Cities as engines for mobility transitions

Co-benefits and coalitions as enablers for a low-carbon transport sector

vorgelegt von

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Abbreviations

COP	Conference of Parties
GHG	Greenhouse gas
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ITF	International Transport Forum
MLP	Multi-Level-Perspective
SDGs	Sustainable Development Goals
UNFCCC	United Nations Framework Convention on Climate Change

Deutsche Zusammenfassung

Co-benefits und Koalitionen als Treiber für den Übergang zu einer kohlenstoffarmen urbanen Mobilität

Fallstudie über die Rolle der städtischen Mobilität bei der Schaffung von Synergien zwischen politischen Zielen, die eine Grundlage für Koalitionen zwischen lokalen und nationalen politischen Akteuren bilden

Zusammenfassung

Die Transformation der Städte hin zu einer nachhaltigen und integrativen Entwicklung ist ein Hauptziel der New Urban Agenda (United Nations 2017). Die Verkehrsinfrastruktur spielt eine entscheidende Rolle bei der Gestaltung der Städte, der Bestimmung der Energieintensität der Mobilität und des Zugangs zu wesentlichen sozialen und wirtschaftlichen Möglichkeiten. Der Verkehrssektor spielt eine wichtige Rolle bei globalen Klimaschutzstrategien, da er derzeit für etwa 23% der weltweiten energiebedingten Treibhausgasemissionen verantwortlich ist (IPCC 2014). Es besteht ein erhebliches Potenzial zur Verbesserung der Mobilität in Städten, der Luftqualität, der Sicherheit und der Lebensqualität in Städten sowie zur Senkung der Treibhausgasemissionen, wenn ein integrierter politischer Ansatz verfolgt wird, der alle Interventionsbereiche für die Verkehrspolitik vereint und alle Regierungsebenen integriert. Um dieses Potenzial zu nutzen, ist jedoch ein integrierter politischer Ansatz erforderlich, der alle Interventionsbereiche für die Verkehrspolitik vereint und alle Regierungsebenen einbezieht. Ein Paket, das einen kohlenstoffarmen Verkehr erreicht und nachhaltige Entwicklung fördert, umfasst vermiedene Fahrten durch kompakte städtebauliche Gestaltung und Umstellung auf effizientere Verkehrsträger, verbesserter Fahrzeugtechnologien, kohlenstoffarme Kraftstoffe und Investitionen nachhaltige Verkehrsinfrastruktur. Politikgestaltung und -prozesse sind eng miteinander verknüpft, da die Fähigkeit politischer Institutionen, einen politischen Konsens zu finden und die politische Stabilität zu erhalten, starken Einfluss auf den Erfolg von Maßnahmen zur Gestaltung des Transformationspfads hin zu einer nachhaltigen Mobilität hat.

Diese Arbeit zielt darauf ab, diese Zusammenhänge zu analysieren und die Rolle verschiedener Politik- und Steuerungsansätze aufzuzeigen. Diese Analyse baut auf der Verkehrs- und Stadtentwicklungsforschung auf, verfolgt jedoch eine transdisziplinäre Forschungsperspektive, die auf der Multi-Level-Perspektive von Nachhaltigkeitsübergängen aufbaut (Geels 2002) und zielt darauf ab, das Potenzial für einen konsensorientierten Politikansatz (Lijphard 1999) aufzuzeigen über die Co-Benefits der wichtigsten politischen Ziele und Koalitionen der wichtigsten politischen Akteure, die zu der Hauptfrage für diese These und die Schwerpunkte

für die Analyse führt (Abbildung 1).

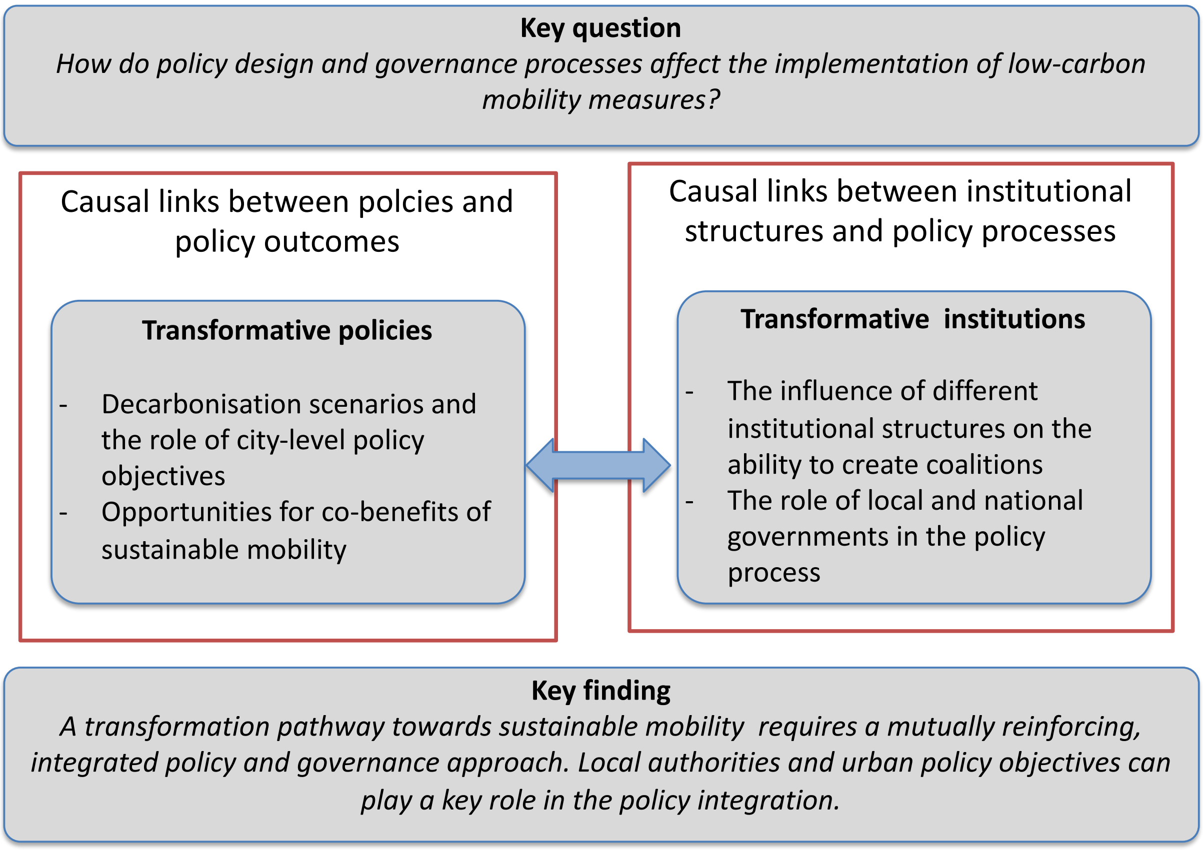


Figure 1 Structure of the thesis

Fallstudie: Städte als Hot-Spots für Co-Benefits

Diese Dissertation geht von der Perspektive aus, dass technologieorientierte Lösungen in globalen Dekarbonisierungsszenarien eine zu prominente Rolle spielen. Es wird argumentiert, dass ein stärkerer Fokus auf Transitionspfade auf lokaler Ebene ein Potenzial für Co-Benefits bietet, das die Unterstützung wichtiger Interessengruppen sichern und damit die Koalitionsbildung befördern kann. Eine kohlenstoffarme Mobilität in der Stadt kann Vorteile generieren, die weit über den Klimaschutz hinausgehen und die Gesundheit und das Wohlergehen der Menschen unmittelbar verbessern. Ein hoher Anteil nachhaltiger Verkehrsträger und kompakte Städteplanung können eine Reihe von positiven Effekten freisetzen die zu nachhaltigeren und lebenswerten Städten beitragen. Das große Potenzial für Co-benefits und Synergien eines integrierten Politikkonzepts, aber auch das Risiko von Trade-offs isolierter Maßnahmen, macht den Transportsektor zu einem besonders interessanten Fall für die in dieser Arbeit vorgestellte Analyse. Das Wechselspiel zwischen lokalen und nationalen politischen Maßnahmen und Institutionen ist ein Schlüsselmerkmal bei der Steuerung des Übergangs zu einer nachhaltigen Mobilität, die darauf abzielen wird, ein neues Licht auf die

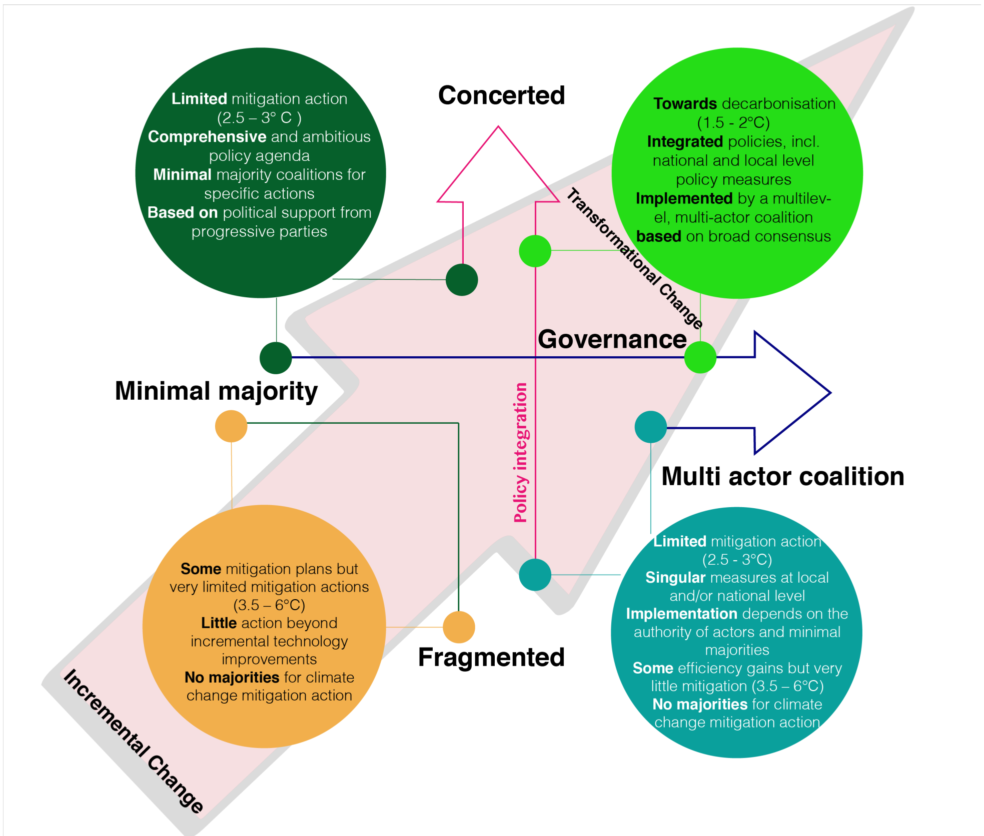
Beziehung zwischen Politikgestaltung und Umsetzungsprozess zu werfen. Der integrierte Politikgestaltungs - und - führungsansatz wird als ein entscheidender Faktor betrachtet, um von schrittweisen Veränderungen zu den transformatorischen Veränderungen überzugehen, die zur Erreichung der Dekarbonisierungsziele und der Ziele für nachhaltige Entwicklung erforderlich sind. Die in dieser Arbeit vorgestellte Analyse zeigt, dass eine Integration von Politik und Governance aus drei Perspektiven notwendig ist:

Erstens: aus der Perspektive von Dekarbonisierungsszenarien, in denen Elemente wie Stadtplanung und Verkehrsverlagerung ebenso wichtig sind wie Fahrzeugtechnologien und Treibstoffe;

Zweitens: Lokale und nationale Politiken können nur dann ihr volles Potenzial entfalten, wenn sie sich gegenseitig verstärken;

Drittens kann ein konzertierter, politischer Ansatz eine Grundlage für Koalitionen mehrerer Akteure bieten, die auf lokaler und nationaler Ebene langfristige Übergänge zu kohlenstoffarmer Mobilität ermöglichen (Abbildung 2).

Abbildung 2 Integrierter Politik- und Governance-Ansatz für Transformationsänderungen



Koordination, Konsens und Kontinuität

Konsensorientierte Gesellschaften zielen darauf ab politische Entscheidungen auf eine breite Koalition zwischen großen politischen Parteien und relevanten Interessengruppen stützen. In Ländern mit einem hohen Organisationsgrad von Interessengruppen und einer relativ kleinen

Anzahl von Spitzenorganisationen haben Entscheidungsträger eine überschaubare Anzahl von Verhandlungspartnern. Durch die Koordinierung mit den wichtigsten Spitzenorganisationen verfügen die Mitglieder des Parlaments, die Stadträte, die Bürgermeister und die Minister über ein relativ hohes Maß an Gewissheit über die Positionen der maßgeblichen Interessengruppen. Dies trägt dazu bei, Maßnahmen so zu gestalten dass sie einen Weg für eine erfolgreiche Umsetzung zu ebnen und Kontinuität waren können. Diese Analyse basiert auf den Konzepten von Korporatismus und koordinierter Marktwirtschaft von Lijphard 1999; Hall und Soskice 2001 und reflektiert einige der Hauptmerkmale dieser Konzepte auf lokaler und nationaler Ebene. Dies hilft dabei, Möglichkeiten für Konsensbildung auf der Grundlage der politischen Ziele der wichtigsten Interessengruppen und der potenziellen Synergien der vorgeschlagenen Politikpakete zu ermitteln.

Co-Benefits und Koalitionen

Luftqualität, Sicherheit, Energieeffizienz, Zugang zu Mobilitätsdiensten und andere Faktoren, die aus der Sicht des Klimawandels als Vorteile von nachhaltigen Verkehrsmaßnahmen betrachtet werden, sind in der Tat die treibenden Faktoren für politische Interventionen, insbesondere auf lokaler Ebene (Jacobsen 2003; Goodwin 2004; Hultkrantz, Lindberg und Andersson 2006; Rojas-Rueda et al. 2011). Da der Transport fast ausschließlich auf Erdölerzeugnissen beruht, ist die Energiesicherheit ein wichtiges Thema für die Sektorprodukte (Sorrell und Speirs 2009). Costantini et al., 2009; Cherpet al. 2012). Es besteht eine direkte Verbindung zwischen Energiesicherheit und Klimaschutzmaßnahmen, die sich auf Brennstoffwechseloptionen wie Biokraftstoffe und Elektrifizierung (Shakya und Shrestha 2011; Leiby 2007; Jewell, Cherp und Riahi 2013) und nachfrageseitige Maßnahmen wie Kraftstoffeffizienz konzentrieren Übergang zu effizienteren Verkehrsträgern und kompaktem Stadtdesign (Leung 2011; Cherp et al. 2012; Sovacool und Brown 2010). Diese Strategien dürften auch den Zugang zu Mobilitätsdienstleistungen verbessern und die Transportkosten senken, was sich positiv auf Produktivität und soziale Eingliederung auswirkt (Banister 2008; Miranda und Rodrigues da Silva 2012) und einen besseren Zugang zu Arbeitsplätzen, Märkten und sozialen Diensten bietet (Boschmann 2011; Sietchiping , Permezel und Ngomsi 2012; Banister 2011). Ein verbesserter Zugang ist ein Hauptziel der New Urban Agenda, da sie Möglichkeiten für Beschäftigung, Bildung und andere Grundbedürfnisse bietet (Misselwitz, Overmeyer und Polinna 2016). Ein wesentlicher Kostenfaktor, der durch ineffiziente Verkehrssysteme entsteht, sind Staus. Die im Verkehr verlorene Zeit wurde im Vereinigten Königreich mit 1,2% des BIP bewertet (Goodwin 2004); 3,4% in Dakar, Senegal; 4% in Manila, Philippinen (Carisma und Lowder 2007); 3,3% bis 5,3% in Peking, China (Creutzig und He 2009); 1% bis 6% in Bangkok, Thailand (Weltbank 2002) und bis zu 10% in Lima, Peru mit täglichen Reisezeiten von fast vier Stunden (JICA 2005; Kunieda und Gauthier 2007). Die Kombination verschiedener politischer Ziele, die durch einen integrierten Politik- und Governance-Ansatz auf mehreren Ebenen angegangen werden können, bietet eine solide Grundlage für dauerhafte Strategien, die langfristige Auswirkungen haben können. Klimawandel, Luftqualität, Lärmprävention, Sicherheit, Energiesicherheit und Produktivität sind zentrale politische Ziele für die lokalen und nationalen Entscheidungsträger, wenn auch in unterschiedlichem Maße (de Hartog et al. 2010; Rabl und de Nazelle 2012; Tiwari und Jain 2012; Jewell, Cherp und Riahi 2013).

