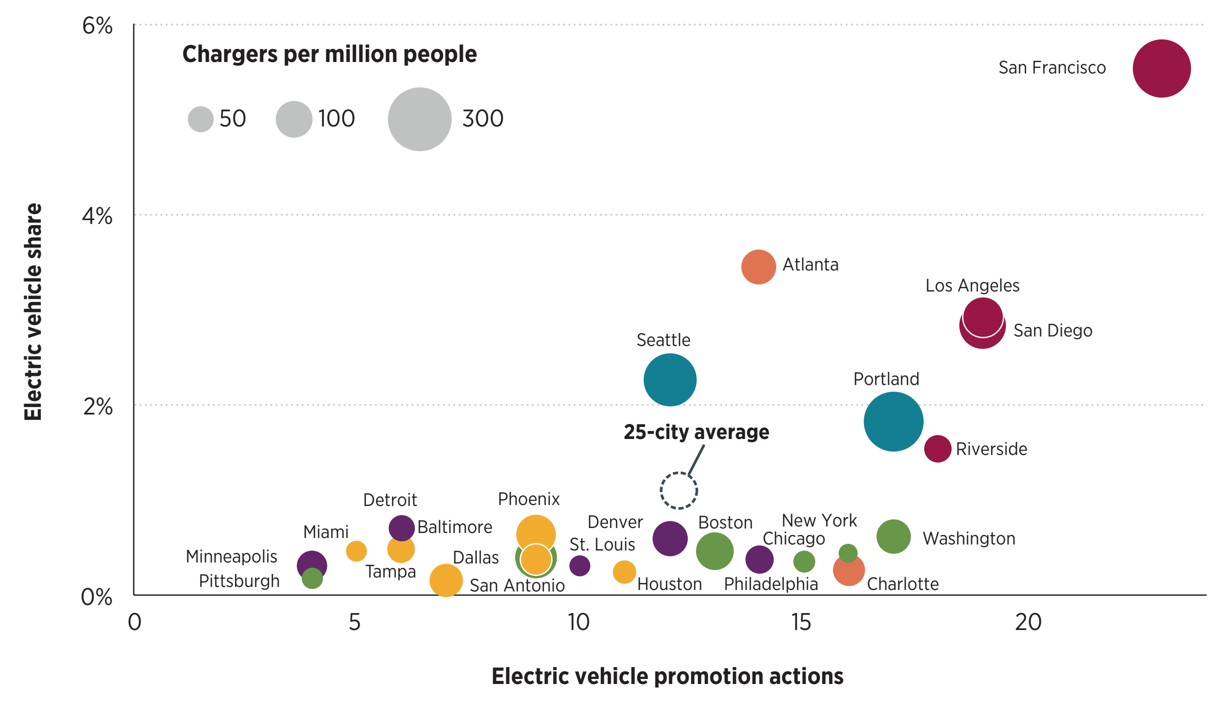
only about 150 000 electric and hybrid electric vehicles on the road as of the beginning of 2016 (Spiegel, 2016). Besides government-set targets, there are various private-sector initiatives in the EU to increase electric mobility.

Latin America is also starting to focus on electric vehicles. Colombia is a leader in its efforts to promote a switch to electric vehicles. The country has a national development plan to 2018 with aggressive goals for promoting electric vehicles. The goals are not just focused on passenger vehicles, but include promoting electric urban freight, bus and rail transport. Colombia planned to have over 300 hybrid-electric buses on the road by the end of 2015 (Figure 22). Colombia also has one of the highest shares of renewable electricity in its power mix in the world, at around 75% in 2015.

In the US, electric vehicle sales are centred in a few states and are driven by state and local financial incentives, with further financial support from a Federal Tax Credit. And studies show there is a strong direct correlation between the number of promotion actions and adoption of EVs (Figure 23). As of 2015, 27 US states have local or state incentives to assist buyers in purchasing electric vehicles. This makes the total cost of ownership much more favourable than internal combustion engines, in the order of 25% cheaper. It also cuts operation and maintenance costs (including energy), which are about a third lower (all compared to mid-sized vehicle markets). Consumers are starting to take notice, as the recent success of the new Tesla Model 3 shows. The new, mass-market-oriented BEV has booked over 400 000 pre-orders (valued at around USD 14 billion in sales) as of April 2016. However, while BEV sales are on the rise, the biggest current and anticipated future market is for hybrid electric vehicles. Their sales are expected to rise significantly. According to estimates by the University of California, Davis, hybrid electric vehicles could make up 5% of the market by 2020, rising to as much as 15% by 2025. Plug-in electric vehicle sales are also rising, with cumulative sales reaching more than 300 000 at the end of the second half of 2015. Sales have been dominated by a small number of vehicles, with about six models (out of 21 sold) accounting for 80% of the total.

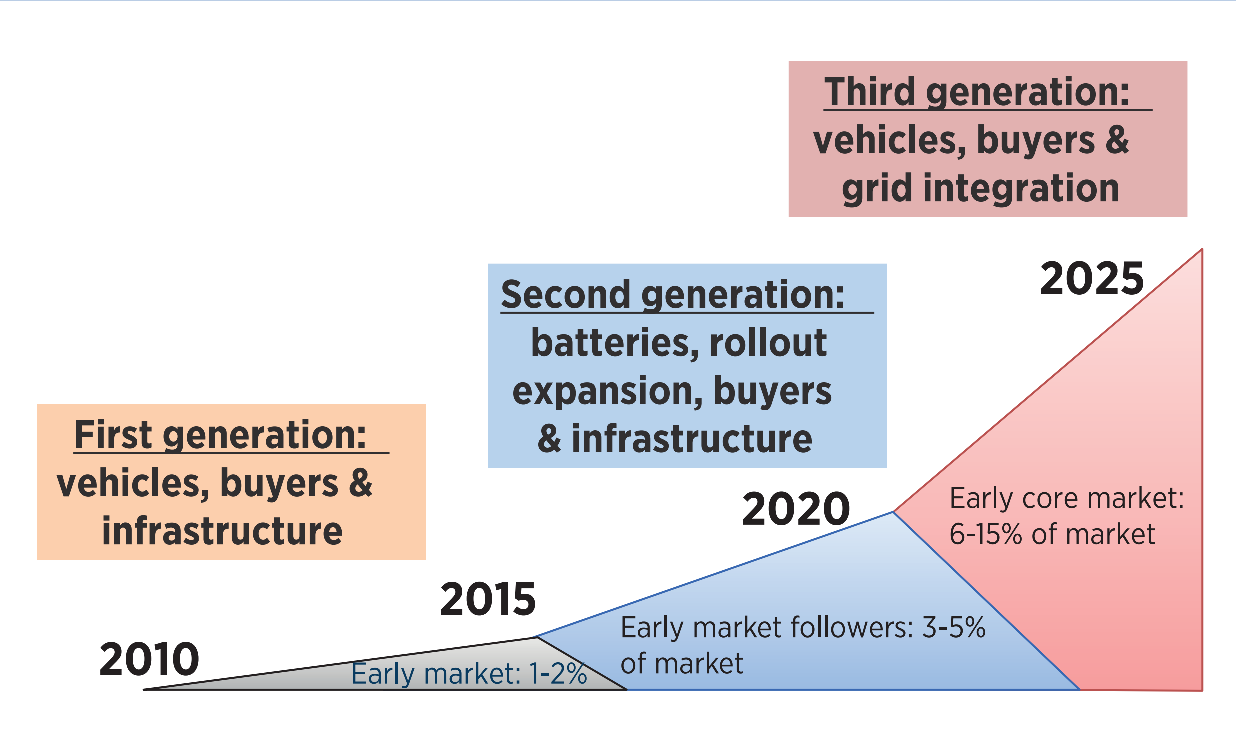
This growing electric vehicle stock is supported by a growing charging infrastructure. There are over 32 000 individual outlets (14 000 public charging stations) in the US. More than 2 000 of these are in California (Energyfuse). This infrastructure growth is partly due to state policies. As of 2015, nine US states have adopted zero emission vehicle mandates. These states make up 30% of the US car market, and over 80% of electric vehicle sales.

Figure 23: Share of EVs in US cities and number of promotion actions, 2014



Source: ICCT (2015)

Figure 24: Battery and plug-in hybrid electric vehicle sales in the US



Source: UC Davis (2015)

3.3 Systems thinking and interlinking transport and other sectors

The shift to increase electric mobility, especially in cities, will require that regions and cities start to consider the coupling of energy sectors, and think in terms of entire systems. Systems thinking is the process of understanding and identifying synergies between systems and their influence on one another within a complete or larger energy system.

Role of cities

Cities will be the largest source of both rapidly rising energy demand and transport needs over the coming decades. One of the main drivers of electric mobility will be efforts to make cities more liveable. Therefore, climate change targets alone are unlikely to catalyse a transformation of the transport sector. Sustainable development concerns, such as reducing pollution in urban areas, will also drive this change.

As society becomes increasingly more urban, EVs offer the potential to alleviate some of the issues that have plagued cities in the past, such as air pollution, noise and congestion. It is likely that EVs will be some of the first vehicles to be part of smart transport networks. Given that a large share of transportation takes place in urban areas, especially with passenger cars using internal combustion engines, modal shift will gain more importance.

Road transport is responsible for a growing portion of greenhouse gas (GHG) emissions and contributes substantially to urban fine particulate air pollution, thought to cause about 1.3 million deaths per year, and the accumulation of tropospheric ozone and its subsequent health effects (Haines *et al*., 2012). The EU estimated in 2012 that cars used within its member states have external costs of USD 341 billion-493 billion per year. These include environmental costs of car traffic such as air pollution, noise and climate change (Becker, Becker and Gerlach, 2012). Additionally, a recent study shows that an astonishing 87% of the world's population lives in areas that exceed World Health Organization guidelines for levels of $PM_{2.5}$, with 35% living in areas that significantly exceed safe guidelines (Brauer *et al.*, 2015).

Electric mobility offers an opportunity to reduce some of these external effects compared to passenger cars with internal combustion engines. But it is important to consider the power generation mix of a country or city for vehicle charging. What is the share of renewables or the share of coal-fired electricity used to produce electricity? Generally, the power system is expected to be less emission-intensive by 2030 than today. REmap shows that nearly half of all power generation could be sourced with renewables. A study by Michalek *et al*. (2011) presents a hypothetical optimistic case, where zero-emission electricity is used for charging, and a pessimistic case, where coal-fired power is used. In the pessimistic case, the battery electric vehicle would be responsible for USD 5 000 more in life-cycle externality damages and oil premium costs than the hybrid electric vehicle (difference mainly driven by GHGs and SO_2 emissions). In the optimistic case, the battery electric vehicle could reduce lifetime air emissions damages. Although the cost of damages from vehicle-associated emissions are significant, the damage reductions that can be gained through electrification are small compared to the total cost of owning and operating a vehicle.

Beyond emission reductions and the related benefits to our environment, electric mobility has other benefits. Electrified transport reduces the dependency on passenger cars in cities, which can reduce emissions through both more efficient energy use (by a factor of approximately 5 depending on the transport mode) (Figueroa *et al*. 2014) and the addition of renewables to the electricity supply. Modal shift can also take other forms. Put simply, a citizen choosing to bike to work instead of taking the bus uses an emission-free and clean mode of transport. Beyond the urban setting, high-speed, long-distance trains can substitute airplanes as well as truck-based, long-range freight transportation.

Electric vehicles can also reduce noise pollution in cities. In many cities, noise pollution from transport systems can surpass 55 decibels (dB) in certain areas, which, according to the World Health Organization can pose health risks. Electric vehicles can be much quieter than ICE automobiles, with many operating at just 21 dB. However, further study should examine the direct health benefits of lower noise pollution in cities resulting from higher deployment of EVs.

Additionally, cities will need to evolve their transportation networks to electrified mass transit, moving people from modes such as individual passenger vehicles to electric buses and trams. Electrified rail systems and high-speed passenger trains should serve longer distances. Today, more and more countries are investing in high-speed railways as an alternative to air travel. High-speed trains take passengers directly to the city centre, not to an airport in the suburbs. Many cities are also investing in bike paths, typically starting with recreation in mind, but citizens gradually embrace these for all sorts of daily use. Modal shift can also have adverse effects. In Germany, deregulation of the long-distance bus system has resulted in a cheap alternative to its railways, which are sourced with 100% renewables.

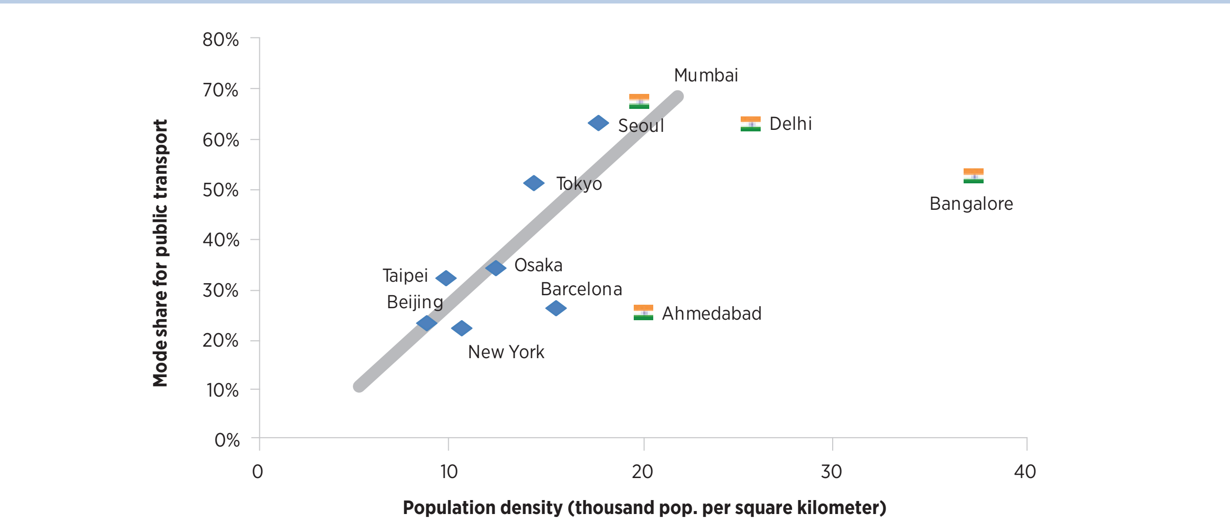
In the urban context, EVs are also likely to be some of the first cars to incorporate automated driving capabilities, and possibly the first to be completely self-driving or autonomous. EVs also serve as an enabling technology for decentralised variable renewable power, which will increasingly be built in cities as solar PV deployment accelerates.