Politikintegration

Ein integrierter politischer Ansatz beruht auf einem systemischen Ansatz, der darauf abzielt, Synergien zwischen den politischen Zielen zu schaffen, was mit dem Wunsch zusammenhängt, Koalitionen zwischen Interessengruppen zu bilden. Zum Beispiel können die Energieeffizienz von Fahrzeugen und kohlenstoffarme Kraftstoffe aus einer Perspektive des Klimaschutzes das größte CO2-Emissionsminderungspotenzial bieten, dies spiegelt jedoch nicht umfassend eine umfassendere Perspektive der nachhaltigen Entwicklung wider. Ein multimodaler und integrierter Politikansatz kann Rebound-Effekte minimieren, Split-Incentives überwinden und ein höheres Niveau an sozioökonomischen Co-Benefits erreichen (Givoni 2014). Energieeffizienz und kohlenstoffarme Kraftstoffe spielen eine Schlüsselrolle bei der Dekarbonisierung des Verkehrssektors. Allerdings sind die Strategien, insbesondere die Vermeidung von Reisen durch kompaktes Stadtdesign und die Umstellung auf kohlenstoffarme Verkehrsträger, Maßnahmen, die erhebliche Möglichkeiten bieten, zu einer nachhaltigen Entwicklung beizutragen. Ein Ansatz, der politische Maßnahmen auf städtischer und nationaler Ebene kombiniert, wird als entscheidender Faktor für den Übergang zu einer nachhaltigen Mobilität angesehen. Während institutionelle Strukturen nicht ohne weiteres übertragbar sind, kann der allgemeine Ansatz der politischen Integration und die Suche nach Synergien die Grundlage für einen umfassenderen Ansatz für die Politik und Planung der städtischen Mobilität bilden. Dies würde die Entwicklung eines umfassenderen strategischen Rahmens und das Ziel beinhalten, breitere Koalitionen zu bilden, um die Kontinuität der Politik zu gewährleisten, was besonders wichtig für den städtischen Verkehrssektor ist, der auf langfristige Infrastruktur und Investitionen angewiesen ist.

Co-benefits and coalitions as enablers for the transition towards a low-carbon urban mobility

Case study on the role of urban mobility in creating synergies among policy objectives that create a basis for coalitions among local and national policy actors

1. Summary

The transformation of cities towards sustainable and inclusive development is a key objective of the New Urban Agenda (United Nations 2017). Transport infrastructure is a critical factor in shaping cities, determining the energy intensity of mobility and providing access to essential social and economic opportunities. The sector also plays an important role in global climate change mitigation strategies, as it currently accounts for about 23% of global energy-related greenhouse gas emissions (IPCC 2014).

There is substantial potential to improve urban access, air quality, safety and the quality of life in cities along with reducing Greenhouse Gas Emissions if an integrated policy approach is applied that combines all intervention areas for transport policy and involves all levels of government. A package that achieves low-carbon transport and fosters sustainable developed includes avoided journeys through compact urban design and shifts to more efficient modes of transport, uptake of improved vehicle and engine performance technologies, low-carbon fuels, investments in related infrastructure, and changes in the built environment. From a governance perspective, all relevant political institutions at the local and national level need to be involved in the coalition building along with key societal actors, such as unions, industry and civil society organisations. Bringing the policy objectives of these actors together with an integrated policy package is a vital step towards a low-carbon, sustainable mobility system.

Policy design and governance are critically interlinked as the ability of institutions to find a political consensus and to maintain policy stability heavily influences the success of measures to shape the transformation pathway towards sustainable mobility. This thesis aims to analyse these linkages and highlight the role of different policy and governance approaches. This analysis builds on transport and urban development research, but takes a transdisciplinary research perspective, building on the Multi-Level-Perspective on sustainability transitions (Geels 2002) and aims to highlight the potential for a consensus oriented policy approach (Lijphard 1999) that builds on co-benefits among key policy objectives and coalitions among key political actors, which leads to the main question for this thesis and the focus areas for the analysis (Figure 1).

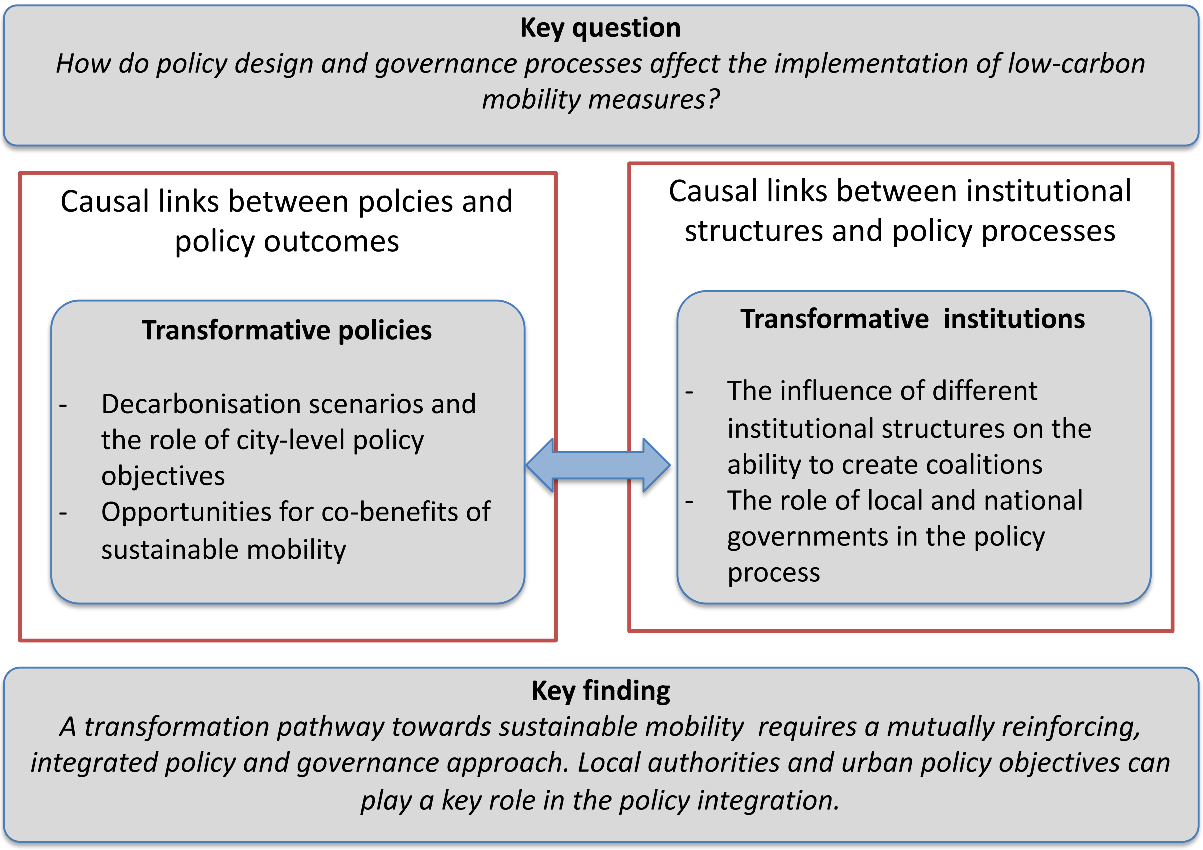


Figure 2 Structure of the thesis

Case-study: Cities as hot-spots for co-benefits

The research group starts from the perspective that technology-oriented solutions play an overemphasised role in global decarbonisation scenarios. It is argued that a greater focus on sustainability transitions at the local level yields a potential for co-benefits[1] that can trigger the support of key stakeholders, which helps forming coalitions[2] that can endure over the long-term.

Low-carbon urban mobility can deliver benefits well beyond the climate change mitigation aspect and can help improving human health and wellbeing. High shares of low-carbon modes, mixed-use and compact city design can also unlock a number of co-benefits that contribute to wider sustainable and liveable cities. The great potential for co-benefits and synergies of an integrated policy approach, but also the risk for trade-offs of isolated measures, makes the transport sector a particularly interesting case for the analysis of urban transitions. The interplay between local and national policy actions and institutions is a key feature of governing the

[1] Co-benefits in the context of this thesis refers to the potential positive effects of a policy aimed at one objective on other objectives
[2] Coalitions refers to partnerships of political actors, institutions and stakeholders that support the development and implementation of a measure

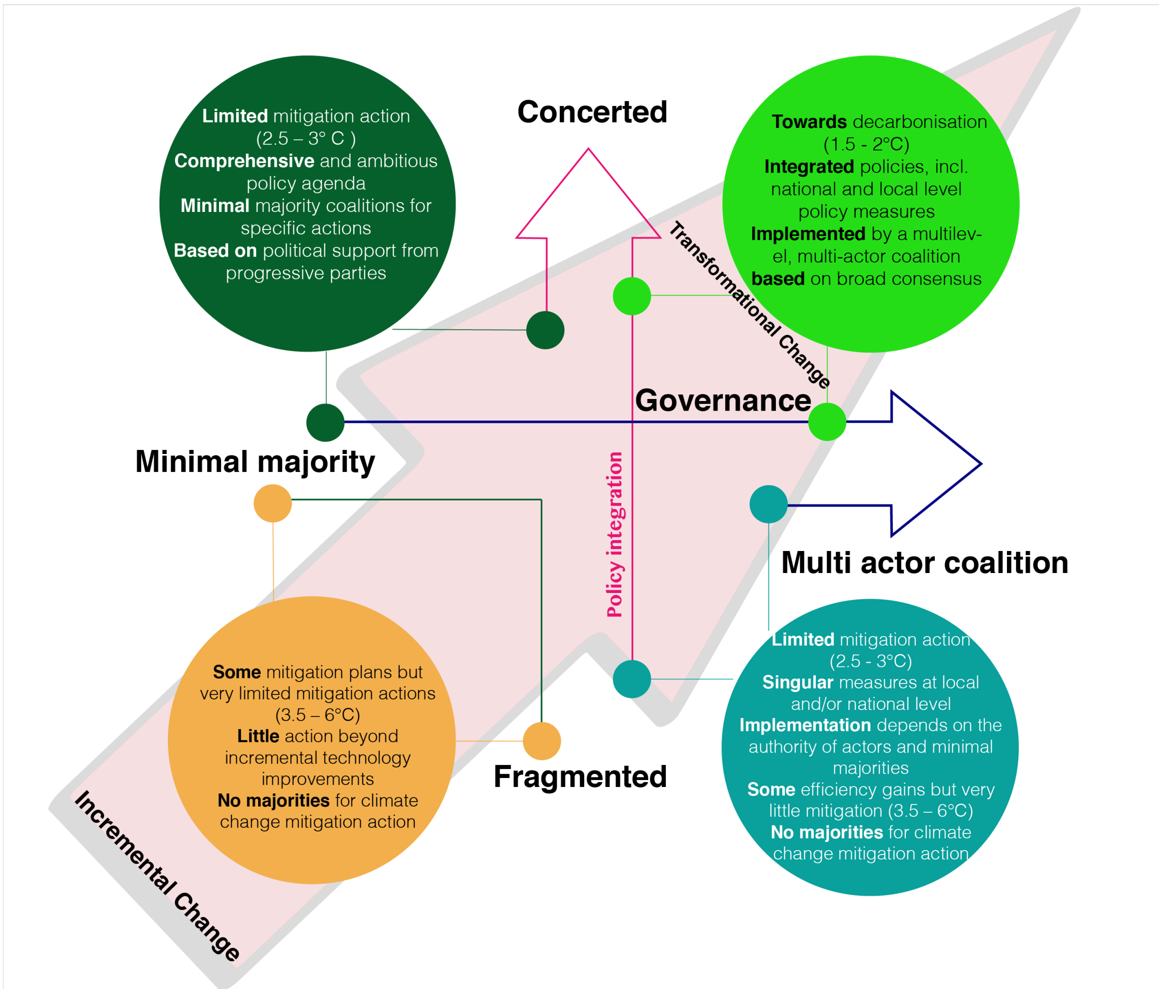
transition towards sustainable urban development and mobility. This thesis will aim to shed new light on the relationship between policy design and implementation process. The integrated policy design and governance approach is considered to be a vital enabler to move from incremental change to the transformational change that is needed to achieve decarbonisation targets and the Sustainable Development Goals. The analysis presented in this thesis shows that three aspects related to policy and governance design are relevant for urban mobility transitions,

First: decarbonisation of the transport sector can only be achieved when urban and mobility transitions are integrated and strategies on urban design and modal shift are implemented along with low-carbon vehicle technologies and energy carriers;

Second: local and national policies can only deliver on their full potential when they are mutually reinforcing;

Third a concerted, multi-level policy approach can provide a basis for multi-actor coalitions that can enable long-term transitions to low-carbon mobility at the local and national level (Figure 2).

Figure 3 Integrated policy and governance approach for transformational changes



Coordination, consensus and continuity

Consensus oriented societies aim to base political decisions on a broad coalition between major political parties and relevant stakeholders. In corporatist countries, there is a high level of organisation and interest groups are represented by a small number of peak-organisations, which means that decision makers have a manageable number of negotiating partners who represent large constituencies. Coordination with the major peak organisations leaves the Members of Parliament, City Councils, Mayors and Ministers with a relatively high level of certainty about the positions of relevant stakeholders, which helps to shape policies and to pave the way for successful implementation. This analysis builds on the concepts of corporatism and coordinated market economies by Lijphard 1999; Hall and Soskice 2001 and reflects on some of the key features of these concepts at the local and national level. This helps to identify opportunities for consensus building based on the policy objectives of key stakeholders and the potential synergies of proposed policy packages.

Co-benefits and coalitions

Air quality, safety, energy efficiency, access to mobility services and other factors that are considered to be co-benefits of sustainable transport measures from a climate change perspective are in fact the driving factors for policy intervention, in particular on the local level (Jacobsen 2003; Goodwin 2004; Hultkrantz, Lindberg, and Andersson 2006; Rojas-Rueda, Nazelle, et al. 2011). As transport relies almost entirely on petroleum products, energy security is a major issue for the sector at the national level (Steve Sorrell and Speirs 2009) Costantini et al., 2009; Cherp et al. 2012). There is a direct link between energy security and climate change mitigation actions that focus on fuel switch options, such as biofuels and electrification (Shakya and Shrestha 2011; Leiby 2007; Jewell, Cherp, and Riahi 2013) and demand side measures, such fuel efficiency, shift to more efficient transport modes and compact urban design (Leung 2011; Cherp et al. 2012; Sovacool and Brown 2010). These city level strategies are also likely to improve access to mobility services and reduce transport costs, which affects positively productivity and social inclusion (Banister 2008; Miranda and Rodrigues da Silva 2012) and low-carbon urban mobility systems provides better access to jobs, markets and social services (Boschmann 2011; Sietchiping, Permezel, and Ngomsi 2012; Banister 2011). Improved access is a major objective in the New Urban Agenda as it provide opportunities for employment, education and other basic needs (Misselwitz, Overmeyer, and Polinna 2016). A major cost factor generated by inefficient urban transport systems is congestion. Time lost in traffic was valued at 1.2% of GDP in the UK (Goodwin 2004); 3.4% in Dakar, Senegal; 4% in Manila, Philippines (Carisma and Lowder 2007); 3.3% to 5.3% in Beijing, China (Creutzig and He 2009); 1% to 6% in Bangkok, Thailand (World Bank 2002) and up to 10% in Lima, Peru with daily travel times of almost four hours (JICA 2005; Kunieda and Gauthier 2007a). The combination of various policy objectives that can be addressed by an integrated multi-level policy and governance approach provides a solid basis for durable polices that can have long-lasting impacts. Climate change, air quality, noise prevention, safety, energy security and productivity are key policy objectives for policy makers at the local and national level, even though to varying degrees (de Hartog et al. 2010; Rabl and de Nazelle 2012; Tiwari and Jain 2012; J. Jewell, Cherp, and Riahi 2013). While this creates substantial opportunities for benefits across these policy areas, it also creates a highly complex policy environment with a large number of actors and stakeholders.

Policy integration

An integrated policy approach is driven by a systemic approach that aims to generate synergies among policy objectives, which links to the desire to build coalitions among stakeholders. For example, while from a climate change mitigation perspective vehicle efficiency and low-carbon fuels may provide the biggest CO2 emission reduction potential, this does not fully reflect a broader sustainable development perspective. A multimodal and integrated policy approach can minimise rebound effects, overcome split-incentives and achieve a higher level of socio-economic co-benefits (Givoni 2014). Energy efficiency and low-carbon fuels have a key role to play in decarbonizing the transport sector. However, the strategies, in particular avoiding travel through compact city design and shifting to low-carbon modes are the measures that yield substantial opportunities to contribute to sustainable development.

An approach that combines city and national level policy interventions is considered to be a vital factor to enable the transition towards sustainable mobility. While institutional structures are not easily transferable, the general approach of policy integration and seeking of synergies, can provide a basis for a more comprehensive approach to urban mobility policy and planning. This would include the development of a wider strategic framework and the aim to build broader coalitions to create policy continuity, which is particularly important for the urban transport sector, which relies on long-term infrastructure and investment.

1. Relevance, concepts and theoretical framework

Transport is a key sector in global climate change mitigation efforts and urban mobility is a core element of this, in particular because of the ability of sustainable urban mobility to un-lock a great potential of co-benefits among key policy objectives, such as health, access, safety and energy security.

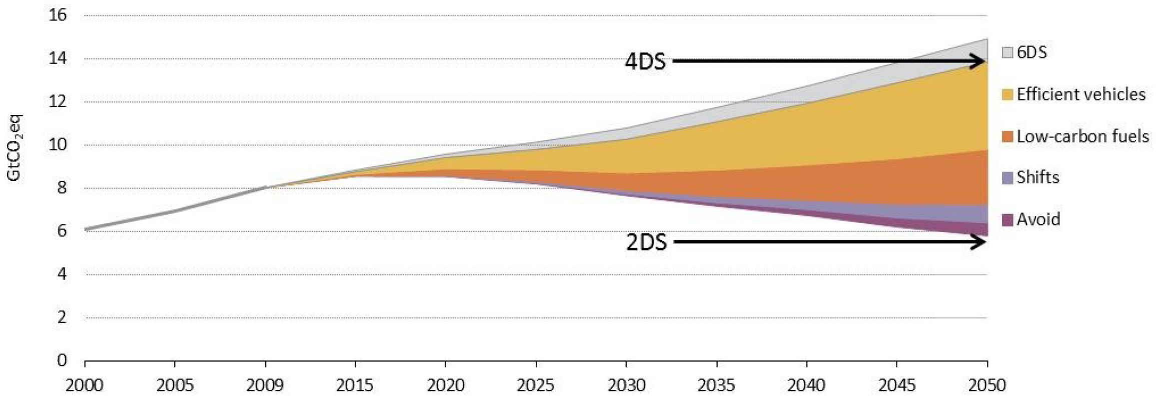
Considering the importance of the transport sector and the lack of progress towards decarbonisation, the thesis aims to make a contribution to the current body of literature, by developing an integrated perspectives on decarbonisations scenarios and related policy requirements, policy design and the role of co-benefits and the impact of institutions and governance structures on policy outcomes. As part of this concept, Paper 1 (*Fulton, L., Lah, O., & Cuenot, F., 2013. Transport Pathways for Light Duty Vehicles: Towards a 2° Scenario. Sustainability, 5(5), 1863–1874*) develops relevant scenarios that highlight the different policy options to decarbonise the transport sector and the interactions of them under different assumptions, which shows that the transport sector is currently on track to continue to stay at current levels of greenhouse gas emissions even under very optimistic scenarios and outlines scenarios for the sector and the role of efficient vehicles technology and some modal shifts, transport CO_2 emissions in transition pathways towards 2050. The wider socio-economic benefits that can be generated by a policy process that maximises co-benefits are assessed in Paper 2 (*Stechow, C., McCollum, D., Riahi, K., Minx, J. C., Kriegler, E., van Vuuren, D. P., Lah, O., Edenhofer, O. 2015. Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. Annual Review of Environment and Resources, 40(1), 363–394*). This is then developed further into a policy design framework that utilizes the potential of co-benefits in particular at the urban level and highlights the role of the integration of key political and institutional actors in Paper 3 (*Lah, O. (2017). Sustainable development synergies and their ability to create coalitions for low-carbon transport measures. Transportation Research Procedia, 25, 5088–5098*). Paper 4 highlights the risks associated with political volatility and changing political priorities and the opportunities that can be generated by a consensus oriented policy approach that takes advantage of the potential of co-benefits of urban mobility (*Lah, O., 2017. Continuity and Change: Dealing with Political Volatility to Advance Climate Change Mitigation Strategies—Examples from the Transport Sector. Sustainability, 9(6).*).

1.1 Cities as enablers for the transition to a low-carbon economy

Urbanisation is increasing rapidly, particularly in developing and emerging economies, which creates great opportunities, but also poses significant challenges. Cities currently account for about 70 percent of energy consumption and about 80 percent of energy related Greenhouse Gas Emissions, while only covering 2 percent of the earth´s landmass. However, cities can also be a hotspot for synergies and co-benefits when addressing global climate change and sustainable development objectives. Improving the efficiency of urban energy, resource and transport systems can help unlocking co-benefits, such as improved air quality, health, energy security and productivity. Urban mobility has a particularly important role to play in this by providing access to economic and social activities and being one of the key sources of CO_2 emissions and air pollutants.

The New Urban Agenda, which was approved by countries at the Habitat III summit in Quito in 2016 highlights the vital role of urban mobility to deliver on the Sustainable Development Goals (SDGs) and the Paris Agreement at the city level (UN 2016a). The drive towards sustainable mobility provides the social, economic and environmental rationale through the provision of access, equality and the provision of development opportunities for all (UN 2016b). The New Urban Agenda is now an integral part of the success of global climate change and sustainable development agendas, which recognises cities role as powerhouses of the global economy, drivers of innovation and centres of social interaction (Caprotti et al. 2017). The Conference of the Parties in 2015 (COP 21) achieved a remarkable consensus on climate action and emphasized the role of cities in implementing climate action measures. The target of limiting global warming to 1.5° C above pre-industrial levels will not be feasible without decisive action at the local level. Transport decarbonisation scenarios are beginning the acknowledge the importance of urban mobility measures, but their role in the transition towards sustainable mobility is still not sufficiently acknowledged (e.g. Figure 4).

Figure 4 Greenhouse gas emissions mitigation potential from the transport sector for a 4° and a 2° scenarios (IEA 2013)



Critical preconditions for the delivery of urban mobility services are a human-centred, inclusive and multi-level governance approach, integrated urban development, applying the principle of subsidiarity and appropriate legislative frameworks and enforcement mechanisms and ensure coordinated action. To support this, intra- and inter-city learning and capacity building can help to leap-frog to sustainable solutions.

International efforts to implement the New Urban Agenda need to focus on all levels of governance and decision-making, to ensure that all multilateral and bilateral organisations, local authorities as well as national governments conform to and adopt the Urban Agenda. The New Urban Agenda stressed the point that access for everyone to all urban basic services is an essential precondition to enable the achievement of the Sustainable Development Goals. Delivering appropriate mobility services that provide access to jobs, social opportunities, health and education to everyone requires concerted action from the national, regional and local levels. The principle of subsidiarity was emphasised by the New Urban Agenda considering that local infrastructure and policy decisions need to be enabled by the provision of sufficient funds from the national level.

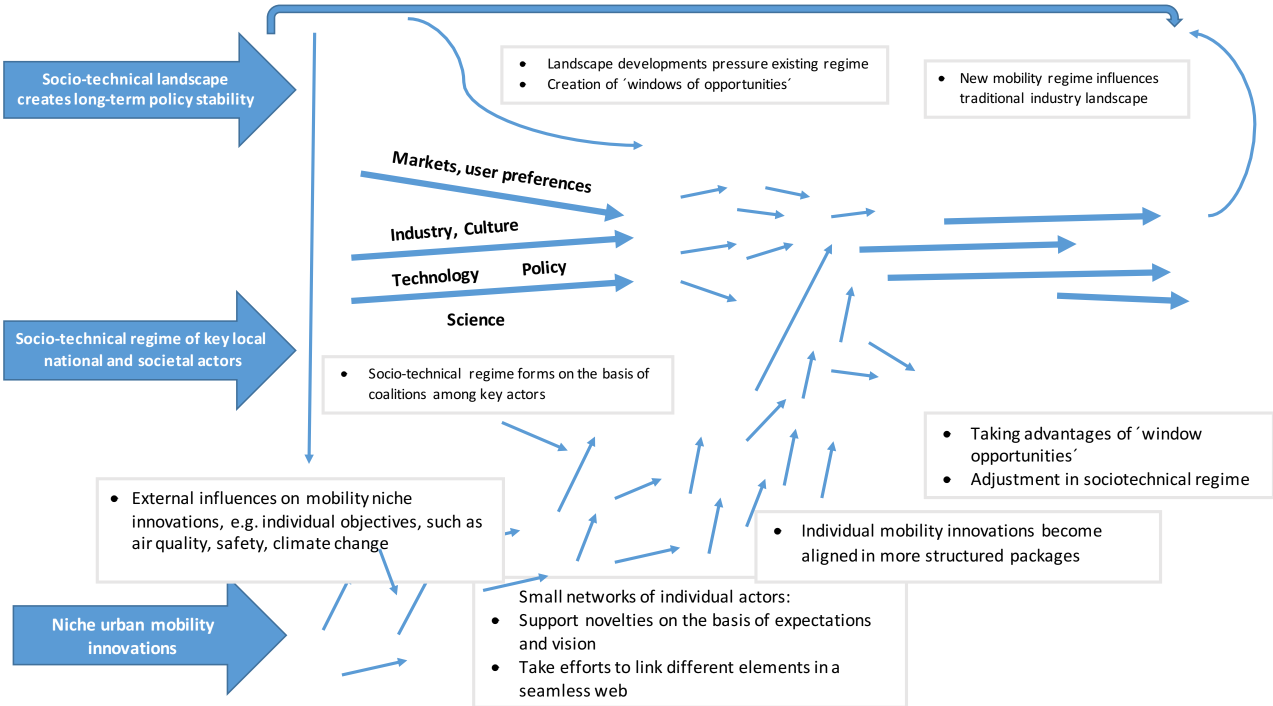
Urban mobility is a vital enabler for social and economic development and with that is a cornerstone to achieve the Sustainable Development Goals. Access and mobility are regarded as basic human rights, which needs strong support from the local and national policy level (UN 2016a), which puts integrated urban and mobility policy and planning at the centre of local and national governments.

1.2 Transport research, transition theory and beyond

Transport research is increasingly recognising the importance of a broader perspective towards mobility and the importance of urban development and mobility in setting the sector on a low-carbon development path. Transition theory has been acknowledged as a useful approach to guide more comprehensive policy and governance approach. Bringing transport policy into the classical transition theory context already helps recognising the benefits of applying transition theory to the context of transport policy.

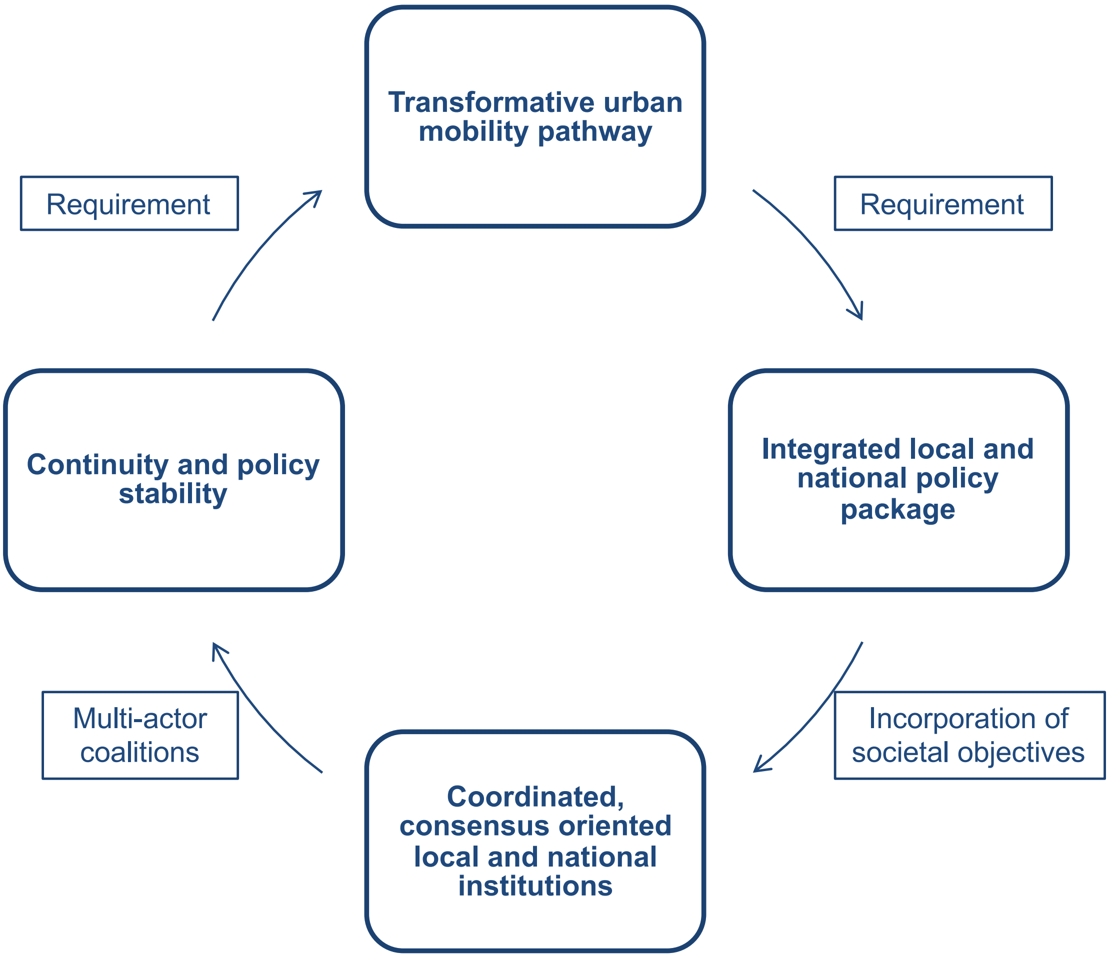
Transition Management is gaining attention as a way to conceptualise the complex processes in various aspects of sustainable development, including urban low-carbon development (Loorbach 2017). The Multi-Level-Perspective (MLP) to sustainability transitions has been widely recognised as a potentially useful framework to better understand the narratives of transition processes in urban areas (Næss and Vogel 2012; Loorbach 2017; Ehnert et al. 2018; Dowling, McGuirk, and Maalsen 2018) and transportation (Nilsson and Nykvist 2016; Berkeley et al. 2017; M. J. Figueroa, Fulton, and Tiwari 2013). However, there are a number of shortcomings of the general framework when looking into the specific policy design and process perspectives of individual sectors. Næss and Vogel 2012 point out that is very challenging to clearly define regimes for highly complex transition processes, such as urban development and mobility. The basic MLP framework (Geels 2002) slightly amended from an urban mobility perspective is the starting point for the transition perspective to the analysis of transport policy design and governance presented in this thesis (Figure 5).

Figure 5 Transport policy and innovation in the context of a Multi-level perspective on transitions



Transitioning from isolated policy interventions and innovation niches to a mature sustainable mobility landscape is a complex and challenging process that requires a policy and institutional environment that is dynamic, which is vital to enable innovations, but is also stable, which is essential to attract investments. Urban mobility innovations can be a driving force towards the shift to a low-carbon economic system. The drivers for the changes that are required for the transition are particularly strong at the urban level. Innovative solutions that address local issues such as air quality, efficiency, safety and access in an integrated way can be the niche innovations that then gradually emerge through the sociotechnical system and help transforming the entire transport system (Geels, 2002, 2011). While transition theory holds a number of aspects that reflect on the need for a more integrated perspective to policy design and multi-level governance, the general approach has also a few short-comings when looking into the applicability at a sectoral level. This thesis focuses on the role of a comprehensive policy approach that includes local and national policy measures and aims to highlight the importance of interlinkages of urban design, public and non-motorised transport, vehicle technologies and fuels. This mix of policy interventions is not just essential from a decarbonisation perspective, but the co-benefits unlocked by this approach also helps addressing key societal objectives, which in turn can help generating a more consensus oriented policy environment and coalitions among institutions that are vital for continuity and long-term policy stability. Figure 6 reflects on the key elements of the Multi-level perspective on transitions and brings this into a policy and governance cycle that outlines the key aspects of this thesis and the main linkages between policy design and governance.

Figure 6 Critical interlinkages in the transition cycle



The transition cycle provides a basis for the analysis of this thesis and aims to capture the main hypothesis of critical interlinkages between co-benefits and coalitions as key ingredients for a sustainable mobility transition strategy.

1.3 Co-benefits and coalitions for low-carbon urban mobility

Urban development and transport policies generally require a consensus on the need for policy intervention and a strategic, coherent, and stable operating environment. Policy interventions that help delivering on a Sustainable Urban Mobility Plan, such as taxation of fuel and electricity use, are highly visible and politically sensitive. They require a strong political commitment to appear on the policy agenda and to remain in place as they rely on investments that are only cost-effective over the medium to long-term (IPCC, 2014).