Developments expected in India over the coming decades provide a good case study on how changes in cities and urbanisation will require the interlinking of energy sectors. The country is experiencing very rapid urbanisation, with 68 cities expecting more than 1 million inhabitants by 2030. Generally, population density and the share of public transport increase together (see Figure 25). But the ratio of public transport use to population density is generally much lower in Indian cities. Because the infrastructure in these cities was built before their population boom, efforts to increase public transit will have to focus in part on using existing infrastructure. The types of systems that can be built will be differentiated by volume. Typical high-volume routes will use metros and light rail. But the medium volume routes can be serviced by electric buses using real-time power supply (overhead electricity lines), or battery electric buses with en-route or end-point charging (end of line). The last mile can then be serviced with electric-based small commercial vehicles. These electric buses and commercial vehicles result in less local pollution, but will also need to interlink with the power sector. While electric passenger vehicles can provide complementary services to the grid in the form of midday storage, public and commercial vehicles will be less able to provide these services, so their effect on power demand should be considered.

Material needs

Electric vehicles have material requirements other than internal combustion engines, including rare earth materials, some of which are near critical supply risk. For example, battery production for electric vehicles requires lithium. Lithium is produced from brine lake deposits and pegmatites, a type of crystalline rock. Brines account

Figure 25: Ratio of population density to public transport use



Source: Based on Tata Motors (2014)

for about 60% of the total global production. Lithium demand has grown exponentially in the past years with the introduction of new technologies, not only in the energy sector, but also in communications and other sectors. Batteries account for about 20% of the total lithium demand today. This segment is expected to make up an increasingly higher share as electric vehicle sales drive demand for lithium.

An average battery for a four-wheel vehicle has a capacity of 30 kWh. Depending on the type, these batteries contain 2-13 kilogrammes (kg) of pure lithium. Based on the growth in electric vehicles according to REmap (all types, including two-, three- and four-wheelers), total battery capacity in use will grow by about 290 gigawatt-hours (GWh) per year between now and 2030. That is equivalent to 40-110 kilotonnes (kt) per year of pure lithium demand, or 200-600 kt per year of lithium carbonate equivalent (LCE) production. This is twice the total production of lithium today for all applications, indicating a possible resource constraint given demand for other lithium uses will also grow.

There are number of solutions to limit this challenge. Rather than taking the historical approach of increasing mining to meet rapidly growing demand, the key will be to improve material life-cycle efficiency through increased recycling, recovery and reuse. Thinking outside of the box, developing new technologies that rely less on such rare earth metals will be another strategy. Solutions will focus on developing new types of battery storage. A recent REmap technology roadmap for electricity storage identifies some of these new technologies (IRENA, 2015c). However, battery storage options for use in vehicles require certain defining characteristics, such as high energy density, light weight, and durability. Some emerging technologies look able to fulfil this need. Supercapacitors, for example, can store 10-100 times more energy per unit volume than conventional batteries, and they also charge much faster than lithium-ion batteries. Depending on how they are made, they can use materials that are in ample supply, such as graphene (form of carbon). They may soon be used in limited applications in vehicles, such as for start-stop functionality, or for brake energy recovery. However, technology development in the future will show whether such capacitors can work over long distances and be manufactured in large quantities affordably.

Power system and battery storage from electric mobility

As urbanisation accelerates, the systems in cities that provide heat, power and transport will require interlinking. A higher share of electric vehicles will create an important sector linkage of heating and transport with power generation. Transport is the key sector for coupling end-use demand with power generation.

Decentralised power production will increasingly be the norm, and cities will be an important source of demand-side management and storage through local heating and transportation networks. Integrated urban energy systems and planning will emerge as a key necessity to meet this increased energy need and keep local pollutants and adverse health effects to a minimum.

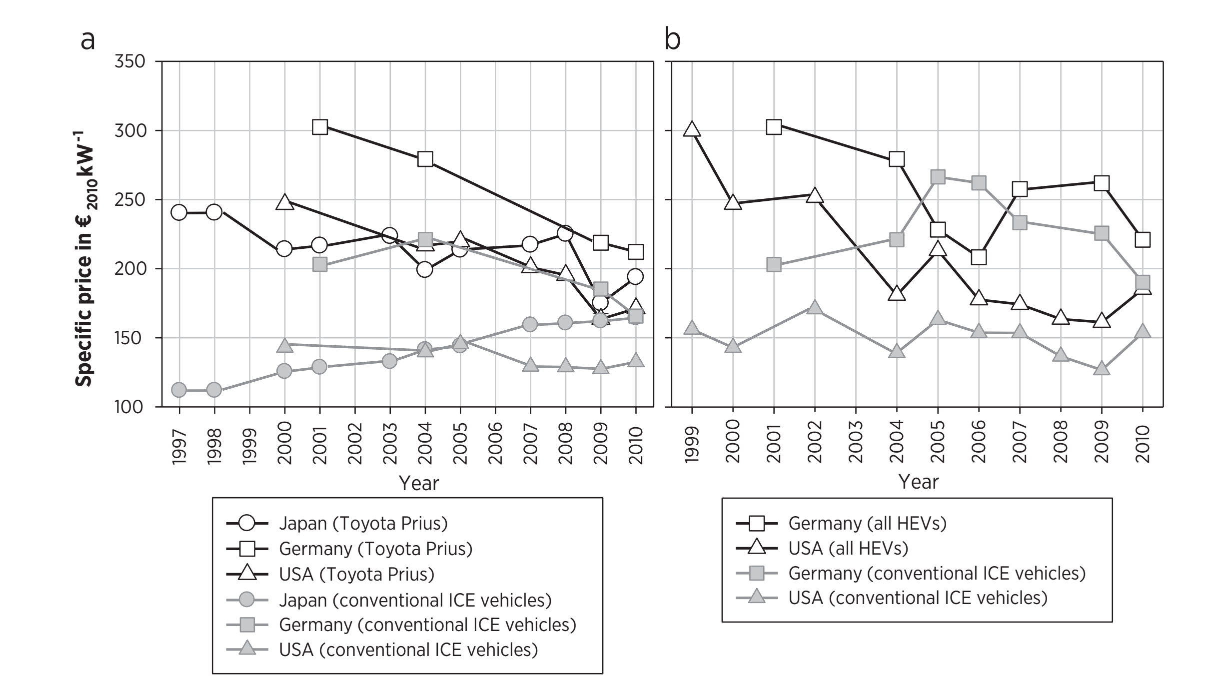
REmap shows that as many as 160 million electric vehicles (excluding the two- to three-wheelers) will be on the road by 2030. The energy storage capacity combined in the transport sector therefore be significant. Electric vehicles can offer further benefits to energy systems after the end of their life. The battery packs in these vehicles are usually warrantied for 8-10 years, and after that period, most will have reduced energy storage capacity. Battery manufacturers expect that they will on average retain 80% of their original capacity. Assuming a 25% recovery rate, by 2030 around 150 GW of total energy storage capacity will be available. Electricity stored in such systems can be released when the user needs them. Electrification in transport can be an effective way to increase the share of variable renewable energy, reducing the need for other flexibility measures and grid-integration costs associated with higher shares of variable renewables. Hence there is an important synergy between the transport and power generation sectors that can help increase the share of renewables in both.

3.4 Action areas for electric mobility

Costs of electric vehicles

Battery prices for EVs have dropped by two-thirds in the past five years, but electric vehicles remain more expensive than conventional passenger cars, mainly because of high vehicle costs. However, technological

Figure 26: Specific prices for HEVs offered on the market



Source: Weiss et al. (2012)

Note: Specific prices of the Toyota Prius (a) and of all HEVs offered on the market (b); data points represent price averages, which are un-weighed for vehicle sales.

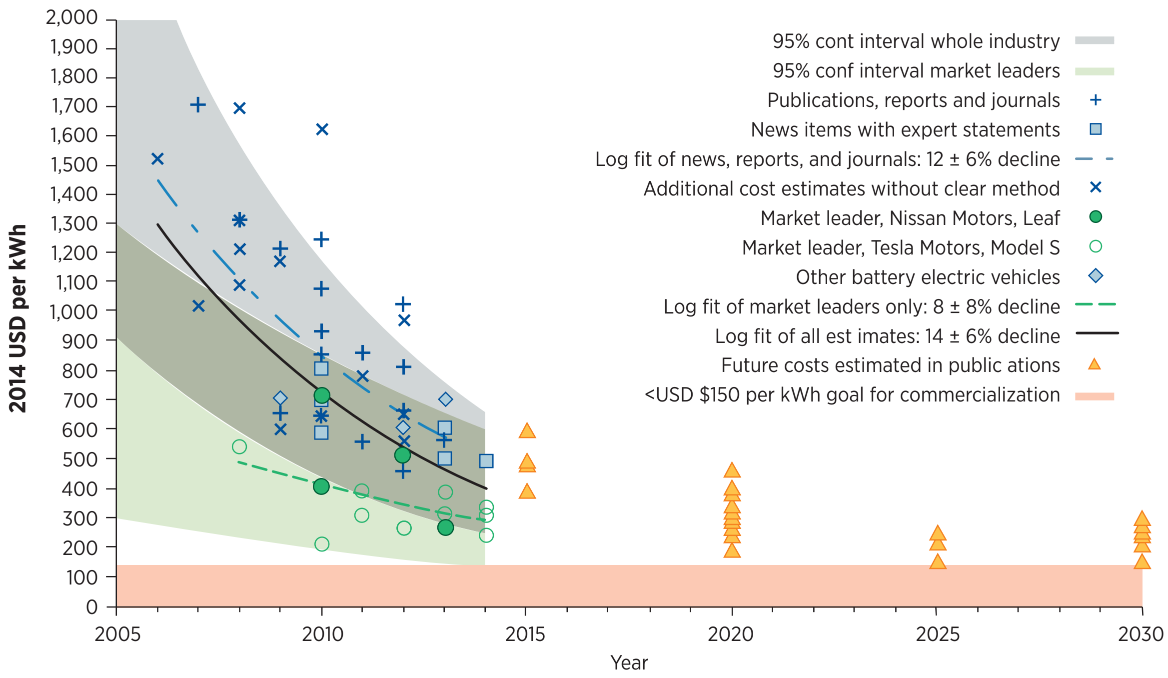
learning in battery technologies may reduce their price. The important metric of cost per passenger or freight kilometre is highly dependent on variables such as fuel cost, electricity price and cost of capital. EV ownership costs also depend on oil price developments, but parity for mid-sized vehicles is expected sometime between 2020 and 2023, depending on how these variables develop.

Figure 26 shows the decline in HEV prices since 1997. Between 1997 and 2010, the price in Japan declined by 19% to EUR 194 per kilowatt (kW) (USD 214). The price declines in the US and Europe were even higher. Some difference in prices across countries exists, explained by the cost of shipment and pricing strategies. Battery costs play the main role today and this will remain so in the years ahead, accounting for up to 40% of the total price of a passenger car (Handelsblatt, 2015). Prices of battery packs have fallen from EUR 1000 per kWh (USD 1100) in 2005 to around EUR 200-250 per kWh today (USD 220-280). According to some studies, EVs can be cost-competitive at around EUR 120 per kWh (USD 130) (Gerssen-Gondelach and Faaij, 2012). A breakeven can be achieved with production of 50-80 million battery electric vehicles, based on technological learning studies (Weiss *et al.*, 2012).

Global learning investment would amount to EUR 100-150 billion worldwide (USD 110-165 billion). The low end of this range can already be achieved with the Reference Case totals. Recent announcements from General Motors indicate the carmaker expects the battery in its upcoming Bolt EV to cost EUR 130 per kWh (USD 145), and that this cost will decline to around EUR 90 per kWh (USD 100) in the next decade (SNE Research, 2015) (see Figure 27). A recent study also shows that battery manufacturing prices have fallen faster than forecasted, with manufacturers now building batteries for prices that were only expected by 2020 (VDMA/PEM/RWTH, 2015). So it is possible the trend of declining prices may accelerate. The Tesla Gigafactory in Nevada, USA, and a major plant under consideration by Volkswagen, among others, could result in cost declines that are faster than predicted (Spiegel, 2016c).

Emerging battery technologies also have the potential to reduce costs further and could in the coming decades become an alternative to lithium-ion batteries, as there

Figure 27: Costs of lithium-ion battery packs in BEVs, historical and future projections



Source: Nykvist and Nisson (2015)

are many potential technologies under development (IRENA, 2015d). Some offer the advantage of increasing the energy density of the battery, which in turn can allow high levels of electricity storage and increase driving distances. Carmaker Nissan, for example, recently said that using sodium within the battery instead of carbon could increase density by up to 150%. Most batteries currently have a density of around 400 watt-hours per litre, with advances in storage density to 700 watt-hours expected by 2020, rising to 1000 by 2025 (FT, 2016).