Developing consensus can be difficult because urban development is complex and multifaceted and policy interventions can have unintended consequences. Linking and packaging policies is vital to generate synergies and co-benefits between measures can help aligning objectives of different political, institutional and societal actors. An integrated policy approach that creates consensus and coalitions among diverse stakeholders and interests can help to overcome implementation barriers, minimize rebound effects, and motivate people, businesses, and communities. This type of integrated policy approach is especially critical because current GHG reduction measures alone can make important contributions but cannot achieve the levels of reduction needed to shift to a 1.5°C pathway (IPCC 2014).

Decision making on urban mobility and infrastructure investments is as complex as cities themselves. Rarely ever will a single measure at the local or national level achieve comprehensive climate change impacts and also generate economic, social and environmental benefits without creating trade-offs. Many policy and planning decisions have synergistic effects, meaning that their impacts are larger if implemented together. It is therefore generally best to implement and evaluate integrated programs rather than individual strategies. For example, by itself improvements of public transport services may only cause minimal reductions in individual motorized travel, and associated benefits such as congestion reductions, consumer savings and reduced pollution emissions. However, the same measure may prove very effective and beneficial if implemented with complementary incentives, such as efficient road and parking pricing, so travellers have an incentive to shift away from individual car travel (Lah, 2015). In fact, the most effective programs tend to include a combination of qualitative improvements to alternative modes (walking, cycling, ridesharing and public transit services), incentives to discourage carbon-intensive modes (e.g. by efficient road, parking and fuel pricing; marketing programs for mobility management and the reduction of commuting trips; road space reallocation to favour resource-efficient modes), plus integrated transport planning and land use development, which creates more compact, mixed and better connected communities with less need to travel. Hence, a vital benefit of the combination of measures is the ability of integrated packages to deliver synergies and minimise rebound effects, examples of which are outlined below (Table 1).

Table 1 Low-carbon transport co-benefit mapping

	Effect on policy objectives

Transport climate change mitigation measures		**Economic**		**Social**		**Environmental**
Reduction of fuel carbon intensity: e.g. electricity, H_2, CNG, biofuels and other measures	↑ ↑ ↑	Energy security (diversity and reduced oil dependency/exposure to oil price volatility) **(m/m)** Terms of trade for oil-importing countries (via reduced oil imports) **(l/l)** Technological spillovers (e.g. battery technologies for consumer electronics) **(l/l)**	? ↓ ↑ ↓ ↓	Health impact via urban air pollution by CNG, biofuels: net effect unclear **(m/l)** Electricity, hydrogen: reducing most pollutants **(r/h)** Shift to Diesel: potentially increasing pollution **(m/m)** Noise (electrification and fuel cell LDVs) **(r/h)** Road safety (silent electric LDVs at low speed)	↓ ↑	Ecosystem impact of electricity and hydrogen via Urban air pollution **(m/m)** Material use (unsustainable resource mining) **(l/l)** Ecosystem impact of biofuels ***(l/l)***
Reduction of energy intensity	↑	Energy security (reduced oil dependency and exposure to oil price volatility) **(m/m)**	↓ ↑	Health impact via reduced urban air pollution Road safety (via increased crash-worthiness)	↓	Ecosystem impact via urban air pollution
Compact urban form + improved transport infrastructure **Modal shift**	↑ ↑ ?	Energy security (reduced oil dependency and exposure to oil price volatility) **(m/m)** Productivity (reduced urban congestion and travel times, affordable and accessible transport) **(m/h)** Employment opportunities in the public transport sector vs car manufacturing jobs **(m/m)**	↓ ↑ ↑ ↑	Health impact for non-motorized modes via Increased activity **(r/h)** Potentially higher exposure to air pollution **(l/m)** Equitable mobility access to employment opportunities, particularly in DCs **(r/h)** Road safety (via modal shift and/or infrastructure for pedestrians and cyclists) (m/**m**)	↓	Ecosystem impact via urban air pollution
Journey reduction and avoidance	↑ ↑	Energy security (reduced oil dependency and exposure to oil price volatility) **(h/h)** Productivity (reduced urban congestion, travel times, walking & cycling) **(m/h)**	↓	Health impact (non-motorized transport modes) **(r/h)**	↓ ↑ ↓	Ecosystem impact via Urban air pollution New/shorter shipping routes Land-use competition from transport infrastructure

Based on a contribution of the author to IPCC 2014

The thesis stresses the point that Veto players need to be identified early on the policy process as they are political actors who have a distinctive institutional role in the policy process and have the legal power to put a hold to an initiative. Typical veto players are finance ministries and parliaments with legislative prerogatives. This is a substantially different role from stakeholders, who have a vested interested in a particular policy process, but do not have the (legal) power stop it. However, both groups need to be involved in the process to successfully implement a measure. Public participation can help ensuring durability and support beyond political parties. There is a causal relationship between policy objectives, agenda setting, institutional structures and policy outcomes (Tsebelis 2002, Lijphart 1984). The synergies explored in this paper provide a basis for the inclusion of veto players into the policy process, which is vital for the uptake of sustainable mobility policies. The table below aims to apply the veto players' approach to coalition formation to identify the links between policy objectives and policy actors (Table 2). This aims to highlight that politics and the policy environment play an important role in the uptake of policy measures.

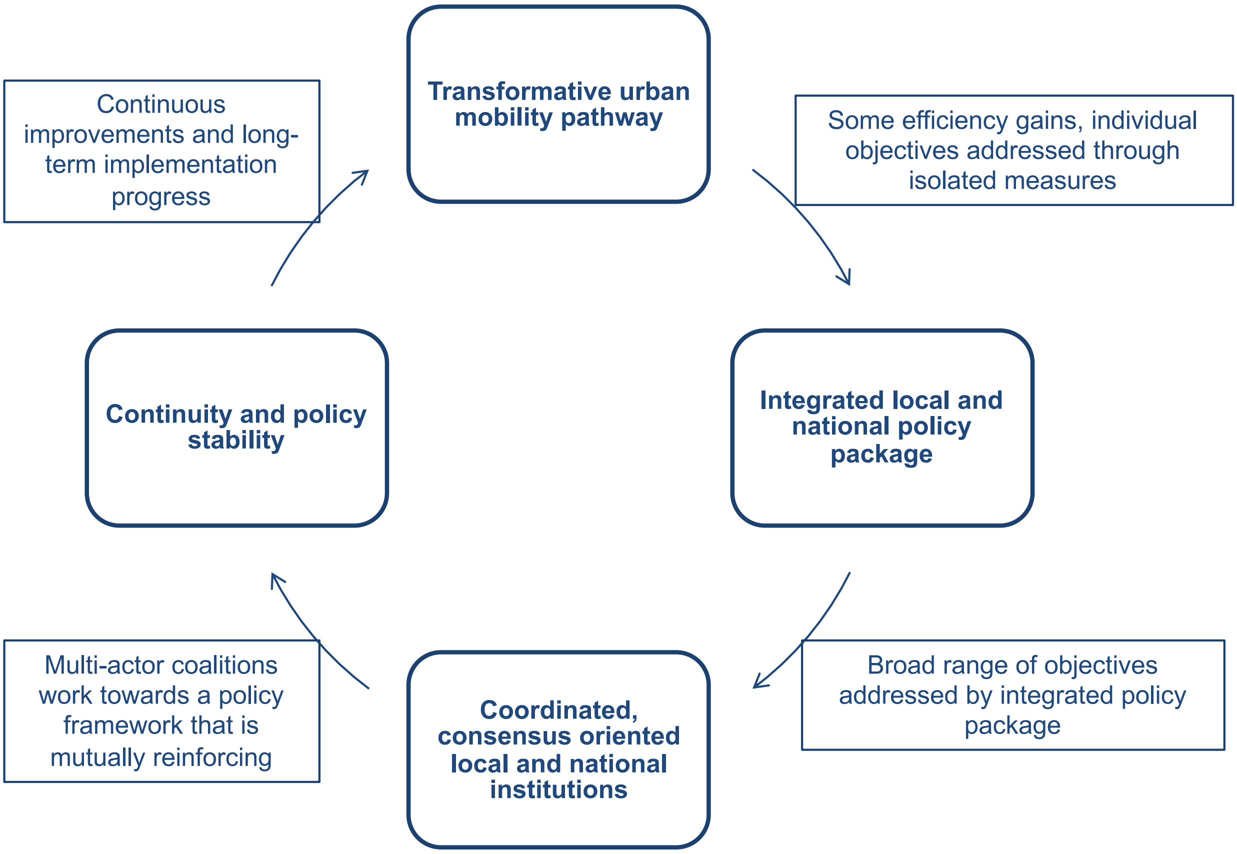
Table 2 Coalition building - examples of potential linkages between climate and other sustainable development policy objectives and actors

Climate change mitigation approach and objective	Economic implications and actors	Social implications and actors	Environmental implications and actors
Activity**: Avoid vehicle travel by reduced trip distances e.g. by developing more compact, mixed communities and telework.**	Reduced congestion: *Local authorities (v)* ↑ More efficient freight distribution: *Businesses and associations* ↑ *Economic development ministry (v)* ↑	Improved access and mobility *Social development ministry* ↑ Accident reductions *Health Ministry* ↑	Reduced land consumption *Local planning authority (v)* →
Structure**: Shift to low-carbon transport modes, such as public transport, walking and cycling**	Improved productivity due to reduced urban congestion and travel times across all modes *Local authorities (v)* ↑	Reduced exposure to air pollution Health benefits from shifts to active transport modes *Local authorities (v)* ↑	Ecosystem benefits due to reduced local air pollution. *Local environmental department & national ministry* ↑
Intensity**: Improve the efficiency of the vehicle fleet and use**	Reduced transport costs for businesses and individuals *Local authorities (v)* and Economic and Social development ministries ↑	Health benefits due to reduced urban air pollution *Health Ministry* ↑	Ecosystem and biodiversity benefits due to reduced urban air pollution *Local authorities (v)* ↑
Fuels**: Reduce the carbon content of fuels and energy carriers**	Improved energy security *Economic development Ministry* ↑ Reduce trade imbalance for oil-importing countries *Finance Ministry (v)* ↑	A shift to diesel can improve efficiency, but tends to increase air pollution *Health and Environment Ministries (v)* ↓	Potential adverse effects of biofuels on biodiversity and land-use *Environment and agriculture ministries (v)* ↓

The selection is not exhaustive and depends on the policy environment. Key: positive ↑ negative ↓ uncertain → , (v) potential Veto Player

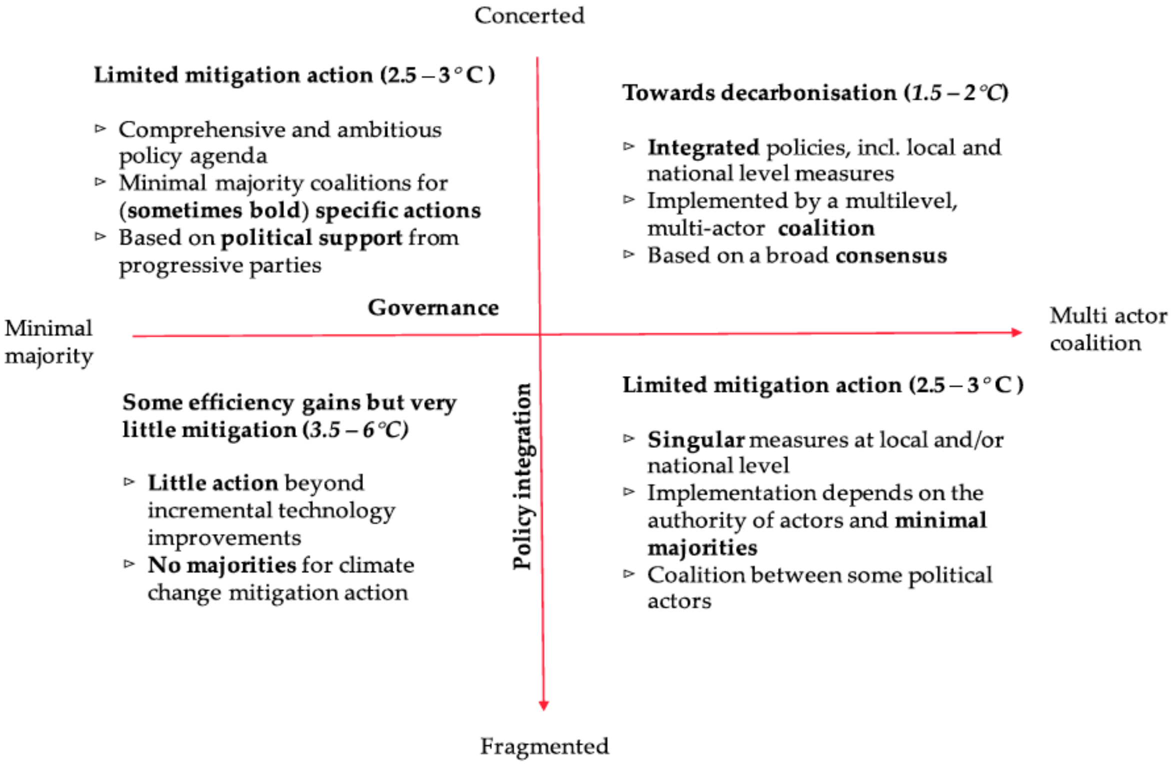
The mapping of key intervention and actors shows that urban passenger transport plays a particularly important role in the generation of co-benefits, e.g. by providing access to urban services, economic opportunities and social participation. The interdependencies of local and national policy provide a case for coordination among different levels of government and multi-level governance (Scharpf 1997; Bache and Flinders 2004), which adds another element to the policy and governance analysis of this thesis developed. The mapping of potential co-benefits and key political actors and their key policy objectives, helps showing that individual measures can only deliver limited efficiency gains and address individual objectives and that coordinated local and national action can trigger a greater range of co-benefits among policy objectives, which contributes to consensus and continuity (Figure 7).

Figure 7 Linking aspects in the transition cycle



When brining this together with the policy requirements of global decarbonisation scenarios for the transport sector the links between policy requirements, design and processes become even more obvious (Figure 8). This framework brings together all main findings of this thesis and aims to summarise the interaction between local and national policy interventions and actors and how an integration of both elements is needed to achieve decarbonisation scenarios. It shows that decarbonisation scenarios in line with the Paris Agreement can only be achieved by an approach that combines polices from the local and national level and provides a basis for coalitions among key actors. In contrast, individual actions will only contribute to incremental efficiency gains.

Figure 8 Policy and institutional integration framework (paper 4)



This framework helped identifying the main factors that affect the ability and need for policy integration and how this helps or hinders coalition building. The analysis aimed to make a contribution to a better understanding of the institutional context and the role policy integration and political structures play in generating policy outcomes. The analysis presented in the papers that comprise this thesis shows clearly that transport is a complex sector and that policy interventions can have unintended consequences, positive and negative as they rarely only affect one policy objective. Linking and packaging policies is therefore vital to generate synergies and co-benefits between measures. As identified in the papers developed for this thesis policy integration is vital to achieve stabilisation pathways that are in line with global climate change mitigation targets and they can also create the basis for coalition building if policy objectives of key stakeholders and veto players are taken into account.

2. Research gaps, research design and methodology

2.1 Decarbonisation scenarios and the role of urban mobility in the transformation of the transport sector

Global decarbonisation scenarios and integrated assessments models underestimate the role of urban form, modal shifts and changing travel patterns and their role to achieve wider sustainable development objectives along with the ability of a broader policy approach to potentially support coalition building of policy actors that represent these objectives (IEA 2012a; Edelenbosch et al. 2017; Roelfsema et al. 2018). This thesis aims to highlight role of different policy interventions in decarbonising the sector, but also in delivering on wider sustainable development benefits, which makes integrated policy design and a strong role of urban mobility a vital element to attract political support from key actors building on Jordan and Lenschow 2010 and van Vuuren et al. 2015.

The analysis of policy actions of recent assessments e.g. Yang et al. 2017; Sims et al. 2014 shows that there is a substantial gap between the mitigation action needed and the proposed policy actions by countries. This strengthens the case for policy intervention in a broader and more comprehensive manner as carried out in most countries as markets fail to deliver on the (socio-)economic potential of sustainable mobility measures (Jaffe, Newell, and Stavins 2005; Edelenbosch et al. 2017). Recent papers on transport climate policy fail to acknowledge the linkages between policy interventions and also the potential contributions to the formation of political and institutional coalitions (e.g. Cooper 2016; Antimiani et al. 2016; Zhang and Pan, 2016; Cassen and Gracceva 2016), which is the intended added value of this thesis. The analysis presented in this thesis shows aims to show the role of urban passenger transport in a 1.5°C warming stabilisation pathway and highlight the particular opportunities for co-benefits of sustainable urban mobility.