Making EVs affordable for the average buyer and shifting from the luxury market to the mid-market segment, while providing ranges of over 200 miles (320 kilometers), will require significant cost reductions. Tesla's upcoming Model 3, with a retail price of USD 35000 without subsidies, still includes an expected battery cost of around USD 15000 (FT, 2015a). The distance the automobile can travel between charges is based on the amount of battery storage available. So to drive down vehicle cost, battery costs will need to continue to decline (see Figure 28). But this is not the only important driver for improved range. Range can be extended by increased efficiency of electric drive and reductions in vehicle weight. In this respect, efforts by conventional automobile producers will be important, such as the recent decision by Ford Motor Company to double its share of electric vehicles by the end of 2020 with an investment of USD 4.5 billion. This will increase the share of Ford's electric cars to 40%. The main driver behind this choice is growing urbanisation and GHG emission reduction targets (FT, 2015b).

The cost of recharging must also be addressed. In the Netherlands, the total number of charging stations had increased to 13300 by mid-2015. Based on different business models, providers offer a range of prices for charging EVs, from as low as EUR 0.30 per kWh (USD 0.33) by ANWB and as much as EUR 0.83 per kWh (USD 0.92) by Fastned. Fastned says a charging station costs up to EUR 200000 and it can only achieve profits if at least 15 cars per day use the station. Part of its business model is an unlimited charging package for EUR 121 per month (USD 133). At its gas stations, Total offers a 10 minutes of charging for EUR 4 (USD 4.4), which is equivalent to approximately EUR 0.50 per kWh (USD 55 cents) (FT, 2015b). And some automobile manufactures, such as Tesla, offer free charging for owners at select charging stations.

Infrastructure needs

Electric mobility requires a dual policy focus, one to accelerate uptake and another for infrastructure. The benefits are significant efficiency gains, and lower CO_2 and air pollution emissions. However, the main challenge of this shift to electric mobility is the need for new infrastructure to reliably provide services to the public. This requires investment and integration into the existing network. The time needed to build new infrastructure and the volume of investment needs require consideration in planning for electric mobility. For example, India will need around USD 3 billion in investment between today and 2020 to meet its target of 5-7 million electric vehicles by that time (NIUA, 2015). Infrastructure costs also differ based on transport mode – railway infrastructure is about 10 times more expensive than that of road vehicles.

Electric vehicles also come with additional costs for infrastructure. According to a German White Paper (BMWi, 2015), increasing electric mobility depends on the development of charging infrastructure (Germany still lags behind other European countries in this respect). Whereas hybrid electric vehicles are charged by regenerative braking, EVs require enabling infrastructure (charging stations) that must be developed in parallel to capacity growth. To some extent, this is a chicken-and-egg problem: car companies need charging stations so that cars will sell, but power providers will make a loss on such stations until a sufficient number of electric cars are on the road. Policy makers can solve this dilemma by providing incentives to spur these actors. Additionally, power utilities may welcome EVs as a source of new demand, so they may assist in expanding infrastructure to enable more widespread and faster charging. Finally, international standards are needed for charging stations, so policy makers should work with industry and other countries to prevent competing standards.

Early infrastructure development is important to increase early adopter acceptance and the effective use of electric vehicles through the availability of home, public, and workplace charging options (NREL, 2014). Recharging infrastructure must be planned and tailored to the individual circumstances of cities and surrounding areas. Each city has different existing road infrastructure, parking facilities and transport options (Crolius, 2010). For example, less than half of the vehicles in the US have reliable access to a dedicated off-street parking space at an owned residence where charging infrastructure could be installed. While approximately 79% of households have off-street parking for at least some of their vehicles, only an estimated 56% of vehicles have a dedicated off-street parking space – and only 47% at an owned residence. Approximately 22% of vehicles currently have access to a dedicated home parking space within reach of an outlet sufficient to recharge a small plug-in vehicle battery pack overnight (Traut, 2013).

Access to faster charging will be a key driver of electric vehicle use for longer range travel. Charging stations will usually require infrastructure investment ranging from several hundred to several thousand dollars, depending on construction requirements (Traut, 2013). Fast charging, also known as supercharging, can charge a vehicle up to 80% in 15-30 minutes, and is also a key driver for consumers (Important Media, 2015). The largest current network is the Tesla supercharger

Table 4: Comparison of energy use and costs of infrastructure of various transport modes

Mode of transport	Specific energy consumption (MJ/passenger-km)	Infrastructure costs (EUR/passenger-km)
Passenger car ICE	1.65-2.45	2 500-5 000
City bus	0.32-0.91	200-500
Biking	0.1	50-150
Long distance bus	0.24	500-600
Walking	0.2	50-150
City tram	0.53-0.65	2 500-7 000
Long distance train	0.15-0.35	15 000-60 000

Source: based on Figueroa et al. (2014)

network, which had 617 stations in the US, Europe and China as of April 2016.

In addition to passenger cars, alternative electric vehicle initiatives are also focused on heavy duty vehicles, bus systems and fleet vehicles. Some companies are discussing electric highways as a solution for some modes, such as freight, where vehicles can draw on electricity while on the road, usually through overhead lines. In addition to charging equipment, such systems require additional infrastructure (similar to railways) on major highways, including in neighbouring countries, and sometimes, for access to distribution centres of goods that require transport. Other options for electrification include battery switch or swapping stations, where, for instance, electric buses can quickly replace a depleted battery with a fully charged one (Zou, 2014). This raises capacity utilisation for vehicles that don't have to spend time parked at a charging station.

Finally, electric mobility increases demand for electricity. This requires investment in generation and power infrastructure. REmap assumes the additional demand for new electric vehicles will be mainly met by variable renewable power capacity, amounting to 120 GW of solar PV and 120 GW of wind. Depending on a country's power system, this could bring additional costs for implementing flexibility measures and grid integration.

Synergies between transport and other sectors

Energy supply can no longer be regarded as a set of discrete, individual parts. Action taken in one sector has an impact on another. Some consequences are positive, while others require planning and effort in related sectors. Countries will need to make better use of the storage role of EVs to accommodate higher shares of variable renewables.

Once EVs reach end of their lives, the choice is either to recycle the battery (back into another EV, or broken down into its component materials), or to find another business opportunity, such as stationary energy storage. These batteries will be ideally suited for stationary storage applications in which lower energy density is not much of a problem, but cost is. Some of these second-life batteries would need to compete with cheaper new batteries in the market. Policies should aim to find a balance between the two.

Furthermore, implementing all REmap Options, including various types of electric mobility, would reduce total energy demand by about 5%, as electric mobility is two-to-three times more efficient than internal combustion engines. The essential role of electric mobility as a contributor to improving the energy efficiency of the economy should be part of future energy and climate policy making.

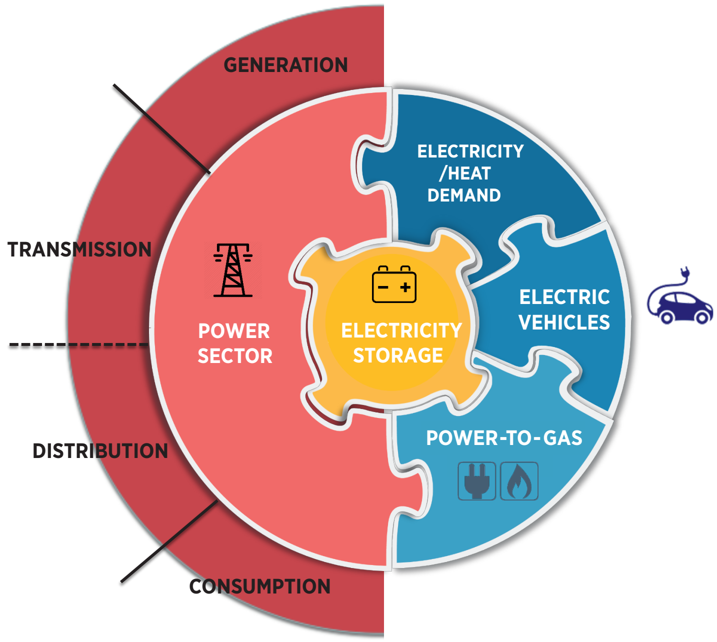
At a national and state level, policy makers have started to consider the role and extent to which electricity storage is needed for a transition towards renewables. In a country like Germany, this debate continues, while California has already set targets to ensure that storage will be part of the solution. The answers to these questions depend on a number of factors. They include the characteristics of present and future energy demand, present and future grid infrastructure, renewables ambitions, and autonomous developments in electricity storage in industries such as home appliances and electronics.

Furthermore, clear trade-offs exist between the need for electricity storage systems in the power sector and other solutions for variable renewable energy integration. They include transport electrification, electricity/heat demand developments in residential and commercial buildings, and the potential to convert electricity into gas or hydrogen (see Figure 28). For instance, transport electrification will result in growing electricity demand.

3.5 Suggestions to increase electric mobility

To overcome the barriers related to the upfront cost of electric vehicles, innovation and R&D is needed in both technology and infrastructure. Additionally, to create economies of scale, national governments need to focus on supporting infrastructure and electric vehicle deployment. The latter can be accelerated by target-setting and offering incentives for electric vehicles. This will help create planning certainty for manufacturers to invest in these technologies. Public-private partnerships and academic partnerships will be key in the development of new technologies, specifically battery storage, and in lowering costs. The synergies that can be gained from systems thinking need a better understanding and require integration and streamlining of policy efforts across the power and transport sectors.

Figure 28: Different system options available for storing electricity produced from variable renewables



Source: IRENA (2015c) (Renewables and electricity storage roadmap for REmap)

- **Electric mobility in the urban context and infrastructure needs:** Since most passenger transport takes place in urban settings, REmap shows that up to 95% of all vehicles will be for the passenger segment as opposed to freight. Local governments and municipalities will play an essential role. They will need to focus on providing sufficient charging infrastructure, taking city planning into account, and enabling benefits for electric vehicle owners who drive, park and charge vehicles in urban areas. To rapidly increase the attractiveness of electric vehicles for passenger and freight uses, governments should focus on expanding infrastructure for charging, particularly in public spaces, by incentivising publicly accessible, shared stations in cities, shopping centre parking lots, etc., but also in suburban and rural areas.

  There are a few areas where more specific action can be taken. The main requirements for a sustainable, reliable and affordable transition to electric vehicles are batteries that can last long enough to ensure transport over distances of 500 km, development of fast charging systems of around 10 minutes, and smart charging systems that create opportunities for consumers to charge at different times of the day and reduce peaks in demand. Recharging stations can be set up with meters, and people can pay with their cell phones, credit cards, etc. Central parking garages offer an early opportunity for such system implementation, as opposed to streets where infrastructure can be under the threat of vandalism. Such options can complement overnight charging at home. Cities should also enable car sharing among urban residents. Governments should also consider electric buses as a way of reducing pollution and noise in populated regions where point-to-point charging is possible.

  As cities and regions move to support the deployment of EVs, they will also need to continue to take into account city planning that promotes the public transit system. Cities will always have a need for individual transit, but as they grow in population and sprawl, it will be important to get people out of cars and into public transit networks. Long-term development and planning strategies will need to be considered with larger transit master plans.

- **Synergies between transport and other sectors:** Modern energy systems and higher shares of renewables will require an integrated approach to energy systems. The coupling of supply and demand with power and transport energy needs is prominent and enabling this will become increasingly important. The solutions will require cooperation between governments, industry and research to develop technologies and market frameworks that can enable high levels of integration.

  How the power sector couples with the transport sector will be important. As variable renewables increase, technological solutions that include the electrification of transport will expand. Electricity storage provided by a growing fleet of electric vehicles offers an attractive solution, and supporting market and pricing frameworks that regulate charging and vehicle-to-grid supply will be key. Increasingly, cities will be at the centre of the discussion. And integrated urban systems that combine electric buses and trams will emerge. System compatibility and charging infrastructure will need to be developed.

There are, however, uncertainties around the implications of transport on the power sector. It is not entirely clear how the storage capacity offered by electric vehicles can be utilised to accommodate higher shares of variable renewables. This will depend on the time of the day and location where cars will be charged, which is a challenge to predict. Likewise, storage capacity from two- to three-wheelers can be significant, but again, driving and charging behaviours will determine their actual role. While the potential of second-life battery storage is significant, the extent to which this can be used is not clear. This is an area that has yet to be tested, and the quality of second-hand batteries could be significantly worse than expected. From a renewable energy perspective, policy makers need to have a close look at these areas of new policy making.

Policy suggestions for each action area to increase electric mobility:

1. **Accelerate electric vehicle uptake by incentivising car sales. A cities and urban-area approach should promote car-sharing schemes and electric two- and three-wheelers, and support for non-passenger modes such as fleet vehicles, buses and light-duty trucks.**
2. **Accelerate investment in charging infrastructure and plan for infrastructure needs by taking into account the specific needs of cities and long distance transport.**
3. **Capture the synergies between transport and the power sector by meeting the new electricity demand from transport with renewables and by using electric mobility as a key flexibility measure to accommodate more wind and solar PV.**

Relevant IRENA work in this field:

Renewables and Electricity Storage – A technology roadmap for REmap

The Age of Renewable Power: Designing national roadmaps for a successful transformation

Synergies between renewable energy and energy efficiency

Technology Brief: Electric vehicles (forthcoming)

REmap – Renewable Energy Prospects for Germany

4 ADVANCED LIQUID BIOFUELS

REmap shows that liquid biofuels, including both conventional and advanced forms of ethanol and biodiesel, could account for 10% of transport-sector energy use by 2030, more than triple the share today, and equivalent to fourfold growth in absolute terms. In view of today's stagnant investment trends, significant market development is required to enable such expansion. In particular, investment must expand for advanced liquid biofuel production capacity, which today accounts for only 1% of the liquid biofuel market. According to REmap, a quarter of the global market for motor fuels in 2030 can be covered by advanced liquid biofuels that are sourced from sustainable feedstocks and which do not compete with the same resources as for food and feed production.

4.1 Recent developments and near-term outlook

Liquid biofuels offer an alternative fuel for all types of internal combustion engines currently running on gasoline, diesel, or kerosene. Potential exists for passenger vehicles, trucks, ships and airplanes.

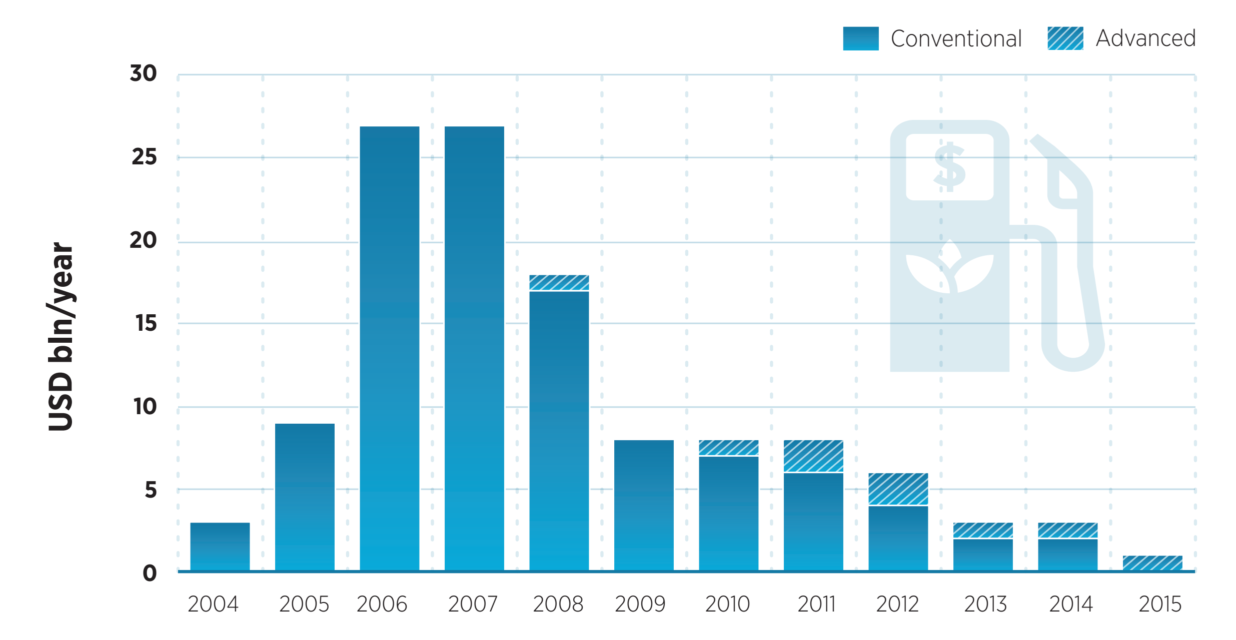
To date, the focus has been on passenger vehicles, blending gasoline with ethanol and diesel with biodiesel. Ethanol and biodiesel use has been promoted by blending mandates, which specify the percentage of renewables in a fuel mix. This made passenger cars among the first to receive the attention of the renewables industry. In some countries, such as in the United States, volumetric biofuel targets have also played a role. Some of these targets and the role of government intervention in the market are now being debated, with some arguing that leaving developments to the market alone can yield better results. The level at which mandates should be set has also been the subject of heated debate. In the US, the fossil fuel lobby pushed hard at the end of 2015 to limit biofuel quotas to below 10%, with strong opposition from liquid biofuel producer coalitions (BNEF, 2015). Many voluntary sectoral initiatives address the aviation sector, but with limited results (see next section). Numerous technology pathways exist for the production of biofuels and research has been dealing for decades with the technical, economic and social aspects of various production pathways.

Global investment in biofuels peaked in 2007 at USD 30 billion, but has since declined to below USD 2 billion per year (BNEF, 2015). Falling oil prices are one reason, as is uncertain policy support due to public concern about the possible impact of biofuels on land use (greenhouse gas emissions and biodiversity), competing uses of natural resources (land and water), and development (land ownership and adequacy of food production for growing populations). Growth in biofuel supply is expected to be limited in the next few years, with some projections indicating just a 5-10% increase by 2020 compared to today (IEA, 2015b). Much of the investment up until 2010 went to conventional biofuels (also known as first generation). Since 2011, a larger share of the money was put into advanced (or second generation) biofuels, however, the absolute investment volume is still very low (less than 20% of the total on average invested in biofuel plants in 2010-2015).

In the transport sector, progress has been mixed in recent years. Liquid biofuel production reached approximately 129 billion litres in 2014, with three-quarters of this total in the form of ethanol. Advanced liquid biofuels from lignocellulosic biomass, agricultural residues and waste still have low production volumes, about 1% of the total.

At present, the investment costs for a cellulosic ethanol plant are more than three times greater than for a corn-based conventional ethanol plant, which makes the production cost of cellulosic ethanol still considerably higher (IRENA, 2013). Although the general expectation is that feedstock costs are lower than food-based crops, the lack of collection and transport systems for residues is one constraint that limits supply, and if remains unresolved will raise the costs of feedstock supply. There are also other technical barriers to be overcome and technology needs that require significant deployment. Several pathways are far from commercialisation, so innovation and R&D will play a key role to accelerate technology development. This needs to be combined

Figure 29: Global investment in liquid biofuels, by technology

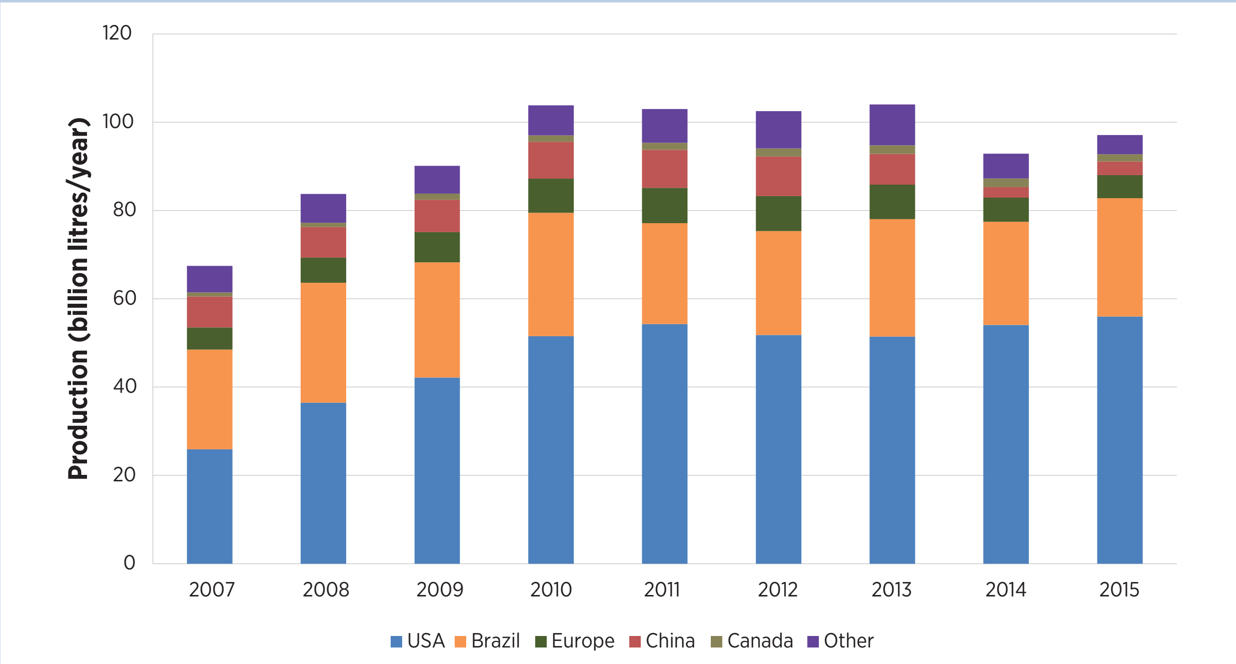


Source: IRENA analysis based on BNEF/UNEP/FS (2015)

with economies of scale that can reduce higher capital costs through technology learning.

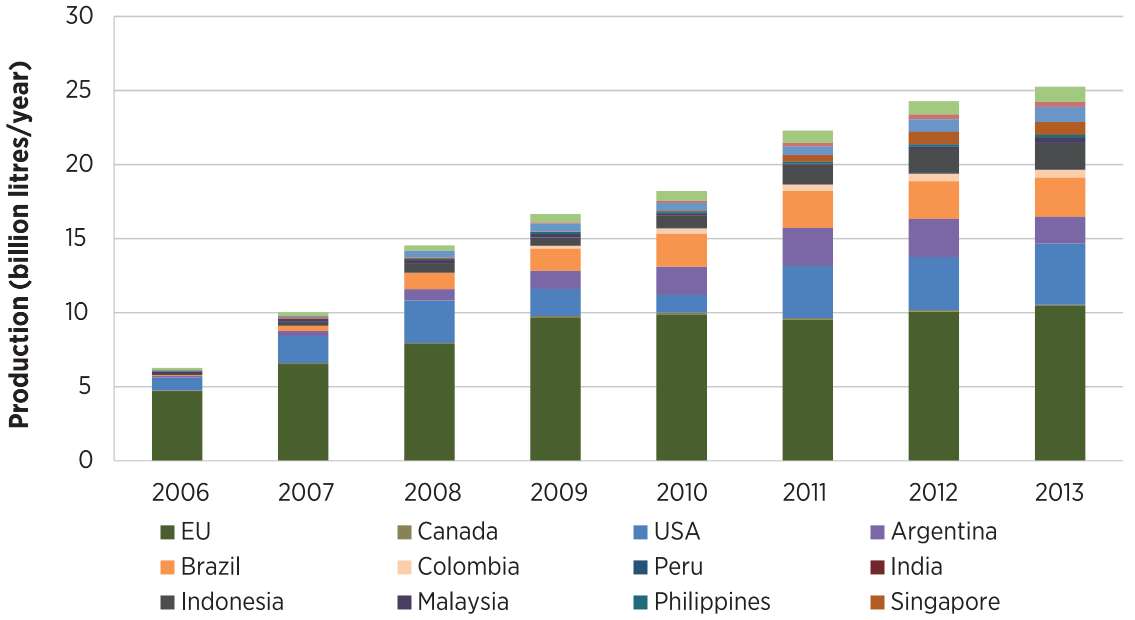
Ethanol production peaked in 2013 at over 100 billion litres. In 2014, production declined to just over 90 billion, and increased in 2015 to above 95 billion. The largest producers of ethanol in the world are the United States and Brazil. The United States produced around 58% of the global total in 2015, with Brazil accounting for just over a quarter. Other major producers are Canada and

Figure 30: Global ethanol production by country and region, 2007-2015



Source: Based on US DOE (n.d.)

Figure 31: Global biodiesel production by country and region, 2006-2013



Source: Based on F.O. Licht (2013)

China. In contrast, Europe, the third largest producer, accounts for only around 5% of global production of ethanol, while biodiesel is the main fuel produced. Production of ethanol in the United States is based almost exclusively on corn as a feedstock, whereas in Brazil sugar cane is used. Around half of the total sugar cane production in Brazil is used for ethanol production, with the rest devoted to sugar production. Although agricultural yields for sugar cane have improved significantly over the past decades, sugar cane production can be land-intensive. For instance, to double total production of sugar cane ethanol in Brazil an additional five million hectares of land would be required.

Global biodiesel production grew 47-fold between 2000 and 2013. Europe, where biodiesel production grew from 17 PJ to 378 PJ (around 10 million tonnes) in the same period, has led the growth. The rapid growth in biodiesel has been driven by the biofuels mandate; also, the large share of diesel light-duty vehicles in Europe means that any mandate for biofuels requires a greater proportion to be biodiesel. Brazil increased its production of biodiesel from zero in 2005 to 2.5 million tonnes in 2013 to become the world's second largest biodiesel producer, thanks to a mandate that sales of diesel should include 5% biodiesel. Total global biodiesel production reached 25 billion litres in 2013.

The distinction between conventional and advanced biofuels is not black and white; it is based on multiple factors, including feedstock choice, conversion technology, greenhouse gas emission reduction potential, environmental impacts, technology maturity or product quality.

One major difference, however, comes from the choice of feedstock. Agricultural residues (processing and harvesting), forestry residues, biogenic waste, non-food energy crops and algae can be considered suitable for advanced biofuels production. By comparison, today most production of conventional biofuels is from starch (corn, potato), sugar (beet, cane) or vegetable oil-based food crops.