Urban passenger transport plays a particularly important role in providing access to urban services, economic opportunities and social participation and national policy frameworks manage to efficiency of the vehicle fleet and investment flows into transport infrastructure. The interdependencies of local and national policy provide a case for coordination among different levels of government and multi-level governance (Scharpf 1997; Bache and Flinders 2004), which adds another element to the policy and governance framework this thesis developed. Growing travel demand in developing economies as a vital component of economic development further boosts the role of transport on the local and national policy agenda. Several international assessments have analysed the technological potential and effort required to decarbonise the transport sector (Sims et al. 2014; International Transport Forum 2017). These analyses show that, moving on to a stabilisation pathway that is consistent with global climate change targets, transport needs to decarbonize substantially over the coming decades and almost entirely in industrialised countries by the middle of this century (IEA 2016, ITF 2017). Taking this path will unlock direct and indirect benefits that outweigh the costs, with savings of between USD 50 trillion and 100 in trillion in fuel savings, reduced vehicle

purchases, needed infrastructure and fuel costs (IEA 2014, 2016). The additional co-benefits and synergies generated by sustainable mobility, such as improved safety and air quality and reduced travel time make an even stronger case for the shift towards low-carbon transport, which is the guiding framework for the scenarios developed for this thesis. The contribution of countries to the global decarbonisation efforts of the transport sector and the role of urban mobility in this is reflected in the scenarios developed for this thesis that show travel demand, technology deployment and role of policy interventions and their effect on different scenarios.
From a climate change perspective vehicle technology and fuel switch options provide the biggest mitigation potential (Kahn Ribeiro and Figueroa 2012), but this does not fully reflect a broader sustainable mobility perspective. A broader multimodal approach will be applied for this thesis, which shapes travel demand through urban form and manages demand and modal shares, It is suggested in this thesis that such an approach will yield important benefits in air quality, traffic congestion, safety and overall societal mobility that may trigger substantially higher socio-economic co-benefits and the provide the basis for political coalitions between key local and national policy actors, which is considered to be the main contribution to the literature of this thesis. From the perspective of global decarbonisation scenarios it is vital for this thesis to show the necessity of policy approaches that go beyond a pure technology shift in transport and which include a strong role of urban design and modal shift.
The mitigation potential of a number of local and national transport policies has been well-established, e.g., shift to public and non-motorized transport and efficiency improvements of internal combustion engines (Sims et al. 2014; Kok, Annema, and van Wee 2011; Wright, Fulton 2005; Macchion et al. 2015). However, a more integrated view that combines technology shifts potential in a balanced perspective to the wider sustainable development approach is required to highlight the role of different levels of intervention, in particular urban mobility, which is considered to be a major area for potential co-benefits. This analysis will focus on the question: *What is the role of urban mobility in the transition towards a low-carbon transport sector and how can mitigation pathways provide the basis for co-benefits and synergies among key policy objectives?*

2.2 The potential of co-benefits and its role as basis for coalitions

It is often claimed that transport is one of the hardest sectors to decarbonise (Vale 2016; Cai et al. 2015; van Vuuren et al. 2015). This view is challenged by a number of more recent papers, which show that an integrated policy approach can address create synergies with other key policy objectives, such as health, productivity, energy security and safety, which can lead to a maximum of socio-economic benefits (Bollen 2015; Dhar and Shukla 2015; Schwanitz et al. 2015; Dhar, Pathak, and Shukla 2017). This thesis builds on this and focuses on the synergies between policy objectives and how this may hold the potential to incorporate the positions of relevant political actors, which can help forming coalitions to support policy implementation, which is often neglected in studies on the decarbonisation potential of the sector. Jänicke, Schreurs, and Töpfer 2015 emphasise that climate actions should take advantage of co-benefits, to build coalitions of government, business and civil society actors operating at all levels of the global multi-level system of climate governance. This part of the thesis translates this concept into a policy mix that helps addressing key objectives for political and societal actors.

Policy agenda setting and policy design are affected by the policy environment, which is a result of political and institutional relationships (Fankhauser, Gennaioli, and Collins 2015; Marquardt 2017). These relationships, including the interactions between different levels of government (e.g. local, state, federal, supra-national) and recognition of different policy objectives varies greatly between key political and societal actors (Never and Betz 2014). The policy environment, or context in which decisions are made, is as important as the combination of policy decisions and infrastructure investments that make up a low-carbon transport strategy (Justen, Schippl, et al. 2014). This policy environment includes socio-economic and political aspects of the institutional structures of countries. These structures help building coalitions if the proposed policy mix addresses key policy objectives, but can also increase the risk that a policy package fails because one measure faces strong opposition (Sørensen, Hedgaard, et al. 2014). A core element of success is the involvement at an early stage of potential veto players and the incorporation of their policy objectives in the agenda setting (Tsebelis and Garrett 1996), which provides opportunities for broader coalitions that help to make decarbonisation strategies resilient to political change.

If applied in isolation policy measures are unlikely to achieve goals without generating trade-offs that create a risk of a veto player blocking the implementation process. For example, increased fuel taxes, without the provision of modal alternatives and measures to ensure a supply of efficient vehicles, would impact negatively on mobility and transport affordability (Greene, D.L., Patterson, P.D., Singh, M., Li 2005; Sterner 2007), which could result in relevant veto players blocking this initiative (Tsebelis 2000). However, a balanced and integrated policy approach combines measures such as vehicle efficiency standards, fuel tax, differentiated vehicle taxes with the provision of modal choices and compact city design, has the potential of addressing policy objectives that can ensure relevant actors (including veto players) support the implementation, which is the main focus of the second part of this thesis that provides answers on the question:

What is the potential of co-benefits and synergies between key policy objectives and how would an integrated policy strategy need to be designed to un-lock this potential and address policy objectives of key actors?

2.3 Institutions at the local and national level and pathways towards an integrated, multilevel governance structure

Parts I and II of this thesis focus on the role of local and national policies and their ability to deliver co-benefits and synergies among policy objectives. This will be complemented by an analysis of institutional settings that enable a broader consensus on the need for policy intervention and provide the basis for a strategic, coherent, and stable operating environment. Policy interventions in the transport sector, such as fuel and vehicle taxation, and transport infrastructure are highly visible and politically sensitive. They require a strong political commitment to appear on the policy agenda and to remain in place as they rely on investments that are only cost-effective over the medium to long-term (IEA 2010a; IPCC 2014a). In particular at the local level, transport infrastructure projects are highly visible as they have the potential to shape cities substantially, which makes these projects politically very sensitive. To set clear and reliable political signals taxation and regulatory measures require policy stability to enable long-term investment planning by industry and individual transport users.

Individual transport policy interventions can have unintended consequences, which makes a broader policy approach essential to avoid trade-offs and address policy issues that are relevant for key political and societal actors. This part of the thesis builds on the key features of majoritarian and consensus oriented systems (Lijphard 1999) and aims to show the link between the policy design and consensus building.

Consensus oriented political institutions as outlined by Lijphart and Crepaz (1991, 1996) may lead to higher levels of policy continuity, which in turn would have positive effects for the success of climate change mitigation strategies in the transport sector. This approach also adopts the theoretical concept of “encompassing organisations” (Olson 1982) and examines the relationships between political and societal actors and their ability or inability to negotiate policies that are based on broad majorities in both, politics and society. Lijphard and Crepaz (1991, 1996) and Lijphart (1999) provide conceptual frameworks and supporting evidence that, governments with consensual, inclusive, and accommodative constitutional structures and wider popular cabinet support act more politically responsible than more majoritarian, exclusionary, and adversarial countries. The strong interlinks between industry, banks, government and non-governmental organisations in coordinated market economies are considered to cause inertia, but also can result in continuity and policy stability, which provides the basis for the analysis of transport policy continuity (Amable 2003; Hall and Soskice 2001; Schmidt 1982; Streeck and Yamamura 2001; Whitley and Hedesstrom 2000).

Based on these concepts the third part of the thesis aims to bridge the gap between policy requirements derived from the scenarios and pathways, the role and impact of policy interventions and the influence of the policy environment and the political institutions on the implementation of policy action, which will aim to provide an answer to the question:

Which institutional features at the local and national policy level are relevant when designing urban mobility measures in order to utilize the potential of co-benefits and move towards a low-carbon transition path?

2.4 Methodology and paper structure

This study focuses on a specific policy area to disentangle drivers that influence policy development and outcomes. The approach this thesis takes also highlights the nuances in political attitudes, policy makers' objectives and responsibilities, and aims to demonstrate causal connections between policy design, process and outcomes. Institutional factors were compared to a number of energy and climate indicators for a selection of countries for a high level analysis. This will highlight contextual clusters for a more in depth analysis in the case study to examine in institutional arrangements and their impact on policy process and outcomes. The second part of the thesis will then look more closely at the role of co-benefits and their ability to enable coalitions among key institutional players. This will shed light on the relationship between policy design, processes and institutions at the local and national level, which will help to get a better understanding of the feasibility of decarbonisation pathways. Linkages between low-carbon, sustainable development pathways, policy design and governance factors will be examined, which will be guided by key concepts for each thematic area and respective research questions outlined below. Following this structure this thesis is comprised of peer-reviewed papers (2 single authored, 2 co-authored) that deal with specific aspects of the conceptual framework. The table below briefly summarises the logical flow of the three parts of this thesis and their respective papers as well as the key messages for each step.

Table 3 Questions, methods and results from this thesis

Decarbonisation scenarios and the role of urban mobility in	The potential of co-benefits and its role as basis for coalitions	Institutions at the local and national level and pathways

the transformation of the transport sector		**towards an integrated, multilevel governance structure**
Key questions		
What is the role of urban mobility in the transition towards a low-carbon transport sector and how can mitigation pathways provide the basis for co-benefits and synergies among key policy objectives?	What is the potential of co-benefits and synergies between key policy objectives and how would an integrated policy strategy need to be designed to un-lock this potential and address policy objectives of key actors?	Which institutional features at the local and national policy level are relevant when designing urban mobility measures in order to utilize the potential of co-benefits and move towards a low-carbon transition path?
Papers		
Transport Pathways towards a 2 Degree Scenario, *Sustainability*	Integrating global climate change mitigation goals with other sustainability objectives: a synthesis, *Annual Review of Environment and Resources* Sustainable development synergies and their ability to create coalitions for low-carbon transport measures. *Transportation Research Procedia*	Continuity and Change: Dealing with Political Volatility to Advance Climate Change Mitigation Strategies, *Sustainability*
Methodologies		
Development of quantitative scenarios and comparative sensitivity cases	Literature review, quantification of co-benefits and development of a conceptual framework to identify policy objectives and related political actors.	Semi-structured interviews with local and national government officials and surveys among officials and transport policy experts
Key findings		
Decarbonising the transport sector requires concerted action incl. planning, modal shift, technology and fuels. Isolated measures as in place in most countries will fall short delivering on climate and wider sustainable development objectives.	There is a wide range of benefits that can be un-locked by sustainable mobility. Isolated measures are likely to create trade-offs, which may create opposition from potential veto-players. Integrated policy packages can be a basis for broad coalitions.	The presence of consensus oriented institutions can support the formation of coalitions and support continuity. Consensus oriented societies are more likely to take into account policy objectives from a wider group of political and societal actors.

This thesis combines several methodologies to provide an integrated view on the decarbonisation of the transport sector based on scenarios, policy analysis, regression analysis, assessments of institutional indicators and interviews with experts and practitioners. The thesis assessed the quantitative basis potential climate change mitigation pathways and then looked into policy and institutional aspects that relate to the feasibility of these pathways. This combination of quantitative and qualitative analysis to measure the potential, options and feasibility of climate change mitigation strategies in a particular sector aims to synthesise perspectives on the subject that help understanding the strong relationship between policy design, coalition building and the ability to create long-term support for the transition towards low-carbon and sustainable transport systems.

The following section outlines the main approach and methodologies for the papers comprising this thesis.

Decarbonisation scenarios and the role of urban mobility in the transformation of the transport sector (Part I)

What is the role of urban mobility in the transition towards a low-carbon transport sector and how can mitigation pathways provide the basis for co-benefits and synergies among key policy objectives?

The first papers analyses current scenarios and develop sensitivity cases to highlight the interlinkages between different aspects of a decarbonisation strategy for the transport sector, which provides the quantitative basis for the assessment of the role of policy packaging in the co-benefits part of the thesis.

Paper 1 assesses the mobility demand and efficiency gains, to show the role of technological solutions and urban design and modal shift options. This aims to highlight need for transformative changes the transport sector and highlights the importance of policy intervention at the local and national level. The analysis carried out for in this paper builds on a range of assessments of the climate change mitigation potential of the sector, i.e. the GEA 2012; IPCC 2014; IEA 2013; ITF 2013 and applies their data in different quantitative scenarios that aim to provide a coherent picture of the role various local and national policy options. This scenario analysis will aim to provide a quantitative perspective on the role of mixed-use city design, high capacity public transport system, efficient logistics solutions, fuel efficiency and fuel switch options in achieving climate change mitigation targets and Sustainable Development Goals.

The paper shows that developed countries will have to rapidly decarbonise their transport sector over the coming decades (-80% by 2050) and developing and emerging countries will have to curb growth (+70% by 2050), which will require substantial policy action. The scenarios developed for this paper identify the role technological innovation and compares this with actions focusing on urban form and modal shifts, which challenges more technology driven perspectives such as Bolton and Hannon 2016; Fox, Axsen, and Jaccard 2017; Golob et al. 1993; Eppstein et al. 2011. The sensitivity cases developed for this paper aim to provide a policy relevant perspective in different intervention options. The assumptions applied to the scenario development build on the ranges of potentials of different interventions summarised in the Fifth IPCC Assessment Report (Sims et al. 2014) and shows the interdependencies, but also the technical feasibility and cost-efficiency of strategies that rely on individual measures as opposed to a broad integrated approach.

The development of alternative scenarios provides different perspectives on possible futures and allows the identification of key elements in the transition path that are relevant for the policy design and governance. The methodology for this paper builds on the scenario typologies outlined by van Notten et al. 2003 and focuses on an assessment of the feasibility and desirability of different paths for policy interventions to guide decision making. In order to achieve this a back casting scenario was developed based on transport emissions data from the International Energy Agency (IEA 2012a). Greenhouse gas emission reductions were calculated for a development path until 2050 that would be in line with a 2 Degree Celsius warming scenario as outlined in the Fifth IPCC Assessment Report (Edenhofer et al. 2014). Based on this global scenario sensitivity cases were developed to highlight regional differences between developing and industrialised countries and to show the interlinkages between different types of policy interventions, in particular, the role of urban planning and design, public- and non-motorised transport as well as vehicle technologies and fuels. This analysis reflects on the scenarios developed by the International Energy Agency and challenges the overemphasis on vehicle technologies and fuels of these scenarios, which are used widely as a quantitative basis for energy and transport policy decisions.

The paper shows the relevance of a broader approach to the decarbonisation of the transport sector with a much stronger role of urban planning and public transportation, which leads to a more cost-effective climate change mitigation strategy for the sector, but also addresses wider socio-economic objectives and generates synergies and co-benefits among them. This aims to provide the quantitative basis for policy action and show the relevance of a coordination of measures within urban and national transport policy from the perspective of the decarbonisation of the sector.

The potential of co-benefits and its role as basis for coalitions (Part II)

The two papers developed for the second part of this thesis deals with the question:

What is the potential of co-benefits and synergies between key policy objectives and how would an integrated policy strategy need to be designed to un-lock this potential and address policy objectives of key actors?

This thesis aims to go beyond the economic or technical feasibility of measures to decarbonise the transport sector. It aims to identify the interactions between pathways, policy design and institutions at different levels. For this it draws on the concepts of policy mix and integration and co-benefits of environmental policy and shows the interdependencies of these aspects. "Policy mixes are complex arrangements of multiple goals" (Kern and Howlett 2009). From the perspective of this thesis the design of this policy package is considered to be a vital determining factor for policy outcomes, which will be analysed in the other parts of this study.

Paper 2 carries out an extensive literature review, building on the co-benefits chapters of the 5th IPCC Assessment Report (IPCC 2014). This article reviews and synthesizes results from disparate strands of literature on the co-effects of mitigation to identify policy levers for different political actors. The paper summarises the many potential co-benefits of mitigation for non-climate objectives, such as human health and energy security, but little is known about their overall welfare implications. Integrated assessment model studies highlight that climate policies as part of well-designed policy packages reduce the overall cost of achieving multiple sustainability objectives, which provides a strong narrative for an integrated policy approach that support the policy objectives of various political actors.