Wood from sustainably managed forests, reforestation of degraded forest land, enhanced collection of forest residues, and planting of short rotation coppice trees (rapidly growing species such as poplar and eucalyptus) on agricultural land, which is already cost-effective for some heat and power applications, represent an enormous resource that advanced refineries could make available for liquid biofuel. Agricultural residues, which could be more systematically collected from farmland as food output grows, already provide process heat for first-generation biofuel production from maize and sugar cane but would provide a lot of additional biofuel if second-generation processes were applied to the cellulosic portion of other crops. Rapidly growing, high-yielding grasses such "energy cane" (reputed to have four times the energy content of sugar cane), miscanthus, switchgrass, and many other varieties, are suited to a wide range of climates and could be planted on farm and pasture land that becomes available through higher crop yields, more efficient livestock production, and reduced food waste, representing further advanced biofuel potential (IRENA, 2016b). The sustainability impacts of feedstock choices have also been driving the policy discussions around the shift to advanced liquid biofuels.

Advanced liquid biofuels have been the focus of government-supported research, development and demonstration programs because they greatly expand the range of sustainable feedstocks from which biofuels can be refined. In particular, they have gained significant importance for climate change concerns. The US and EU transport policies promote the use of advanced liquid biofuels over conventional ones, mainly driven by their GHG reduction potential: 50%-70% relative to fossil fuels, compared to 30%-50% for conventional biofuels.

According to IRENA's report *Renewable Energy Innovation Outlook: Advanced Liquid Biofuels for Transport* (IRENA, 2016c), there are more than 90 innovative projects (commercial, demonstration, pilot, R&D) that have been built as of 2015. The total installed capacity of these plants is about 3.3 billion litres, which is negligible compared to the total production of liquid biofuels today. Production capacity is projected to increase by 1.4 billion litres, yet investment has almost dried up entirely. Geographically, Europe and North America account for approximately 80% of the total global capacity installed and planned today.

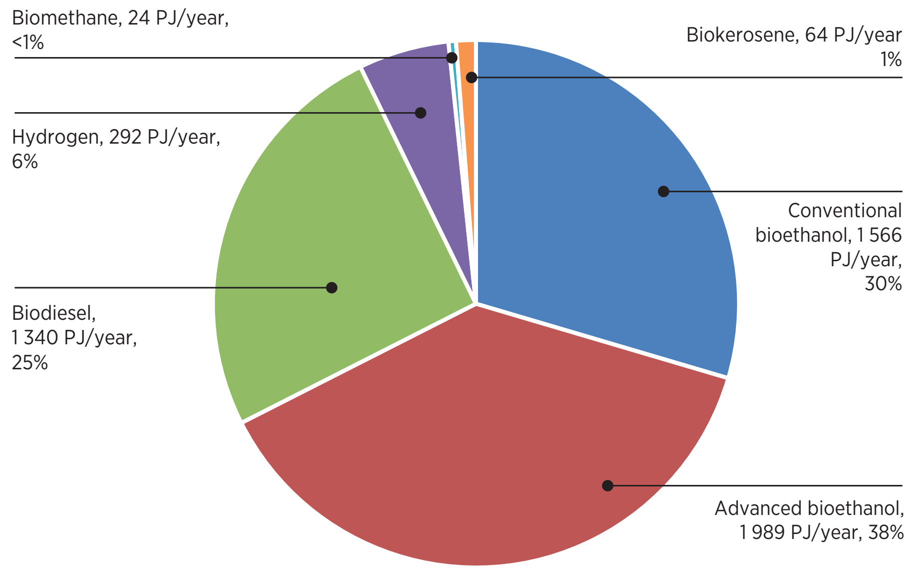
The United States has a capacity of 1.1 billion litres, including the biomass-to-liquids plant completed by KiOR and Ineos at the cellulosic ethanol plant in Florida. Elsewhere, Borregaard has 20 million litres of cellulosic ethanol capacity in Norway; Beta Renewables has 51 million litres of capacity from agricultural waste in Italy, 250 million litres in China; and Brazil has an installed capacity of 40 million litres from sugarcane bagasse and straw (operation starting in the beginning of 2014). Another five plants in the US with an average capacity of 75 million litres per year per plant will process a variety of feedstocks to produce cellulosic ethanol, with production starting in 2014 (Sheridan, 2013). In November 2015, DuPont opened the world's largest cellulosic ethanol plant with 120 million litres of cellulosic ethanol production (based on corn stover, the leaves and stalks of maize). The socio-economic benefits of this plant are significant: 500 local farmers provide feedstock, the plant provides 85 full time jobs, and over 150 seasonal jobs were created in Iowa.

Some sources estimate that liquid biofuel production could triple to more than 300 billion litres in 2030 (Novozymes, 2012). At that point, 20% of agricultural residues would be used as feedstock. Advanced biodiesel could also be produced from a wide variety of woods and grasses. And first-of-a-kind pilot plants have been built for different advanced technology pathways, using feedstocks that include wood, waste or the jatropha plant converted into biofuels through a combination of gasification or biomass-to-liquids routes. However, several more plants will likely need to be built for each technology pathway to make it cost-competitive. Advanced gasification and biomass-to-liquids technologies yield high-quality biodiesel. This can be readily used as transport fuel or blended with fossil-based diesel, without the further refining required for palm-based biodiesel to function properly in automobile engines in cold weather.

4.2 Potential identified in REmap to 2030

After strong growth in the mid-2000s, biofuel production has largely stagnated this decade. REmap suggests that, under business as usual, liquid biofuel use can increase to 250 billion litres by 2030. Estimated additions if renewables uptake is accelerated would be at least 80 billion litres of advanced ethanol, representing about 40% of the total renewable energy options identified in REmap (excluding EVs) in the transport sector in 2030. Together with kerosene and advanced biodiesel additions, advanced biofuels can make up a quarter (around 125 billion litres) of the total biofuel use of 500 billion litres estimated in REmap. Today, 99% of liquid biofuels are conventional biofuels. By 2030 this share will decline to around 75%.

Figure 32: Global liquid and gaseous biofuel additions by 2030 from the REmap Options, breakdown of added shares



Compared to today, advanced biofuel estimates for 2030 require more than a thirtyfold increase by 2030 (in terms of its renewable energy share). It would require significant effort, in particular the implementation of a volume nearly identical to today's installed conventional biofuel capacity.

The required annual investment to 2030 is an indication of this. In the past 5 years, average annual investment for liquid biofuels was about USD 4 billion per year. About a one-fifth of this was for advanced liquid biofuels (USD 1 billion per year). Between now and 2030, total investment for liquid biofuels would need to increase to USD 22 billion per year on average, which is around five times the level of investment in recent years. Over half of this yearly investment, or around USD 10 billion per year, would be related to advanced liquid biofuels.

4.3 Action areas for advanced liquid biofuels

Feedstock availability

Total biofuel demand in 2030 will reach approximately 500 billion litres if all REmap Options are implemented. At most, a quarter of this total will be advanced liquid biofuels. The remainder will be conventional liquid biofuels. Cultivating feedstock to meet this volume will require around 200 million hectares of agricultural land. After demand for all other purposes is met, there could be up to 1.4 billion hectares of agricultural land available for biofuel production. This amount may seem sufficient to meet the demand according to REmap, but the same resource will be required for other purposes, such as cattle breeding (for meat production), crop and feed production. Food demand is expected to grow by about 50-70% by 2050, in particular demand for meat that requires more land. Water will be another constraint since growing crops for conventional liquid biofuels also requires water. While all may seem in balance at a global level, this may not hold true at country or regional levels. Some countries already have high water stress, and land availability is limited in others.

Agricultural and woody residues for advanced liquid biofuel production are alternatives to resource-intensive energy crops. According to REmap, up to 60% of the total global bioenergy in 2030 can be supplied by various forms of residues. Moreover, residues can be sourced affordably.

Solid biogenic residues and waste currently have limited potential; however, relatively low costs and few competing uses make them an attractive feedstock. Agricultural residues currently are the largest resource and have relatively low costs. However, some of this resource is currently used in different applications, reducing availability and raising prices, depending on local markets. Current costs of forest residues are relatively low, though potential volumes could be relatively low as well. Established competing markets in many areas may have a negative effect on feedstock availability in the future. Non-food energy crops have a large potential, though with high uncertainty about their potential, and feedstock costs are higher than other categories.

Ensuring the availability and supply of a wide range of affordable, sustainable feedstocks is the first step to accelerating the deployment of advanced liquid biofuels, along with efficient and affordable conversion technologies to utilise the feedstocks. Most available and readily accessible feedstocks are the agricultural and forest residues that are produced along with food and wood products. There is substantial potential to collect additional shares of these residues without compromising the regeneration of soils or using additional land. Sustainable intensification of agriculture, with higher yields on existing land, could make available further feedstocks from rapidly growing trees and grasses without compromising food supplies for growing populations. Reduction of waste and losses in the food chain, which currently amount to a third of all food produced, would make it possible to grow more such feedstocks on land no longer needed to grow the food lost.

Biofuels and climate change

Renewables are significantly less emission-intensive than fossil fuels in their life cycle. This is, however, not entirely the case for biofuels. Liquid biofuels are not entirely greenhouse gas-emission free, particularly conventional biofuels produced from food crops, mainly because of emissions associated with land-use change (LUC). Advanced liquid biofuels in comparison can be produced with much lower GHG emissions, as feedstocks for production are sourced from less land use-intensive feedstocks.

The *Renewable Energy Innovation Outlook: Advanced Liquid Biofuels for Transport* (IRENA, 2016c) shows that nearly all advanced biofuel pathways have GHG emissions that are at least 60% lower than that of petroleum derivatives. Advanced biofuels can show significantly higher performance mainly due to the differences in feedstock. Advanced biofuel production is also energy self-sufficient in the conversion process using by-products as a heat source.

Life-cycle GHG emissions from fossil fuels range between 84 and 107 grams of carbon dioxide equivalent per megajoule (g CO_2-equivalent per MJ), with an average of 92 g CO_2-equivalent per MJ (DG ENER, 2015). A recent review of bioenergy pathways by the Netherlands Environmental Assessment Agency (PBL, 2016) shows promising pathways for liquid biofuels from a GHG-emission perspective. Based on a life cycle assessment (LCA) analysis, GHG emissions could range from around 20 g CO_2-equivalent per MJ for liquid biofuels from woody crops and biomethane from manure and organic waste up to almost 60 g CO_2 equivalent per MJ for ethanol from wheat (see PBL, 2016). Four pathways achieve significantly higher emission reductions per hectare than others: biomethane from woody crops, ethanol from sugar beets or sugar cane, and FAME or biodiesel from palm oil.

In addition to supply chain emissions, liquid biofuel production has emissions from LUC (direct and indirect) driven by the feedstock choice, substituted land type, and the region where this substitution takes place. Uncertainty in LUC emissions is significant. The same study by the Netherlands Environmental Assessment Agency (PBL, 2016) finds that the conversion of forest to bioenergy crops emits large amounts of direct LUC GHGs (up to 360 g CO_2-eq per MJ). The conversion of grasslands shows a range from -74 g CO_2-eq per MJ (palm oil in Indonesia) to +83 g CO_2-eq per MJ (biodiesel from soy beans in Brazil). Other feedstocks that sequester significant amounts of carbon when converted from grasslands are switchgrass, miscanthus, sugarcane, jatropha and forest plantations. Furthermore, a number of recent studies find high uncertainty in overall indirect LUC (iLUC) emissions. Various types of conventional bio-ethanols have an iLUC factor of approximately 20 g CO_2-equivalent per MJ, with a range of 3-61 g CO_2-equivalent per MJ and conventional biodiesels around 35 g CO_2-equivalent per MJ with a range of 7-94 g CO_2-equivalent per MJ. A number of feedstock and pathways can reduce related emissions. Harvest residues have the potential for LUC factors close to 0. Direct or indirect conversion of forest should be avoided since it will lead to high emissions, in particular for biodiesel. Perennials have the potential for relatively lower LUC emissions, since they have higher living biomass carbon and higher soil organic matter carbon. Using marginal land – land not used for any economic purpose, such as agriculture, forestry, or other uses, now or by 2030 – would result in low LUC emissions, but there is often a reason that it is not used, such as low fertility or limited accessibility.

Ways to produce biofuels with a smaller LUC impact include more systematic collection of farm and forest residues, programmes to raise crop yields and make existing agricultural land available for bioenergy crop production alongside food production in developing countries, and efforts to reduce losses in the food chain such as through renewable food drying and refrigeration and improved roads. However, encouraging their development and deployment poses some particular policy challenges.

Technology cost

Currently, markets for advanced biofuels are largely determined by policy. This is primarily because the products, many of which are not yet produced on a commercial scale, have higher production costs than fossil fuels and conventional biofuels. Although feedstock costs are lower, the total cost of cellulosic ethanol is still considerably higher than for conventional ethanol because of high capital costs of building plants (IRENA, 2013c). Technical barriers must be overcome, and larger plants are needed to take advantage of economies of scale. Commercialisation of each technology pathway will require additional development and demonstration projects to reduce capital costs through technology learning so advanced biofuels can successfully compete. In sum, it appears likely that as much advanced biofuel conversion capacity would have to be built to reach cost-competitive levels as has been already been built for conventional biofuel conversion capacity. An important strategy for the cost-effective supply of advanced biofuels is likely to be the design of integrated biorefineries that yield a variety of valuable co-products such as heat, power, food, fertiliser, plastics, chemicals, and neutraceuticals.

In addition to R&D to overcome technology challenges, stable, long-term policies to support advanced biofuels are required to create market certainty, however, this is not yet the case today. At the EU level for example, no policy incentivises the use of biofuels post-2020, and it is unclear if one will be put into place. The US is a similar case. Accellerating the development of biofuels is about more than supporting end products or their conversion technologies. Therefore, policy should consider how it incentivises and mitigates the risks of players along the entire value chain. In addition to conversion of feedstock into fuels, other efforts can focus on: biomass production in agriculture and forestry, fuel distribution, and end-use in vehicles. Feedstock costs can be a major contributor to overall advanced biofuel costs.

A number of actions are needed to ensure a level playing field, including: internalising the externalities of fossil fuels and eliminating related subsidies; RD&D funding; financial support for feedstock supply chain development; and utilising technology and cost synergies from poly-generation of advanced biofuels with other commodities such as food, fertiliser, chemicals, heat and power.

Biomass trade

Policies aimed at the deployment of liquid biofuels generally exist at the national level. This has a significant impact on international trade routes because feedstock availability is limited in some countries, while others do not have the necessary capacity for production, thereby relying on imports.

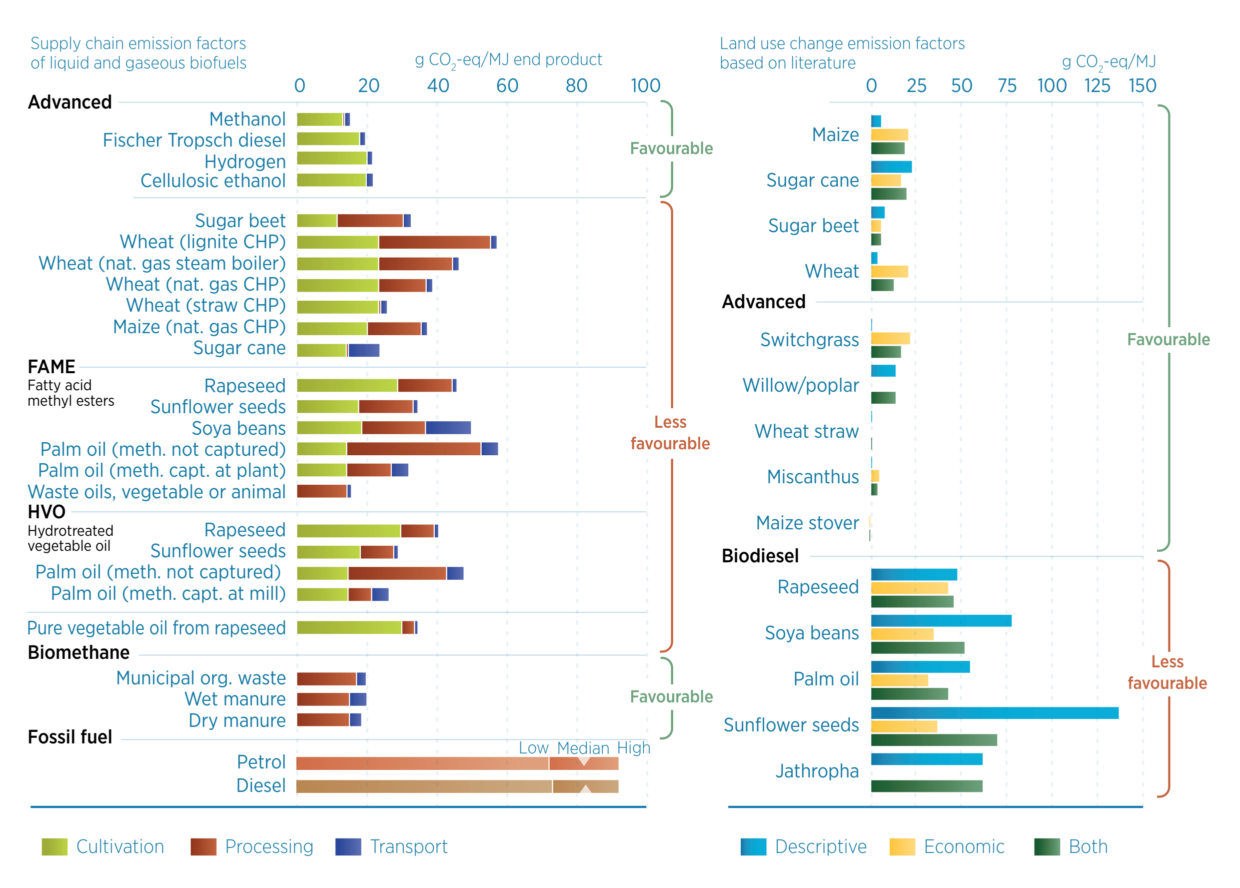
World biofuel production and trade has grown exponentially. Biodiesel imports have been dominated by the EU, whereas the US has imported significant quantities of ethanol, mainly from Brazil. Import duties have largely influenced trade volumes, whereas trade routes have been driven mainly by tariff preferences. With growing demand for biofuel, trade is expected to reach about 25-35% of the total demand, three times higher than the current level of about 10% (for modern biofuels only). While these trends are related to the end-use products explained by the higher energy density of biofuels, feedstock can also be traded for processing, which is especially important to alleviate resource constraints.

Integrated resource management for sustainable biofuels

A sustainable bioenergy sector requires regions and countries to examine the interplay between transport, agriculture and other sectors of the economy.

Many strategies are required to sustainably source biomass, to secure its supply and to realise demand

Figure 33: Supply chain for liquid biofuel production and resulting emissions due to land-use change



Source: Based on PBL (2016); DG ENER (2015)

potential. However, none of them is a panacea. Most of these strategies go beyond energy polices and include agricultural, resourcing and forestry policies. An integrated policy framework that accommodates the issues and challenges of different aspects of the biomass supply chain is needed; one that integrates energy, infrastructure, agriculture (*i.e.* food, feed), resources, forestry, environment, food and technology, and innovation policies. Some of the key components of such an integrated policy framework should be:

- sustainability criteria and indicators (including social, economic and environmental aspects of bioenergy);
- integrated land use, agricultural and resource policies that address sustainability concerns related to biofuel use;
- land ownership policies;
- efforts to create a sustainable and affordable residue feedstock market for advanced biofuels production;
- innovation- and technology-focused policies to use these feedstocks efficiently and cost-effectively.

4.4 Suggestions to accelerate advanced liquid biofuels

Advanced liquid biofuels have clear advantages for reducing the environmental impact of fuel used in transport and for contributing to food security. A number of commercial-scale projects are now underway, and many pathways are being developed. However, current production costs are high, and there no clear signals from policy makers prioritising the use of advanced biofuels. The result is a lack of demand and reluctance to invest.

Advanced liquid biofuel pathways are at various stages of development, requiring different types of intervention to support widespread commercial deployment. There are four key areas for intervention: technology development, company development, market formation and policy development. These different types of intervention should be part of an overall strategy to commercialise advanced biofuels. Such intervention is typically provided by governments and this will remain so in the near future. The key for governments will be to reduce policy uncertainty in order to create market certainty. They must clearly define the sustainability metrics of advanced liquid biofuels, provide the right market signals (*e.g.* targets), and, especially for small-scale producers, offer support for investment in capital-intensive advanced biofuel plants (Huenteler *et al*. 2014; Huenteler & Lee, 2015).

Innovation will also be essential to accelerate deployment. For example, R&D opportunities exist for gasification, because gasifiers are more tolerant to different feedstocks and more energy efficient. Furthermore, bacteria are less susceptible to contamination during syngas fermentation.

Other techno-economic barriers that need addressing are the availability of financing and risks to feedstock supply. Increasing volumes of trade will require sustainability certification, but the associated costs and efforts to harmonise sustainability criteria are large.

Deployment will require the development of policies integrated in technologies, companies and markets and with policies in other areas (energy, transport, agriculture, resource), in close collaboration with all relevant stakeholders, but primarily with industry research and project developers.

Some specific actions for policy makers and stakeholders should include requiring liquid biofuel blending in transport fuels, and promoting biomethane use in transport. Additionally, focus should be paid to niche markets in the more difficult sectors of shipping and aviation, where drop-in biofuels could be considered.

Policy suggestions for each action area to accelerate advanced liquid biofuel are:

1. **Ensure the availability and supply of affordable and sustainable feedstocks by improving agricultural yields, increasing the use of degraded and marginal land, using feedstocks that do not compete with food production, and reducing losses in the food supply chain.**
2. **Develop biofuel targets by considering life-cycle GHG performance to support advanced production pathways, and to prioritise the use and development of low-carbon bioenergy pathways and reduce non-sustainable bioenergy use.**
3. **Implement regulations and provide support to level the playing field of advanced liquid biofuels and non-renewable energy sources by considering their GHG emission benefits.**
4. **Establish or expand registers of origin to ensure sustainable feedstocks and promote the development of cross-border bioenergy trade.**
5. **Streamline bioenergy policy making by better integrating with energy, infrastructure, agriculture, resource, forestry, environment, food and innovation policies.**

Relevant IRENA work in this field:

Global bioenergy working paper: Supply and Demand Projections

Boosting Biofuels: Sustainable Paths to Greater Energy Security

Renewable Energy Innovation Outlook: Advanced Liquid Biofuels for Transport (forthcoming)

Liquid biofuel production – Technology brief

5 EMERGING SECTORS AND TECHNOLOGIES

Electric mobility and liquid biofuels for road transport address a significant share of the global transport sector's total energy demand. However, renewables for aviation and marine applications, which represent 20% of the transport sector's energy demand today, have so far been overlooked. Military applications, depending on the country, are another large energy-using segment relying heavily on fossil fuels. Moreover, a number of renewable energy technologies are still far from commercialisation, but offer significant deployment potential. Diversification of renewable energy supply and a complete transition to sustainability in the transport sector will require efforts beyond electric mobility and the deployment of liquid biofuels.

5.1 Innovative applications and technologies

Aviation, shipping and military sectors today and perspective to 2030

Today, the shipping and aviation sectors each contribute 10% to the total energy demand of the transport sector. The aviation sector alone represents 2-3% of total global CO_2 emissions worldwide. These two segments are characterised by long-distance transportation. Moreover, fuel costs represent a large share of their total costs. For example, approximately one-third of the aviation sector's total operational costs are related to fuel.

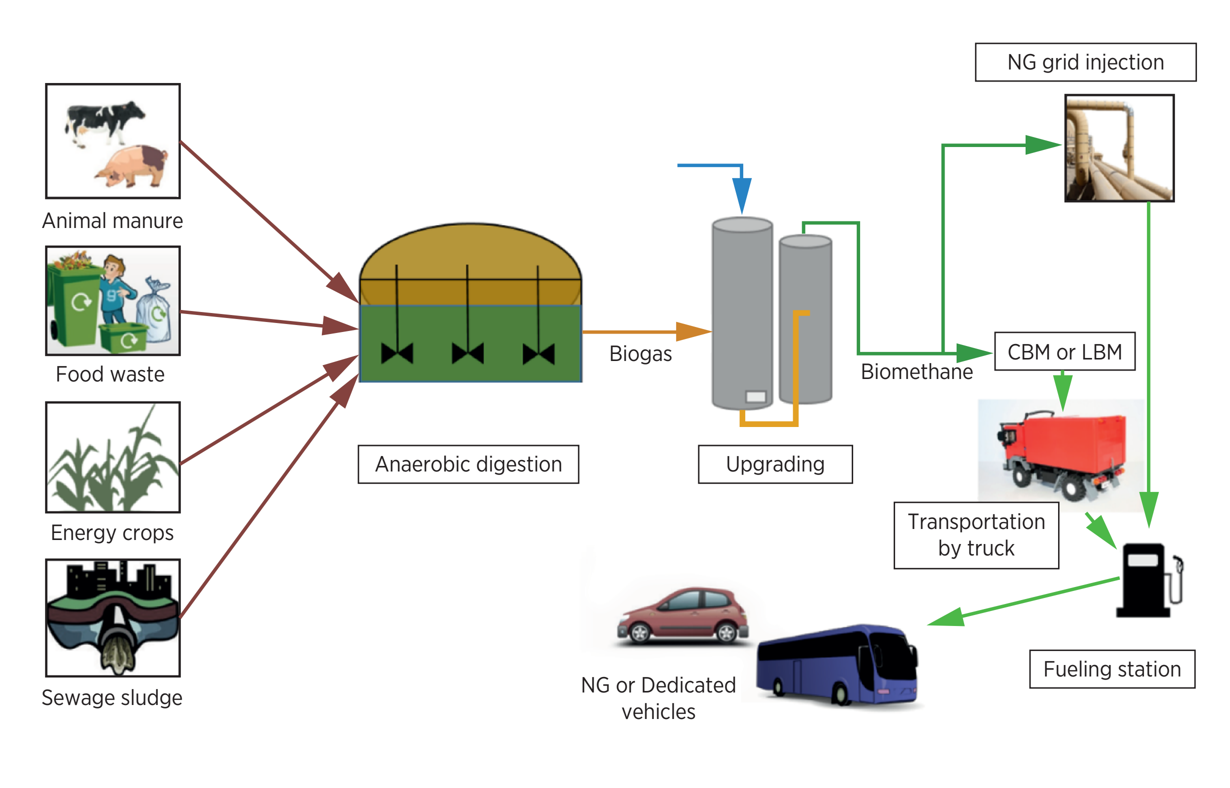
The energy demand of these segments will grow 3-5% per year over the coming decades with increasing population and growing economic activity. For example, India's aviation sector is expected to be the third largest worldwide by 2020 and the largest by 2030. The shipping industry is the backbone of global trade and a lifeline for island communities, transporting approximately 90% of the tonnage of all traded goods. Annual global shipping tonnage increased from 2.6 billion to 9.5 billion tonnes between 1970 and 2013 (UNCTAD, 2014). The demand for shipping is predicted to grow significantly, owing to the changing configuration of global production and the increasing importance of global supply chains and international trade.

Both of these segments have so far received limited attention from renewables. Even with the 2015 Paris Agreement, which has a much wider sector coverage, the transport sector, and in particular aviation and shipping emissions are still overlooked. Following the COP21, the Nordic ministers for climate and the environment issued a statement calling for an increased focus on emissions from the transport sector, and especially for aviation and shipping applications.