The design of the policy mix to address all relevant policy objectives identified in paper 2 reflects on three strategic components: the inclusion of a strategic component, the incorporation of associated policy processes, and the consideration of characteristics of policy mixes (Rogge and Reichardt 2013).

Paper 3 identifies some of the key measures at the local and national level, which yield a particularly high level of efficiency gains and socio-economic benefits and stresses the challenges of the collective action problem (Olson 1965) that affect the wide-spread take-up of low-carbon transport technologies and behaviour. It also highlights the potential for rebound effects (Sorrell 2009) that affect the effectiveness of individual policy interventions. Paper 3 also identifies the opportunities of an integrated policy approach to sustainable transport and identifies potential contributions to coalitions building. This is a vital element in the conceptual framework of this thesis as it creates the link between policy ambition, integration and the potential for coalition building. Practical examples of low-carbon transport policy measures are provided along with quantified co-benefits for key policy objectives and a mapping of institutional actors and potential veto players is proposed. The paper provides a concise overview on potential co-benefits of a selection of specific measures to highlight the contribution of sustainable transport measures to economic, social and environmental policy objectives, which provides the basis for the identification of key policy actors and veto-players. This builds on Jänicke, Schreurs, and Töpfer 2015 and their call for co-benefits as policy lever for broader coalitions.

The analysis of these papers aims to show the institutional opportunities for the take-up of low-carbon transport measures, and shows the potential of policy integration and the opportunities for coalition building associated to this. The papers developed for this part of the thesis assessed the requirements for low-carbon transport policy, the capacity of different political institutions and the link between policy integration and coalition building. This analysis provides a basis for the assessment of the political feasibility of the implementation of a comprehensive strategy to decarbonise the transport sector, which aims to provide insights on the prospects of decarbonising the sector. It shows that isolated policy or technology measures implemented by individual policy actors or minimal political majorities will fall short of bringing the transport sector on a low-carbon development path.

With that the thesis aims to identify the critical linkages between policy design and policy objectives of key political actors in order to operationalise some key political science approaches and apply them in a specific policy area in one specific sector (part III).

Institutions at the local and national level and pathways towards an integrated, multilevel governance structure (Part III)

This part of the thesis deals with the question: *What institutional framework creates sufficient political stability and continuity to support coordination between the local and national policy level and foster the long-term transition towards a sustainable transport system?*

To provide an answer to this question the third part of the thesis provides a combined perspective of a multi-criteria analysis, interviews with policy advisors and policy analysis to test the applicability of institutional in the context of low-carbon transport policy. This allowed an assessment of institutional relationships that goes broader than isolated approaches that have been used in many previous studies, which aim to relate particular institutional features to high level socio-economic indicators.

Paper 4 applies the approach of consensus oriented political institutions as outlined by Lijphart and Crepaz (1991, 1996) and assesses how these structures may lead to higher levels of policy continuity, which in turn would have positive effects for the success of climate change mitigation strategies in the transport sector. This approach also adopts the theoretical concept of “encompassing organisations” (Olson 1982) and examines the relationships between political and societal actors and their ability or inability to negotiate policies that are based on broad majorities in both, politics and society. Lijphard and Crepaz (1991, 1996) and Lijphart (1999) provide conceptual frameworks and supporting evidence that, governments with consensual, inclusive, and accommodative constitutional structures and wider popular cabinet support act more politically responsible than more majoritarian, exclusionary, and adversarial countries. These concepts were reflected in a survey and interviews (23) with experts from the US, EU (and several member states), Brazil, Mexico, India and China. This informed the analysis of institutional structures in relation to policy and processes and their impact on sustainable development and transport policy. The objective of this paper then to draw conclusions on the role of policy coordination among organised interests and how this can facilitate policy integration and generate co-benefits that enable the long-term transition towards low-carbon urban development and mobility.

The policy analysis then covered a selection of major developed and emerging countries and their progress on key low-carbon transport policies, which is followed by the development of a policy integration and governance framework. This combination of quantitative and qualitative analysis of mitigation potential, opportunities for co-benefits and coalitions with a focus on the transport sector goes beyond the state of the art as most studies in this field focus on one of these aspects often at an economy wide-scale. Exploring the potential role of institutional aspects aims to provide an insight into the policy environments in selected countries, which are vital for the success of global climate change mitigation efforts. A factor that was considered to be critical to analyse the link between policy integration and coalition building.

The objective of this research was to identify some of the main factors that affect policy implementation in the area of sustainable transport and develop a framework that can guide the policy development and coalition building. The following sections summarise some of the key findings of each paper and their contribution to the overall concept of this thesis.

3. Key findings and analysis

3.1 Overall findings and synthesis

The climate change mitigation potential assessments manage to show the relationship between the fuels, and technology elements and the planning, and model shift aspects of a decarbonisation pathways for transport (paper 1: Lewis Fulton, Lah, and Cuenot 2013). This goes beyond a number of case studies that provide indications on individual costs and benefits of specific measures (Doll and Jansson 2005; Creutzig and He 2009; Pathak and Shukla 2016; Jacoby, Minten 2009).

The main message from decarbonisation scenarios is that light-duty vehicle (LDV) travel will need to change rapidly in industrialised countries and shift towards more efficient vehicles technologies and more efficient modes of transport. In industrialised economies a reduction of car travel between 4 to 37% combined with average vehicle fuel efficiency (reduction in energy/km) of between 45 to 56% would be required to achieve the desired reduction of 73-80% to be roughly in line with an emission reduction pathway for a 2°C stabilization scenario as suggested by the IPCC (Sims et al. 2014). In developing and emerging countries, light-vehicle travel per capita has still a potential to grow even under a low-carbon development scenario by around 130 to 350 % if accompanied by fuel efficiency and carbon intensity gains of 40 to 50% (paper 1). One vital aspect of the thesis is the factor policy integration, which is needed to achieve sustainable development goals and global climate change goals. This has been tested in scenarios and pathways specifically developed for this thesis. The quantitative analysis carried out builds on the International Energy Agency's data and develops sensitivity cases to highlight the role of an integrated policy approach in the transport sector (IEA 2012a, 2012b; Fulton, Cazzola, and Cuenot 2009).

Papers 2 and 3 (von Stechow et al. 2015; Lah 2017) show that linking and packaging policies is vital to generate synergies and co-benefits between measures, including linking GHG reduction goals with other sustainable development goals, such as increasing energy security, road safety, public health, increasing economic productivity and air pollution, and improving equity and access, but also highlight the linkages to governance issues which goes beyond other recent studies in this areas (e.g. Kanda, Sakao, and Hjelm 2016; Wen et al. 2016). A survey and interviews carried out for this thesis among local and national policy advisors in Europe, Asia, Africa and the Americas shows that the lack of funds, lack of suitable technologies and also public opposition are not considered to be the main barriers for the take-up of sustainable transport measures. The largest barriers for the sustainable transport policy action are insufficient knowledge of the various benefits of sustainable mobility, in particular among political decision makers and institutional barriers that directly affect the implementation process. Knowledge about the potential co-benefits of sustainable transport policy can help aligning different policy actors and institutions, which can be a focus area for capacity building activities in particular in emerging economies.

An integrated policy approach creates consensus and coalitions among diverse stakeholders and interests can help to overcome implementation barriers, minimize rebound effects, and motivate people, businesses, and communities. This type of integrated policy approach is especially critical because current GHG reduction measures alone can make important contributions but cannot achieve the levels of reduction needed to shift to a 1.5°C pathway. Considering these findings of the first two parts of this thesis, that all measures are needed to bring transport on track towards decarbonisation and that integrated transport policies have a great potential for co-benefits, the third part of this thesis aims to translate this into a governance approach that creates coalitions among key political actors.

Several papers assess the emission reduction potential of measures but fall short of identifying the relevance of policy design and integration. The potential for synergies and co-benefits generated by an integrated policy approach and the link to potential coalitions among key veto players is considered to be a vital link between policy design and political institutions that is often neglected.

Decision making on transport policy and infrastructure investments is as complex as the sector itself. Rarely will a single measure achieve comprehensive climate change impacts and also generate economic, social and environmental benefits. Many policy and planning decisions have synergistic effects, meaning that their impacts are larger if implemented together. It is therefore generally best to implement and evaluate integrated programs rather than individual strategies. For example, by itself a public transit improvement may cause minimal reductions in individual motorized travel, and associated benefits such as congestion reductions, consumer savings and reduced pollution emissions. However, the same measure may prove very effective and beneficial if implemented with complementary incentives, such as efficient road and parking pricing, so travellers have an incentive to shift away from individual car travel. In fact, the most effective programs tend to include a combination of qualitative improvements to alternative modes (walking, cycling and public transit services), incentives to discourage carbon-intensive modes (e.g. fuel pricing, vehicle fuel efficiency regulation and taxation), and integrated transport and land use planning, which creates more compact, mixed and better connected communities with less need to travel.

A vital benefit of the combination of measures is the ability of integrated packages to deliver synergies and minimise rebound effects. For example, the introduction of fuel efficiency standards for light duty vehicles may improve the efficiency of the overall fleet, but may also induce additional travel as fuel costs decrease for the individual users (Yang et al. 2017). This effect refers to the tendency for total demand for energy decrease less than expected after efficiency improvements are introduced, due to the resultant decrease in the cost of energy services (Sorrell 2010; Gillingham et al. 2013, Lah 2014). Ignoring or underestimating this effect whilst planning policies may lead to inaccurate forecasts and unrealistic expectations of the outcomes, which, in turn, lead to significant errors in the calculations of policies' payback periods (IPCC 2014). The expected rebound effect is around 0-12% for household appliances such as fridges and washing machines and lighting, while it is up to 20% in industrial processes and 12-32% for road transport (IEA 2013). The higher the potential rebound effect and also the wider the range of possible take-back, the greater the uncertainty of a policy's cost effectiveness and its effect upon energy efficiency (Ruzzenenti and Basosi 2008a).

The current approach to transport policy and infrastructure appraisal that does not take fully into account the wider socio-economic benefits of sustainability mobility (Hüging, Glensor, and Lah 2014), which creates a case for evidence based policy making (Godfrey 2001).While emission reductions can be achieved through several means, such as modal shift, efficiency gains and reduced transport activity, it is apparent that the combination of measures is a key success factor to maximise synergies and reduce rebound effects. For example, overall travel demand reduction and modal shifts would need to be substantially stronger if not accompanied by efficiency improvements within the vehicle fleet and vice-versa.

The political environments can vary by country and change over time, which affects implementation of sustainable transport and other climate change mitigation measures and results in significant differences between countries' progress reducing GHG emissions from the transport sector, which is the main focus for paper 4. For this analysis the paper builds on a number of studies examining the influence of the concepts of institutions and actors within the policy process (for example: Haas 1992, 1999; Jahn 1998; Scruggs 1999, 2001; Jänicke 2002; Tsebelis 2002; Neumayer 2003; Bernauer & Koubi, 2009). The main focus of this analysis is the (potential) support from diverse political and institutional actors, which is considered to be vital for the long-term success of policy and infrastructure decisions. Based on the literature and on a set of criteria (paper 4), the thesis argues that in countries with corporatist institutional structures major policy issues such as sustainable development and transport policy are negotiated in a concerted effort by organised interests, which is likely to take longer than in majoritarian systems, but with a higher probability of remaining in place even if governments change. Policy coordination among organised interests facilitates policy outcomes that normally endure, which may often take more time, however, to form broad societal coalitions that include all relevant actors and stakeholders. According to this, a high level of corporatism may influence the implementation and improvement of policies with a long-term focus. There are a number of elements which may support this, for example: comparatively encompassing interest groups, a consensual social partnership, the 'shadow of state regulation' and a broad acceptance of government regulation due to a history of strong penetration of the state in areas such as the labour market and social policy (Scruggs 1999). Interest groups are integrated into the policy process in a corporatist country and broaden the basis of policies, which creates a high level of continuity that is required for long-term investments. This coalition building locks groups into certain policy directions that further enhance policy progress, which is almost self-reinforcing (Katzenstein 1977, 1978), which reflects the case of transport policy integration that has been outlined in this thesis and provides a direct link between policy design and the local and national political institutions that implement them.

3.2 Paper 1: Transport Pathways for Light Duty Vehicles: Towards a 2° Scenario

The paper Fulton, L. Lah, O., Cuenot, F., (2013) provides an overview on the decarbonisation pathways for different world regions, highlighting the interrelation of the three main pillars of sustainable transport policy – avoiding unnecessary travel, shifting to lower carbon modes and improving the efficiency of the fuels and vehicles. This paper highlights that only a few high-level climate change mitigation potential assessments manage to show the relationship between the fuels, and technology elements and the planning, and model shift aspects of a decarbonisation pathways for transport and it makes a contribution to this perceived lack in the current body of literature. The main message from decarbonisation scenarios developed in this paper is that light-duty vehicle (LDV) travel will need to change rapidly in industrialised countries and shift towards more efficient vehicles technologies and more efficient modes of transport. As decarbonisation scenarios for the transport sector show, all transport policy measures are needed to achieve a long-term stabilisation path for the sector (Figure 9).

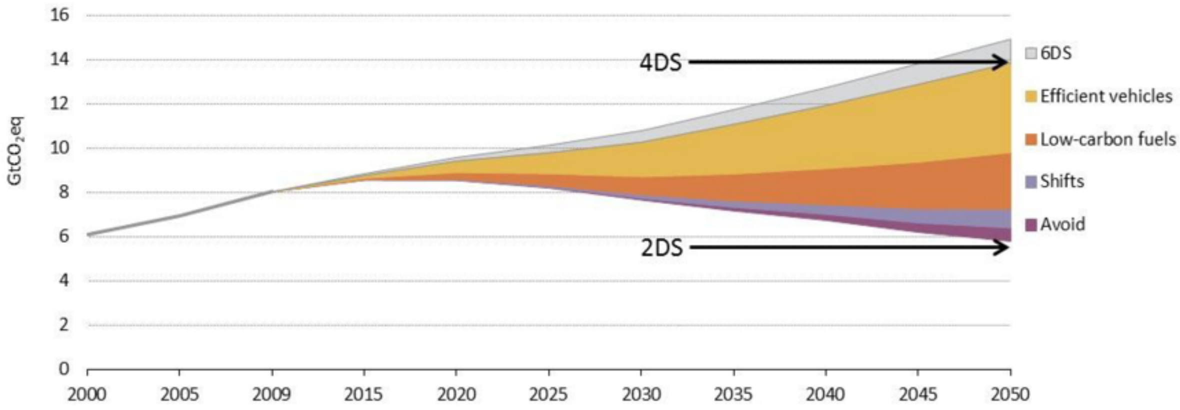


Figure 9 Energy Technology Perspectives (ETP) results for global well-to-wheel greenhouse gas emissions mitigation potential from the transport sector for a 4° and a 2° scenario

The analysis for this paper that builds on the scenarios developed by the International Energy Agency, highlights that in industrialised economies a reduction of car travel between 4 to 37% combined with average vehicle fuel efficiency (reduction in energy/km) of between 45 to 56% would be required to achieve the desired reduction of 73-80% to be roughly in line with an emission reduction pathway for a 2°C stabilization scenario as suggested by the IPCC (Figure 10).

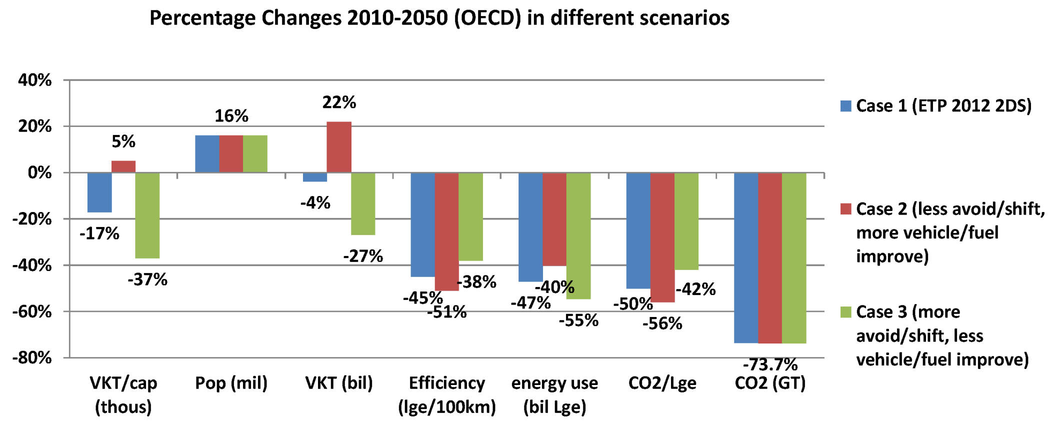


Figure 10 Light vehicle fleet scenarios until 2050 in OECD countries.

In developing and emerging economies low-carbon path would look slightly different whereas light-vehicle travel per capita triples in 2DS case while fuel efficiency and carbon intensity both improve by 40%, leading to a net increase in CO2 of 65% by 2050. Considering that emissions in non-OECD countries would more than tripling without any major additional mitigation strategies, this would be a substantial reduction from the baseline. The two sensitivity cases developed for this paper aim to achieve the same target via different approaches. Case 2 allows for travel growth, which means that efficiency and fuel carbon will have to improve by 50% instead of 40%. The lower growth in car travel achieved through sustained high levels of public and non-motorized transport in Case 3 requires lower efficiency and fuel switch, at 30% instead of 40% (Figure 11).

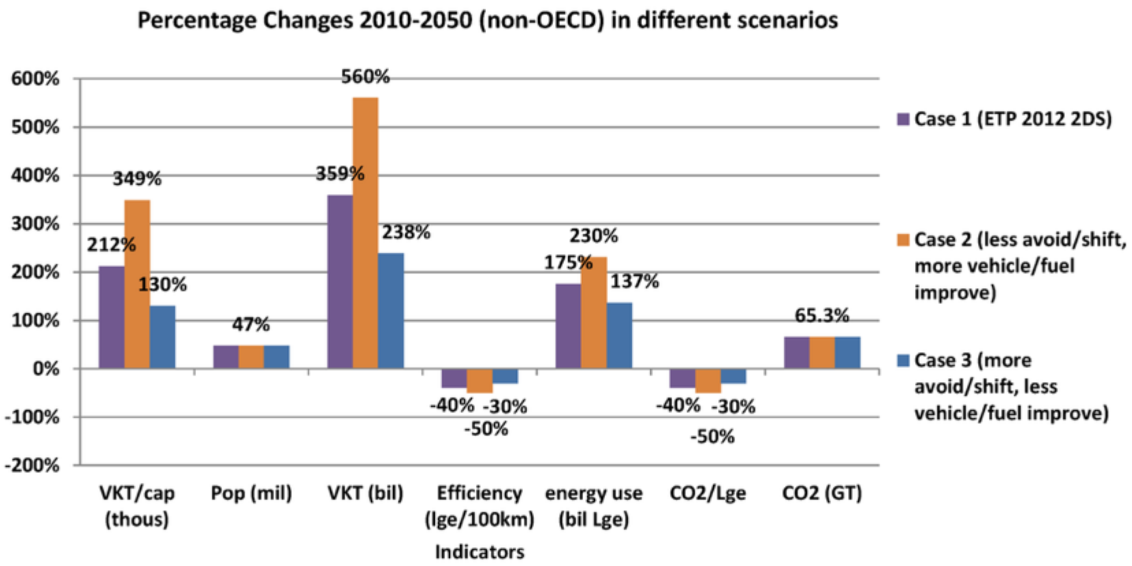


Figure 11 Light vehicle fleet scenarios until 2050 in non-OECD countries.

The analysis presented in this paper shows very clearly that individual policies or technologies are not a feasible scenario to decarbonise the transport sector. The sensitivity cases developed for this paper show that the efficiency gains needed in a technology focused approach require rapid improvements in vehicle technology and a high level of take-up of alternative fuels and energy carriers, which is not likely to be achievable and would be associated with substantially higher costs. Similarly, the stronger focus on low-carbon modes and demand management would affect reduce mobility substantially and would require a major increase in public transport infrastructure.

Isolated perspectives on the theoretical potential of certain transport technologies (e.g. electric drive-trains) to address individual policy objectives (e.g. climate change) will fall short of addressing the policy challenges the sector phases, which is considered to the main contribution of this paper to the literature as it differs other major assessments for the sector e.g. (IEA 2012a; International Transport Forum 2017; IEA 2011, 2010b)

While the first paper shows clearly that low-carbon transport needs to take an integrated policy approach to deliver on wider sustainable development objectives, this second paper quantifies this by developing decarbonisation scenarios that highlight the interaction of different elements of the low-carbon transport policy package. Pure technology-shift options for example from internal combustion powered cars to electric cars will only deliver on some policy objectives s shown in the cases developed for this paper. This is also reflected in the key messages of the

Fifth IPCC Assessment report to which the paper authors have contributed. The analysis presented in the paper highlights the fact that a focus on technology transitions falls short of recognising the wider socio-economic benefits of a more integrated policy approach. This aims to provide a holistic picture compared to the many technology oriented studies in this area e.g. Steinhilber, Wells, and Thankappan 2013; Hackney and de Neufville 2001; Nilsson and Nykvist 2016; Golob et al. 1993; Eppstein et al. 2011; Baptista, Tomás, and Silva 2010.

3.3 Paper 2: Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis

The paper (von Stechow, et al. 2015) takes a broader perspective on the potential benefits of integrated climate change mitigation strategies strengthening the case of policy integration even further and highlighting the political relevance for a comprehensive climate change mitigation policy approach. The paper shows that achieving a truly sustainable energy transition requires progress across multiple dimensions beyond climate change mitigation goals.

The paper reviews and synthesizes results from disparate strands of literature on the co-effects of mitigation to inform climate policy choices at different governance levels. The literature documents many potential co-benefits of mitigation for non-climate objectives, such as human health and energy security, but little is known about their overall welfare implications. Integrated model studies highlight that climate policies as part of well-designed policy packages reduce the overall cost of achieving multiple sustainability objectives. The uncertainties around the quantification of some of the co-effects can become increasingly pervasive the more the perspective shifts from sectoral and local to economy wide and global, the more objectives are analysed, and the more the results are expressed in economic rather than nonmonetary terms. Different strings of evidence highlight the role and importance of energy demand reductions for realizing synergies across multiple sustainability objectives.

The paper highlights that transport is relatively unique among the energy end-use sectors as it depends on petroleum products to 94%, with natural gas, biofuels and electricity making up the small rest (Sims et al. 2014). However, the modes with which people and freight are transported vary greatly with regard to their energy intensity, ranging from walking and cycling to shared modes, such as public transport to car and truck based road transportation, rail, waterborne transport and aviation. The choice of modes, technologies and fuels influences heavily the potential externalities of passenger and freight transport. Air quality, safety, energy efficiency, access to mobility services and other factors that are considered to be co-benefits of sustainable transport measures from a climate change perspective are in fact often the driving factors for policy intervention, in particular on the local level.

Energy security is a major issue for the sector in particular from a national policy perspective (Cherp et al. 2012; Costantini et al. 2007; Steve Sorrell and Speirs 2009). While there is a direct link between energy security and mitigation actions, not all actions to reduce fuel consumption automatically generate positive co-benefits for other objectives. For example, fuel switching and propulsion technology-based options, such as biofuels and electrification can potentially result in co-benefits for energy security, but may also affect land-use change (biofuels) or increase carbon-intense electricity demand (e-mobility). Moreover, isolated technology-oriented strategies, do not yield the potential to generate as many co-benefits for other objectives as many demand-side measures do (Creutzig, Mühlhoff, and Römer 2012). For example, fuel efficiency, shifts to more efficient transport modes and compact urban design can improve energy security (Leung 2011; Cherp et al. 2012; Sovacool and Brown 2010) as well as access to mobility services and reduce transport costs, which affects positively productivity and social inclusion (Banister 2008; Miranda and Rodrigues da Silva 2012) and provide better access to jobs, markets and social services (Boschmann 2011; Sietchiping, Permezel, and Ngomsi 2012; Banister 2011).

Mitigation actions that relieve congestions are also a potential generator for additional co-benefits, providing that the reduced congestion does not induce additional traffic.[3] For congestion relieve measures to be effective a combination of solutions is vital to avoid tradeoffs and induce additional travel; for example, 'Intelligent Transport Systems' and traffic management systems should be accompanied by strategies to shift to lower-carbon modes, such as walking, cycling and public transport. Technology and fuel-based measures are unlikely to impact congestion levels and traffic flows, indicating that these actions should also be part of a wider, more comprehensive strategy (Figueroa et al. 2014; Lah et al. 2014).

Another major factor where climate change mitigation actions can have positive synergies with other objectives is related to the various health impacts of transport activities, such as air pollution, noise, vibration and road safety. Well over one million people are killed in road accidents globally each year, 91% of which occur in low and middle-income countries (WHO 2013). Reducing car-based transport can have an immediate effect on road safety (De Hartog

[3] Time lost in traffic was valued at 1.2% of GDP in the UK (Goodwin 2004); 3.4% in Dakar, Senegal; 3.3% to 5.3% in Beijing, China (Creutzig and He 2009); 1% to 6% in Bangkok, Thailand (World Bank 2002) and up to 10% in Lima, Peru with daily travel times of almost four hours (JICA 2005; Kunieda and Gauthier 2007b).

et al. 2010; Rabl and De Nazelle 2012; Rojas-Rueda, de Nazelle, et al. 2011; Tiwari and Jain 2012). Comparing the multiple health and safety effects of increased physical activity through walking and cycling often implying higher exposure to air pollution is slightly more complicated (Sonkin et al. 2006; Tiwari and Jain 2012), but considered to be positive overall (Rabl and De Nazelle 2012; Rojas-Rueda, de Nazelle, et al. 2011). Hence, a combined approach, for example in conjunction with fuel or technology switch for the public transport and taxi fleets, access restriction for road freight carriers and incentives for more efficient and lower-carbon motorized transport can ensure that air quality is improved to reduce exposure to air pollutants while using active modes of transport (Kahn Ribeiro et al. 2012). Biofuels for transportation as replacement for petroleum products are associated with several uncertainties, not only with regard to their ability to contribute to GHG emission reductions, but also to their air quality and health impacts (Smith et al. 2014). For example, replacing fossil-based transport fuels with biofuels may reduce carbon monoxide and hydrocarbon emissions, but increase NOx emissions (Sathaye et al. 2011). This is likely to change, however with more advanced biofuels (Hill et al. 2009). Similarly the potential contribution of electric mobility to local air quality improvements depends on the source of the electricity generation and the location of power plants in a city (Smith et al. 2012).

While this paper showed that there is a lack of studies managing to provide a comprehensive picture on the costs, benefits of low-carbon transport, it also showed that there is a large potential of co-benefits with key policy objectives, which can form a vital basis for coalitions with key political actors. Measuring the co-benefits of sustainable transport measures is currently not carried out in a consistent manner as different studies apply different metrics and values and some effects are barely assessed at all, such as quality of life in cities. Many of these affects can be powerful policy levers, which makes it vital to identify their role for different policy actors and at least somewhat quantify their potential.

3.4 Paper 3: Co-benefits and coalitions as basis for integrated long-term low-carbon transport strategies

The paper (Lah 2016) identifies the opportunities of an integrated policy approach to sustainable transport and identifies potential contributions to coalitions building. This is a vital element in the conceptual framework of this thesis as it creates the link between policy ambition, integration and the potential for coalition building. Practical examples of low-carbon transport policy measures are provided along with quantified co-benefits for key policy objectives and a mapping of institutional actors and potential veto players is proposed.

The paper provides a concise overview on potential co-benefits of a selection of specific measures to highlight the contribution of sustainable transport measures to economic, social and environmental policy objectives, which provides the basis for the identification of key policy actors and veto-players (Table 4).

Table 4 Examples for energy efficiency measures, their CO2 emission reduction potential, and contribution to other sustainable development objectives

Strategy	Good practice cities/projects	CO_2 emission reduction	Sustainable development benefits (and risks for trade-offs)		
			Economic	Social	Environmental
Avoid					
Road user charging	Road user charge in Stockholm, London, Gothenburg	Example London: 25% CO_2 reduction	Travel time reductions	Social costs: reduction: €144 million / year	Funds can be re-invested in e.g. public transport
Shift					
Bus Rapid Transit (BRT)	Trans Milenio Bogotá (2)	Reduction of carbon dioxide emission by 500.000 tons (in 3 years)	Rationalised bus system, 32% commuting times reduction, increases employment	Access for disabled and poor, 90% lower accidents in BRT corridors	Air quality improvements
Non-motorised Transport (NMT)	Walking and Cycling in Copenhagen: Cycle-friendly city (1)	Overall GHG emission reductions not quantified	Faster transport, Green jobs (650 full time in Copenhagen)	Increased physical activity, reduced health impacts: 5.51 DDK/km (annually €268 million), reduced road accidents	Zero air pollutants, Less noise
Improve					
Fuel switch options for public vehicle fleets	Public Transport fuels switch from e.g. hybrid/electric bus (9)	Medium to high potential for CO2 savings		Emission reductions (greenhouse gas and air pollutants)	CO2 emission reduction potential depends on the electricity mix. SO2, NOx emissions may be reduced significantly if switch to hybrid/electric.

This paper builds on a number of studies that emphasize an integrated approach is vital to reduce transport-sector greenhouse gas emissions cost-effectively (e.g. IPCC 2014, Figueroa Meza et al. 2014). While emissions reductions can be achieved through several means, such as modal shift, efficiency gains and reduced transport activity, it is apparent that the combination of measures is a key success factor to maximise synergies and reduce rebound effects. For example, overall travel demand reduction and modal shifts would need to be substantially stronger if not accompanied by efficiency improvements within the vehicle fleet and vice-versa (Figueroa Meza et al. 2014; Fulton, Lah, and Cuenot 2013). Vital element for this strategy is a policy package as summarised in the table below (Table 2), which can help unlocking benefits beyond the reduction of greenhouse gas emissions.

Table 5 Elements of a multi-modal, multi-level sustainable transport package

Examples measures	Complementarity of measures
National measures **Fuel tax** **Vehicle fuel efficiency regulation** **Vehicle tax based on fuel efficiency and/or CO2 emissions**	Vehicles standards and regulations ensure the supply of efficient vehicles and taxation helps steering the consumer behaviour Fuel tax encourages more efficient use of vehicles, which helps minimising rebound effects that might occur if individuals and businesses drive more or not as efficient as they would have driving a vehicles with lower efficiency standards
Local measures **Compact city design and integrated planning** **Provision of public transport, walking and cycling infrastructure and services** **Road User Charging, parking pricing, access restrictions, registration restrictions and number plate auctions, eco-driving schemes, urban logistics**	Compact and policy-centric planning enable short trips and the provision of model alternatives provides affordable access Complementary measures at the local level help managing travel demand and can generate funds that can be re-distributed to fund low-carbon transport modes

The large and cost-effective potential of sustainable mobility across modes is not yet fully utilised. To bridge this gap between individual and societal perspectives, policies are needed to encourage (via incentives), discourage (via pricing) and require (via regulation) shift to more efficient transport technologies and mobility behaviour. Efficient technologies may also fail to penetrate the market or do it well below their potential due to barriers such as, up-front cost, lack of information and awareness, and risk aversion behaviour on the part of consumers.

There are various levels where local and national governments can shape the energy consumption and the sustainability of urban transport systems through infrastructure development, provided services and policy decisions. The table below briefly outlines key areas for local policy and planning intervention that address the urban transport system in a holistic way focusing on transport activity, the modal structure, the energy intensity and fuels and energy carriers.

Policy interventions in the transport sector can have unintended consequences, positive and negative as they rarely only affect one objective, for example air quality measures may affect fuel efficiency negatively or biofuels may have land-use change implications. Linking and packaging policies is therefore vital to generate synergies and co-benefits between measures. This provides a basis for coalitions that can align different veto players. An integrated policy approach can help to overcome implementation barriers, minimize rebound effects and create the basis for coalitions among key political actors and societal stakeholders.

Reductions in traffic and parking congestion, increased energy security and traffic safety, affordability of transport services, public fitness and health, economic productivity, mitigation of climate change, and the reduction of local air pollution are positive impacts of transport policy that can help motivate people, businesses and communities to implement comprehensive policies and integrated transport programs to reduce transport greenhouse gas emissions and generate sustainable development benefits. Different people, groups and institutions may have different priorities, for example, some may be motivated by economic objectives and others by social equity or environmental objectives. The diverse benefits offered by a comprehensive or integrated measure can help build broad community support. The nature of integrated sustainable, low-carbon transport policies is that they address several objectives simultaneously, which generates synergies and helps creating coalitions.

Vital for the success of long-term policy and infrastructure decisions is support from diverse political actors, stakeholders and the public. A societal perspective and the incorporation of sustainable development objectives is a vital step in forging coalitions and building public support. Policy and infrastructure measures and the combination thereof are an important element in generating sustainable development benefits with low-carbon transport as they provide the content of a low-carbon transport strategy. But vital for the success of the take-up and implementation of measures is the policy environment – the context in which decisions are made (Justen et al. 2014). This context includes not only socio-economic, but also political aspects, taking into account the institutional structures of countries. The combination of policies and policy objectives can help building coalitions, but can also increase the risk of the failure of the package if one measure faces strong opposition, which, however, can be overcome if the process is managed carefully (Sørensen et al. 2014). A core element of success is the involvement at an early stage of potential veto players and the incorporation of their policy objectives in the agenda setting (Tsebelis and Garrett 1996).