The military sector is also overlooked. It relies on energy-intensive equipment, for which efficiency has far lower priority than other functions. The US military, the largest in the world, accounts for about 2% of total US energy demand and about 5% of the US transport sector's total energy demand. Air forces account for about half of this, while navies and armies make up 28% and 18%, respectively. Oil is the main source of energy for military applications, and the military and its combat security depend on secure energy supplies. The US Navy has perhaps the world's most aggressive programme of any military to increase the use of biofuels in its operation. The programme is known as the "Great Green Fleet" and it seeks to decrease petroleum use by 50%, and source at least 50% of energy used from non-fossil sources by 2020.

Biofuels represent the main alternative in aviation, shipping and military applications. So far, 23 airlines have conducted 2 500 commercial flights using biofuels. Today less than 0.05% of the total jet fuel demand is met with biofuels (IATA, 2015b). As of early 2016 targets for biokerosene (or biojet, as it is often called) production are more aspirational than legislative, with the US FAA suggesting that 3.8 billion litres of biojet could be produced by 2018, and the US Air Force hoping to have 50% of its fuel replaced by alternative fuels by 2016 (another 3.8 billion litres) (FAA, 2014). Similarly, the EU has suggested a target of 2 million tonnes of biojet

Figure 34: Biomethane supply chain for transport applications



Source: IRENA (2016d)

Note: The abbreviations in the figure stand for: NG - natural gas; CBM - compressed biomethane; LBM - liquid biomethane

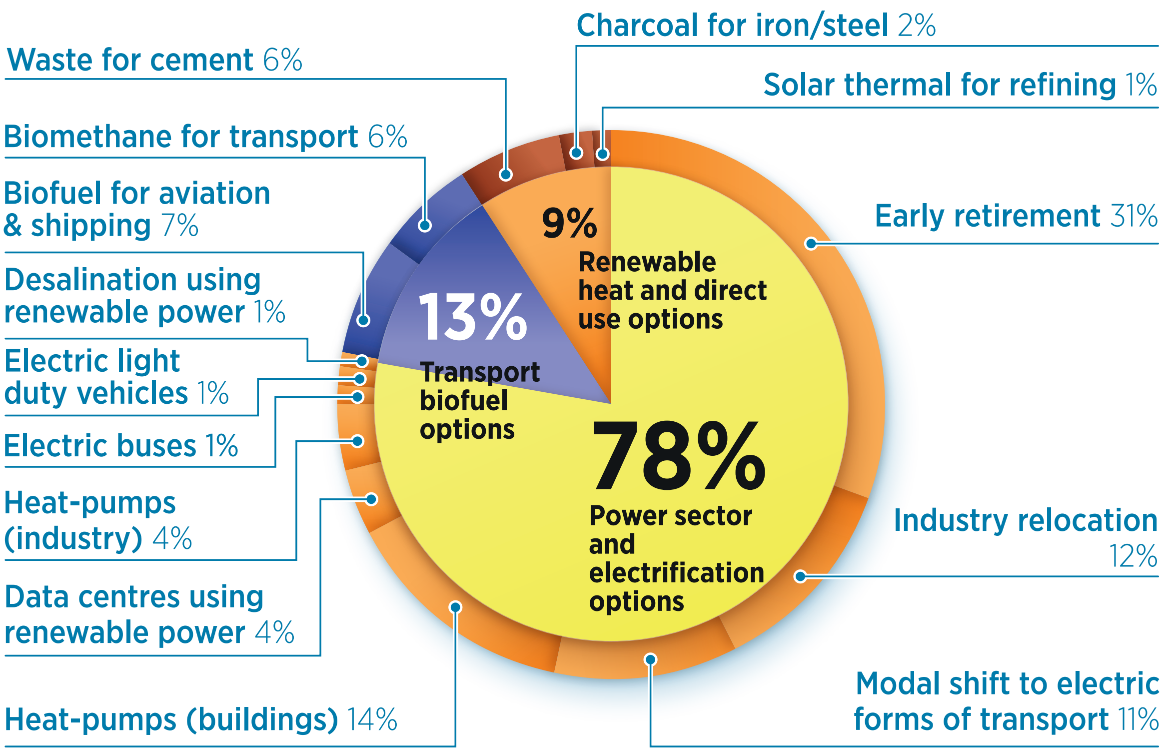
fuel could be produced and used in this region by 2020 (2.5 billion litres) (Insight-e, 2015).

According to REmap, biojet demand could reach about 1.5% of the aviation sector's total fuel demand in the same year – a very low level of deployment but significant growth over today's level. Other technologies that can be used as an aviation fuel include liquid hydrogen or biomethane, however these technologies have not been deployed commercially.

There are various pathways for producing biojet fuels. Oleochemical, biochemical, thermochemical and hybrid technologies can be used to produce drop-in fuels. The oleochemical platform, already used today, offers a simple and low-risk technology; however, costs are still high due to high feedstock prices. Nevertheless, the oleochemical platform could continue to be the major pathway for production in the short-term while other pathways, such as thermochemical, are developed. As of today, hydroprocessed esters and fatty acids are the most highly developed production pathways and they are certified by the American Society for Testing and Materials (ASTM), have been produced in three commercial-scale plants and supply the largest share of demand today. There are other several promising pathways such as Fischer-Tropsch (FT) derived fuels and direct sugars-to-hydrocarbons conversion pathways. Several commercial plants are at the start-up stage for FT fuels, but under current market conditions widespread development seems unlikely. Several companies in Brazil are pursuing sugar-base pathways (Mawhood *et al.*, 2016).

REmap has only identified a few options for shipping and military applications, notably diesel alternatives for shipping. However, the shipping industry has taken notice and is considering lower carbon options. Wind engines and kite systems that improve aerodynamics can save fuel and related CO_2 emissions by 2-12%. Solar panels for auxiliary power can save another 0-3% (Cames *et al.*, 2015), but negligible potential has been estimated to 2030. Hybrid technologies, modern sails, green hydrogen and methanol also exist

Figure 35: Contribution of technology options identified by IRENA to increase the share of renewable energy from 30% to 36%



as options, but their deployment is not expected until after 2030.

Biomethane for transport

Ethanol and biodiesel dominate today's renewable energy use in transport. The deployment of other alternatives such as biomethane and hydrogen has been slow until now. One main barrier to this is cost. A new Honda model will hit the European market in September 2016, but the car will be more expensive in Germany than in Japan (Spiegel, 2016b). Biomethane is used mainly for power and heat generation, but it also has potential uses for transportation, especially as an alternative to fuels used in trucks and buses. Today, 0.4% of total global biomethane production is used in the transport sector. The share is higher in the EU, at 1%, thanks to deployment in Germany and Sweden. Iceland also uses biomethane in its transport.

Usually, upgraded biomethane is stored and trucked to pumping stations. Otherwise, distribution via pipeline is common for short distances between the upgrading plant and place of consumption, such as in the US. Biomethane can be also compressed and transported by road. Another solution would be to transport biomethane as liquefied gas, however, about one-third of the total energy content of the raw material is lost in the process. In Sweden, biomethane is transported and distributed as compressed natural gas (CNG) for distances less than 200 km, while LNG is preferred for longer distances.

The realistic potential of biomethane for the global transport sector is around 2%-5% of the total energy demand, after accounting for its uses in other sectors of the economy, cooking, heating and power generation. According to the Reference Case, biomethane use in the transport sector could rise minimally from 0.01 billion m^3 today to 0.3 billion m^3 by 2030. The REmap case shows a total biomethane demand worldwide of 0.9 billion m^3 in 2030 for the transport sector, around 1% of total demand, hence there is potential for further utilisation. Upgrading transporting and making biomethane available at filling stations would require investment.

One study shows that the investment cost associated with biogas use in transport is USD 9-14 per GJ. But this could be as low as USD 7 per GJ if the marketplace develops (IEA, 2013). The lower value would put biomethane on a competitive footing and have similar costs to natural gas in transport.

5.2 Advancing electrification and biofuels further – the Doubling Options

IRENA has conducted analysis that looks into how the transport sector could see significantly higher renewable energy uptake and decarbonisation beyond the REmap Options. This analysis is known as the Doubling, and the technologies and methods identified as the Doubling Options, which see higher deployment of electrification, emerging technologies in aviation, shipping and heavy freight transport (some of which was addressed in the previous sections), and structural change known as modal shifts (see Figure 36). The Doubling Options are aligned with the aim of doubling the share of renewable energy in the global energy mix by 2030.

The analysis sees further electrification of the transport sector, specifically electric public buses and light-duty freight vehicles is a major area in which gains are possible with the Doubling Options. Their total global stock could increase by 15 million vehicles by 2030, so the number of electric vehicles could reach around 175 million, compared to 160 million in REmap.

Moreover, additional modal shift would have to take place. This largely assumes that individual passenger vehicles are replaced by electric tram and train networks. The majority of these systems are new, but in some countries better utilisation of existing networks is also assumed.

Finally, additional liquid biofuel deployment would take place only in the emerging sectors of aviation and shipping, where the renewables share would increase from meeting 1% of the energy demand for these modes to 5% of their total demand. Finally, biomethane use is also assumed, with around 23 billion m^3 (800 PJ) of additional production.

Using these technology options would increase the renewable energy share in the transport sector to 13%. If renewables-sourced electric mobility is included, this increases to 15%, showing the importance of boosting renewables in the production of electricity.

However, these technologies come at an additional cost to the energy system. Whereas the REmap Options will cost USD 63 billion more annually by 2030, the Doubling Options would result in additional costs of USD 95 billion. But greater deployment of renewables also brings more benefits, and the Doubling Options would result in between USD 66-340 billion annually in additional savings from reduced air pollution. Further cuts in CO_2 emissions would be another benefit, bringing total emission reductions from the transport sector, when combining the REmap and Doubling Options, to as high as 1.9 Gt annually by 2030.

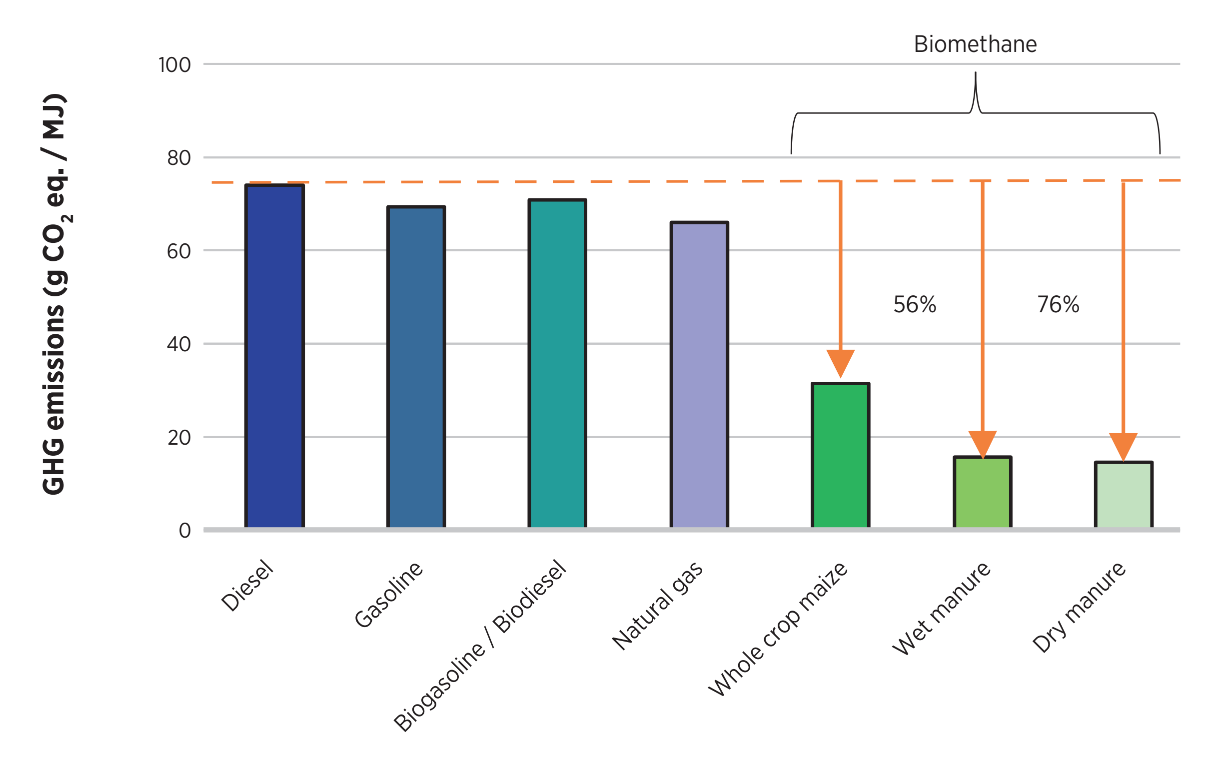
5.3 Action areas for emerging sectors and technologies

Supportive policy and tailored technology solutions for emerging sectors

Given their high costs, specific requirements for fuel quality, and the competitive environment in aviation, shipping and military sub-sectors, biofuels are not picking up. Accelerating the uptake requires the development of supportive policies that can create a level playing field by internalising the benefits of renewables.

A number of such supportive policy efforts are emerging. Stemming the adverse environmental impact of freight transport is one of them. The ICCT identified 21 such programmes in G20 countries focused on shipping, aviation and road sub-sectors (ICCT, 2015b). In view of the growing energy needs in these transport modes and limited alternatives to fossil fuels, these programmes are important because they develop standards and long-term targets. The International Convention for the Prevention of Pollution from Ships (MAPROL) has introduced limits on SO_2 and NO_x emissions from ship exhaust in designated emission control areas (Saddler and van Dyk, 2015). The industry itself has set targets to reduce carbon dioxide emissions by 20% by 2020 and 50% by 2050. Ship operators therefore need to consider cleaner fuel and power options, including the use of renewables, to meet these targets.

Figure 36: Comparison of greenhouse gas emissions for biomethane, liquid biofuels and fossil fuels in transportation



Source: IRENA (2016d)

In 2009, numerous aviation-related institutions committed to reducing global aviation emissions by 50% in 2050 compared to 2005 levels. This commitment is supported by two specific measures: improving energy efficiency by 1.5% per year, and stabilising CO_2 emissions from the sector at 2020 levels through carbon-neutral growth. One of the four pillars of this climate action is technology, notably sustainable fuels (the other three are efficient flying, infrastructure and system efficiency and global market-based measures) (IATA, 2015a). Additionally, in early 2016 the International Civil Aviation Organization (ICAO) recommended a new environmental measure to set standards for lowering emissions from large aircraft, which make up over 90% of aviation-related emissions. The new standards would apply to aircraft types built after 2023.

The aviation sector has very technical and narrow specifications for the type of fuel needed. In shipping, a wider range of fuels can be used (such as pure vegetable oil, biodiesel, etc.), and less processing is required than for biojet. So far, affordable and available liquefied natural gas (LNG) has been the main alternative to petroleum-derived products. The US and Dutch militaries have demonstrated a number of marine and aviation applications using biofuels (Ecofys, 2013).

Drop-in fuels are the only alternatives for aviation and shipping applications. Such fuels are functionally equivalent and fully compatible, thereby complying with existing infrastructure, aircraft and engines. Shipping applications are more flexible in terms of the type of fuel required. Today, the major barrier is cost. More efforts in technology, production and deployment are needed to drive down costs. However, deployment is possible in certain sub-segments. In the aviation sector, there are two types of fuel, kerosene-based jet fuel and aviation gasoline (AvGas). The latter is used in smaller, light aircraft and helicopters. This market is small, and the price of fuel is typically higher. Today, biofuels have become more cost-competitive for this segment and therefore offer the potential to cut costs.

Today, biofuel initiatives are airline-specific. However, airports operate with a common distribution system, in which all airlines have access to fuel. As airline initiatives achieve success, development of "bioports" to ensure distribution and access to all will be important.

The contribution of renewables to the energy mix of the shipping sector is limited in the near and medium term, even under optimistic scenarios. The main barriers to increasing renewable energy solutions for shipping are: 1) the need to commercialise viable alternatives, and 2) the splitting of incentives between ship owners and operators, which limits the motivation to deploy clean energy solutions. For quick-win solutions, support should focus on small ships (less than 10 000 deadweight tonnes), which are more prevalent worldwide. These transport less of the total cargo but emit more greenhouse gases per unit of cargo and distance travelled. The greatest potential lies in using a combination of renewable energy solutions that maximise the availability and complementarity of energy resources in hybrid modes. Achieving the full potential of renewables in the shipping sector will require an integrated systems engineering approach that also addresses the deployment barriers. Additionally, policies will need cross-border coordination regarding carbon leakage. In the shipping industry, it is easy for owners to simply change their carrier's address to a country that does not require efforts to reduce CO_2 emissions (IRENA, 2015e).

Technical and economic barriers of emerging renewable transport technologies

Biomethane yield depends on feedstock composition – such characteristics as dry matter content, its purity and energy yield, and anaerobic digester specifications (length, operating conditions, etc.). Delivering gas with high calorific value is a main goal for using upgraders. Since biomethane has a high methane content compared to raw biogas, the upgrading process results in higher energy performance. As a GHG, methane contributes to GHG emissions with a global warming potential 20 times higher than CO_2. Globally, producing biomethane reduces the emission of methane and other harmful gases into the atmosphere. Moreover, biomethane can be used as a vehicle fuel, thereby reducing fossil fuel consumption and GHG emissions significantly. Another benefit of biomethane is that anaerobic digestion uses organic matter as digestible feedstock, and as a result, digestion is not exposed to the atmosphere, which prevents the loss of methane and other gases.

Biomethane delivered to the end-user has three production cost components: 1) anaerobic digestion, 2) upgrading and 3) distribution. Overall, total costs vary from USD 0.65 to USD 1.08 per m^3 of biomethane, depending on feedstock, the capacity scale and the upgrading technology. Operating costs make up 70-80% of the total. Biomethane production costs using 90% maize are USD 0.95-1.08 per m^3, while the range is lower when waste or sewage are the primary feedstock, equivalent to USD 0.65-0.78 per m^3. Globally, costs can drop when the plant scale increases, especially with water scrubbing as the upgrading process. Hence, biomethane can be cost-competitive in certain parts of the world depending on the feedstock costs, technology used and the relative price of the fuel that it substitutes. However, economic barriers must still be resolved, especially in infrastructure, as filling stations for biomethane are usually expensive. From a technical point of view, using biomethane as vehicle fuel is not as common as for electricity and heat, hence more experience in its utilisation is needed.

Developing innovative ways to produce hydrogen affordably will help commercialise it as an alternative to fossil fuels and liquid biofuels. For decades, research into fuel-cell vehicles has been conducted. Hydrogen is used as a form of chemical energy, which is converted into electricity within a fuel cell. In countries where renewable electricity is abundant and cheap, hydrogen can be produced cost-effectively (*e.g.* Iceland). Alternatively, as power systems around the world increasingly rely on electricity from variable sources such as PV and wind, some countries are now considering what to do with the excess electricity these sources produce. One option heavily discussed is power-to-gas, which uses electricity to produce hydrogen. In turn, this hydrogen can be stored, and also used in hydrogen fuel-cell vehicles. A number of automobile manufacturers have been looking into opportunities for the production of fuel cell cars. In 2015, Toyota released its Mirai model based on this technology.

5.4 Suggestions to increase the use of renewables in emerging sectors and accelerate deployment of new technologies

The higher cost of biofuels for aviation, shipping and military applications is the main barrier to deployment. Bridging the cost gap and ensuring a level playing field will require joint efforts by technology developers and policy makers. With a policy push from targets (volumetric and shares) and incentives for more expensive biofuels, production and consumption can be accelerated to break the vicious circle of high costs and low deployment rates. Creating synergies with the other biofuel sectors, by making use of built experience and technology learning, will also be important. While it is less the case for shipping, developing fuels that comply with globally harmonised acceptance criteria and specifications for aviation and military applications will be necessary. To this end, industry and policymakers need to work closely together.

Much experience in biomethane use for power and heat generation exists, and technical issues related to its use for transportation remain to be resolved. That requires further collaboration of academia and the private sector. From a policy perspective, procedures for developing and constructing biomethane plants and for implementing biomethane stations are far too slow to meet the demand. The lack of awareness among populations likely to buy a biomethane car constitutes a real hindrance for biomethane fuel development. Without diversifying policy efforts to cover all types of biofuels, however, biomethane deployment may still remain slow.

Finally, much more needs to be done in terms of innovation and research, development and deployment for the aviation and shipping sector options. Knowledge must be shared about (the economic viability of) state-of-the-art renewable technology options; research efforts coordinated; and policies, standards, and advocacy efforts aligned.

Policy suggestions for each action area to increase renewables in emerging sectors and accelerate deployment of emerging technologies are:

1. **Tap the potential of niche markets in the more difficult sectors of shipping and aviation, such as electric ferries, hybrid drives for short sea shipping, and drop-in biofuels in aviation.**

2. **Recognise emerging and potential breakthrough technologies for which mass production would reduce costs and boost market prospects, and provide related manufacturing support and R&D funding.**

Relevant IRENA work in this field:

Renewable energy options for shipping – Technology brief

Biomethane for transportation – Technology brief (forthcoming)

Aviation biofuels – Technology brief (forthcoming)

REmap – Roadmap for a Renewable Energy Future

6 NEXT STEPS AND FURTHER ANALYSIS

This paper has detailed some of the recent trends, emerging technologies, and prioritised action areas that should be addressed if the transport sector is to become more sustainable and realise higher shares of renewable energy. Without significantly more action in the sector, the goal of substantially increasing the global share of renewables, and meeting our climate targets, will not be possible.

One of the main policy suggestions from IRENA's 2016 edition of REmap is the need to promote transport based on renewable power and biofuels. This is an area that has so far been largely overlooked by policy makers. Additionally, the sector should unite to end a patchwork of policies and align efforts to drive increased sustainability in the sector. To do so, this REmap working paper provides insights into renewables deployment in the sector and identifies three action areas and ten policy suggestions on how to accelerate renewables in transport.

Increase electric mobility in combination with renewable electricity generation and apply a system strategies approach that interlinks energy sectors

1. Accelerate electric vehicle uptake by incentivising car sales. A cities and urban area approach should promote car-sharing schemes and electric two- and three-wheelers, and support non-passenger modes such as fleet vehicles, buses and light-duty trucks.
2. Accelerate investment in charging infrastructure and plan for infrastructure needs by taking into account the specific needs of cities and long-distance transport.
3. Capture synergies between transport and the power sector by using renewables to meet the new electricity demand from transport and by using electric mobility as a key flexibility measure to accommodate more wind and solar PV.

Develop sustainable and affordable advanced biofuel pathways for all transport modes including non-car modes such as freight, aviation and shipping

4. Ensure the availability and supply of affordable and sustainable feedstocks by improving agricultural yields, increasing the use of degraded and marginal land, using feedstocks that do not compete with food production, and reducing losses in the food supply chain.
5. Develop biofuel targets by considering life-cycle GHG performance to support advanced production pathways, and to prioritise the use and development of low-carbon bioenergy pathways and reduce non-sustainable bioenergy use.
6. Implement regulations and provide support to level the playing field of advanced liquid biofuels and non-renewable energy sources by considering their GHG emission benefits.
7. Establish or expand registers of origin to ensure sustainable feedstocks and promote the development of cross-border bioenergy trade.
8. Streamline bioenergy policy making by better integrating with energy, infrastructure, agriculture, resource, forestry, environment, food and innovation policies.

Explore emerging technology solutions and innovation for emerging transport modes such as aviation, shipping and military applications

9. Tap the potential of niche markets in the more difficult sectors of shipping and aviation, such as electric ferries, hybrid drives for short sea shipping, and drop-in biofuels in aviation.
10. Recognise emerging and potential breakthrough technologies for which mass production would reduce costs and boost market prospects, and provide related manufacturing support and R&D funding.

The IRENA's Work Programme for 2016-2017 has identified a number of tasks to close the knowledge gap on how to increase renewables in transport. IRENA and the REmap Transport Action Team will focus efforts on the following initiatives.

- For the **REmap** programme, deepen the analysis of technology and policy options in end-use sectors by expanding the multi-stakeholder action teams on renewables and transport, paying particular attention to the external benefits of renewables in transport;
- Develop the **REmap Transport Action Team** to further enable it to better share data, best-practice and information. The team should develop an action agenda focused on advancing renewable energy and the overall sustainability of the transport sector.
- Focus on **energy solutions for cities, helping** empower cities to deploy renewable energy by taking a city systems approach that combines end-use analysis with technology-specific solutions;
- As part of IRENA's work on **renewable energy benefits,** aim to standardise information from IRENA Members and develop a set of country policy briefs and synthesis reports for regions, highlighting the status and trends of renewable energy policy in electricity, heating and cooling, and transport;
- Conduct a **regional market analysis** for Southeast Asia to cover important themes intrinsic to the region's energy landscape, involving electricity, heating/cooling and transport sectors;
- Develop an updated **costing** report on biofuels for transport;
- Develop a **REmap information system** to make transport sector data from REmap countries more accessible online;
- Continue to work on **technology briefs** and **technology outlooks** for end-use sectors, including transport.

More information about IRENA's transport-related work can be found online at www.irena.org. To find out more about the REmap Transport Action Team please visit www.irena.org/remap or email remap@irena.org.

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LIST OF ABBREVIATIONS

AvGas	aviation gasoline
BAU	business as usual
BEV	battery-electric vehicles
CHP	combined heat and power
CO_2	carbon dioxide
COP21	Twenty-first session of the Conference of the Parties to the UNFCCC
dB	decibels
DENA	Germany Energy Agency
EJ	exajoule
EU	European Union
EV	electric vehicle
GFEI	Global Fuel Economy Initiative
GHG	greenhouse gas
GJ	gigajoule
Gt	gigatonne
HEV	hybrid-electric vehicles
ICAO	International Civil Aviation Organization
ICE	internal combustion engine
IEEA	International Conference on Informatics, Environments, Energy and Applications
INDC	Intended Nationally Determined Contributions
IRENA	International Renewable Energy Agency
kg	kilogram
km	kilometre
kt	kilotonne
kWh	kilowatt-hour
kW	kilowatt
LCE	lithium carbonate equivalent
LNG	liquefied natural gas
LUC	land use change
MJ	megajoule
mtoe	million tonne oil equivalent
NH_3	ammonia
NO_x	mono-nitrogen oxides
OEM	original equipment manufacturer
PHEV	plug-in hybrid electric vehicles
$PM_{2.5}$	particulate matter less than 2.5 micrometers in diameter sulphur dioxide
SO_2	sulfur dioxide
TFEC	total final energy consumption
TWh	terawatt-hours
UNFCCC	United Nations Framework Convention Climate Change
V2X	vehicle to grid
VOCs	volatile organic compounds

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