The paper stresses the point that Veto players need to be identified early on the policy process as they are political actors who have a distinctive institutional role in the policy process and have the legal power to put a hold to an initiative. Typical veto players are finance ministries and parliaments with legislative prerogatives. This is a substantially different role from stakeholders, who have a vested interested in a particular policy process, but do not have the (legal) power stop it. However, both groups need to be involved in the process to successfully implement a measure. Public participation can help ensuring durability and support beyond political parties. There is a causal relationship between policy objectives, agenda setting, institutional structures and policy outcomes (Tsebelis 2002, Lijphart 1984). The synergies explored in this paper provide a basis for the inclusion of veto players into the policy process, which is vital for the uptake of sustainable mobility policies.

Considering the very strong economical case for energy efficiency measures it is puzzling why measures are not taken up as much as they could. One aspect of this is the lack of information and quantification of the benefits of sustainable mobility measures, which is another aspect covered in the paper. It shows that the lack of suitable tools to assess sustainable mobility measures' costs, benefits and overall impacts is a significant factor impeding their implementation. Cost-benefit analysis (CBA) is often applied to large-scale infrastructure projects, but does not capture all relevant socio-economic impacts. Small-scale but potentially highly cost-effective measures often do not have the critical mass to warrant a thorough cost-benefit analysis.

This paper also aims to highlight the relationship between evidence-based policy advice and the decision making process in transport policy and investments. The imbalance of evidence from Cost-Benefit Assessments between large-scale infrastructure projects and (sometime small-scale) sustainable mobility measures does affect decision making in the transport sector. The proposed approach to treat qualitative and quantitative evidence more equally in transport policy and investment decision-making processes can help providing a more equal-level playing field for different measures, in particular when broader co-benefits are taken into account. The following paper builds on this and aims to highlight the potential contribution of co-benefits in forming coalitions among key political and institutional actors, in particular the potential veto-players.

3.5 Paper 4: Continuity and Change: Dealing with Political Volatility to Advance Climate Change Mitigation Strategies—Examples from the Transport Sector

Building on this analysis the paper (**Lah, 2017**) reflects on the relationship between policy integration, institutional structures and governance approaches and provides a framework that links to the ability of different governances and policy approaches to deliver on low-carbon development pathways. Reflecting on the recent withdrawal of the United States from the Paris Agreement the paper shows how political volatility can directly affect climate change mitigation policies, in particular in sectors, such as transport associated with long-term investments by individuals (vehicles) and by local and national governments (urban form and transport infrastructure and services). There is a large potential for cost-effective solutions to reduce greenhouse gas emissions and to improve the sustainability of the transport sector that is yet unexploited. Considering the cost-effectiveness and the potential for co-benefits, it is hard to understand why efficiency gains and CO2 emission reductions in the transport sector are still lagging behind this potential. Particularly interesting is the fact that there is substantial difference among countries with relatively similar economic performances in the development of their transport CO2 emissions over the past thirty years despite the fact that these countries had relatively similar access to efficient technologies and vehicles. This study aims builds on political science theories on the particular example of climate change mitigation in the transport sector in order to identify some of the factors that could help explain the variations in success of policies and strategies in this sector.

To illustrate the role of institutional factors, the paper provides an example from one of the key policy interventions to improve the efficiency of the light-duty vehicle fleet—fuel efficiency standards in the US and the EU. This type of regulation aims to ensure a supply of efficient vehicles and, even more importantly, aim to limit the level of fuel consumption throughout the vehicle fleet.

The paper also highlights the approach to integrate European peak organisations in the policy process leads to several concessions, but also to a broader coalition on which decisions are being based in the transport sector. Regulations in this sector need to be based on a durable and stable policy and political environment as they require large, long-term investments into research and innovation. A structured non-partisan approach that incorporates the perspectives of peak organisations representing relevant societal and economic actors is more likely to create this stable policy environment (Vogel 2003). In the specific case of vehicle fuel efficiency, the lower levels of the historic emissions and standards in the EU may be one indication of continued and sustained policy progress. These targets are enshrined in EU legislation that went through an extensive consultation process and were adopted by the broad majority in the European Parliament and among the EU member states in European Council. The relatively strong targets adopted in the US adopted through executive action have no legislative backing and are likely to be revised or repealed as part of the broader move of the Trump administration to roll back environmental and climate change policy.

This example illustrates the difference in the institutional settings in the US and the EU and shows with a practical example how political volatility affects policies in the US and the relatively high level of consensus in the EU fosters stability in this key policy area. Political volatility can affect national and local level policy environments. The paper also provides another illustrative example from an emerging economy perspective, with cases from India and Brazil. The two countries are dynamic democracies that face substantial challenges from rapid urbanization and economic development. On the local level, there are a number of cities that have been working very proactively on sustainable mobility solutions for many years, and the paper reflects on two case study cities.

The interviews with officials and NGOs carried out in Brazil and India showed that commitments and capacities of local officials along with the involvement of peak organisations such as unions and an active and organized society can provide a certain level of political stability despite changing political leadership in a city. There has been extensive work on institutional structures and characteristics of different forms of government (e.g. Lijphart 2012; Tsebelis 2000; Jahn 2014) almost all of which is focusing on democracies in industrialised countries. Some analysis has been carried out to create the link between institutions and environmental performance (Scruggs 1999; Lundqvist 1980; Jordan, Wurzel, and Zito 2013; Wurzel 2010) focusing on industrialised countries and not being sector specific. This is where this paper aimed to add value, by making a clear case for the mitigation potential in the transport sector, pointing at specific policies and their potential for coalition building and exploring the relevance of institutional characteristics in developed and emerging countries.

4. Conclusion

This section highlights some of the key findings of the papers and reflects on the relevant discourse and literature.

4.1 Contribution to transformative research

Sustainability transitions require a number of driving forces and pre-conditions, such technological solutions, policies, markets, behaviour shifts, infrastructures and scientific knowledge (Geels 2002). Urban transitions in particular require highly complex policy and governance processes and a high level of coordination among actors and stakeholders. These long-term transitions need an institutional structure that is built on a broad consensus on key policy issues and creates a stable policy environment, which ensures continuity and is resilient to political volatility. This thesis argues that an integrated policy approach that integrates policy objectives of key political actors at the city and national level is best suited to provide a basis for coalitions among political actors, which can contribute to the consensus and continuity that is needed to decarbonise key sectors of the economy. Urban mobility has been selected as a case-study for this analysis as it the energy end-use sector that brings together the highest potential of co-benefits and that heavily relies on an concerted interplay of local and national policy measures to achieve the transition towards a sustainable development pathway (IPCC 2014).

Transitioning from innovation niches to a mature low-carbon urban development and mobility landscape is a complex and challenging process that requires a policy and institutional environment that is dynamic, which is vital to enable innovations, but is also stable, which is essential to attract investments. This transition would be considered a radical shift that requires major changes to the urban design, the role of different modes of transportation and mobility behaviour (Nilsson and Nykvist 2016; Geels 2002). The scope of the change requires innovations that range from technological breakthroughs to longer-term changes within the existing regime, all of which are gradually emerging through the sociotechnical system (Geels, 2002, 2011). While the coordination of relevant actors and institutions within this sociotechnical system is acknowledged as an important aspect of success, the role of consensus-focused institutions and political systems is largely neglected in studies on the application of the transition theory. This thesis aims to contribute to the wider sustainability transitions discourse with a perspective on the role of consensus oriented political institutions and how they can contribute to a more stable sociotechnical system that enables the long-term transition to sustainable transport mobility. Co-benefits of integrated sustainable mobility policy packages are considered to be a key enabler for coalitions that form a wider political and societal consensus. These synergies among policy objectives are particularly strong at the urban level, which is why the integration of measures at the city and national level will be a particular focus of the analysis.

Countries are different and the institutions that define these differences are described by several scholars using different approaches and definitions. This thesis explores some political science theories and how they affect the transition to low-carbon urban development and mobility. There are several studies examining the influence of the concepts of corporatism, coordinated market economy, consensus democracy, epistemic communities, and supra-national integration on policy performance, such as Bernauer and Koubi 2008; Neumayer 2003; Jahn 1998; Scruggs 1999. This thesis will compare some of the key institutional indicators with the ability of countries to move towards a low-carbon urban mobility system. This research aims to shed some light on transition pathways towards sustainable urban development and transportation.

Policy agenda setting and policy continuity is affected by political consensus, which is a result of political and institutional relationships. These relationships, including the interactions between different levels of government (e.g. local, state, federal, supra-national) and acknowledge of scientific consensus on climate change policy, vary greatly between key political and societal actors in different countries.

Political stability greatly affects the ability of governments to deliver on policy objectives. Policy environments and the exposure to volatility varies between countries and changes over time, which affects implementation of sustainable urban development and climate change mitigation measures and results in significant differences between countries' progress reducing GHG emissions. Changing political environments means that policy environments are also influenced by a level of uncertainty. Hence, a shared set of methods and values are generally considered vital for setting the policy agenda, usually delivered through knowledge communities.

The political and institutional context in which policies are pursued is a vital factor for the success or failure of implementation. Institutional aspects, such as the presence/absence of an environment ministry at the national level or environment department on the local level, and their respective roles in the process are likely to have an effect on the implementation of (primarily) climate related transport measures. The legal power, budget and political influence of these agencies are equally important (Jänicke, 2002).

As a measure for continuity and to support broad societal coalitions, participation of diverse political and public stakeholders can be vital for the long-term success of policy and infrastructure decisions. The policy environment, or context in which decisions are made, is as important as the combination of policy decisions and infrastructure investments that make up a low-carbon transport strategy (Justen et al. 2014). This policy environment includes socio-economic and political aspects of the institutional structures of countries. These structures help build coalitions, but can also increase the risk that a policy package fails because one measure faces strong opposition (Sørensen et al. 2014). A core element of success is the involvement at an early stage of potential veto players and the incorporation of their policy objectives in the agenda setting (Tsebelis and Garrett 1996).

4.2 National and urban mobility policy implications

A number of studies emphasize that an integrated approach is vital to reduce greenhouse gas emissions cost-effectively in urban areas (IPCC 2014). While emissions reductions can be achieved through several means, such as modal shift, efficiency gains and a shift to renewable energies, it is apparent that the combination of measures is a key success factor to maximise synergies and reduce rebound effects.

There are various levels where local and national governments can shape the energy consumption and the sustainability of urban transport systems through infrastructure development, provided services and policy decisions. The table below briefly outlines key areas for local policy and planning intervention that address the urban transport system in a holistic way focusing on transport activity, the modal structure, the energy intensity and fuels and energy carriers. Policy and governance at all levels of government play a critical role in delivering a package of measures that is complementary and mutually reinforcing and can unlock co-benefits, which form the basis for political coalitions. Identifying the key measures at the local and national level and their interplay was a key objective for this thesis. The decarbonisation scenarios and policy pathways identify the key elements of an integrated multi-modal, multi-level sustainable transport package (Table 6).

Table 6 Policy packaging –elements of a multi-modal, multi-level sustainable transport package

National Measures	Complementarity of measures	Local Measures
Planning • National Urban Mobility Plans • Legislations governing the powers, resources and capacities of local authorities	• **Objectives of national and local plans are in line and contribute to common goals** • **Compact and policy-centric planning enables short trips and increases access**	• Sustainable Urban Mobility Plans • Compact city design and integrated planning

Infrastructure • National transport infrastructure investment plans and policies	• **National and local transport infrastructure projects are following an integrated planning approach and contribute to the same objectives**	• Local transport infrastructure investment plans and policies
Fiscal • Fuel tax • Vehicle tax based on fuel efficiency and/or CO_2 emissions	• **Fuel tax encourages more efficient use of vehicles, which helps minimising rebound effects** • **Complementary measures at the local level help managing travel demand and can generate funds that can be re-distributed to fund low-carbon transport modes**	• Road User Charging, parking pricing, number plate auctions • Provision of public transport, walking and cycling infrastructure and services
Regulatory • Vehicle fuel efficiency and CO_2 regulation • Emission standards (CO, NOx, PM) • Fuel standards	• **Vehicles standards and regulations ensure the supply of efficient vehicles along with taxation, local regulations and access restrictions help steering consumer behaviour**	• Access restrictions • Registration restrictions
Awareness and information • Awareness raising • Labelling schemes • National freight plans	• **Consistent messaging can help influencing choices and mobility behaviour of individuals and businesses**	• Eco-driving schemes • Car-fee days / zones • Urban logistics

Policy interventions in this sector can have unintended consequences, positive and negative as they rarely only affect one objective, for example air quality measures may affect fuel efficiency negatively or biofuels may have land-use change implications. Linking and packaging policies is therefore vital to generate synergies and co-benefits between measures. This provides a basis for coalitions that can align different veto players. An integrated policy approach can help to overcome implementation barriers, minimize rebound effects and create the basis for coalitions among key political actors and societal stakeholders.

Reductions in traffic and parking congestion, increased energy security and traffic safety, affordability of transport services, public fitness and health, economic productivity, mitigation of climate change, and the reduction of local air pollution are positive impacts of transport policy that can help motivate people, businesses and communities to implement comprehensive policies and integrated transport programs to reduce transport greenhouse gas emissions and generate sustainable development benefits. Different people, groups and institutions may have different priorities, for example, some may be motivated by economic objectives and others by social equity or environmental objectives. The diverse benefits offered by a comprehensive or integrated measure can help build broad community support. The nature of integrated sustainable, low-carbon transport policies is that they address several objectives simultaneously, which generates synergies and helps creating coalitions.

Vital for the success of long-term policy and infrastructure decisions is support from diverse political actors, stakeholders and the public. A societal perspective and the incorporation of sustainable development objectives is a vital step in forging coalitions and building public support. Policy and infrastructure measures and the combination thereof are an important element in generating sustainable development benefits with low-carbon transport as they provide the content of a low-carbon transport strategy. But vital for the success of the take-up and implementation of measures is the policy environment – the context in which decisions are made (Justen et al. 2014). This context includes not only socio-economic, but also political aspects, taking into account the institutional structures of countries. The combination of policies and policy objectives can help building coalitions, but can also increase the risk of the failure of the package if one measure faces strong opposition, which, however, can be overcome if the process is managed carefully (Sørensen et al. 2014). A core element of success is the involvement at an early stage of potential veto players and the incorporation of their policy objectives in the agenda setting (Tsebelis and Garrett 1996). Table 7 provides an overview of the required policy interventions and their potential impact and co-benefits, which gives a first indication of the key policy actors involved and with that the potential veto players.

Table 7 Summary of sustainable urban mobility actions and potential benefits

Low-carbon urban mobility actions	Emission reduction potential	Co-benefits and synergies	Potential Veto Players
Activity **(reduction and management: short distances, compact cities and mixed use)**	Potential to reduce energy consumption by 10 to 30%	Reduced travel times; improved air quality, public health, safety and more equitable access	Urban planning department, Mayor, transport department
Structure **(shift to more energy efficient modes)**	Potential for energy efficiency gains varies greatly, but for example BRT systems can deliver up to 30% reductions at a cost of $1-27 M/km	Reduced urban congestion and more equitable access	Mayor, transport department, public transport authority
Intensity **(vehicle fuel efficiency)**	Efficiency improvement of 40-60% by 2030 feasible at low or negative costs	Improved energy security, productivity and affordability	Treasury/ Finance Ministry, Transport Ministry (national)

Fuel **(switch to electricity, hydrogen, CNG, biofuels and other fuels)**	Changing the structure of the energy consumption, but not necessarily overall demand.	Diversification of the fuels used contributes to climate, air quality and/or energy security objectives	Treasury/ Finance Ministry, Transport Ministry (national)

Source: Lah 2017

5. Outlook

Urban mobility plays a key role in the decarbonisation of the transport sector and in delivering on the Paris Agreement, the Sustainable Development Goals and the New Urban Agenda. The complexity of urban transportation requires a strong policy framework from the national level that supports integrated urban design, enables the shift to low-carbon modes and fosters the take-up of low-carbon vehicle technologies. While this creates challenges for appropriate policy design that avoids trade-offs, it also creates opportunities for co-benefits between climate policy and other objectives, such as safety, air quality and energy security. The interplay of various policy objectives calls for coalitions among key local and national political actors and a coordination between national and urban mobility policies to provide a framework and process for the implementation. This theses identified factors for an effective and efficient policy and governance framework, which forms the basis a coherent national urban mobility policy framework that links national and local policy and investment flows. This framework can help to ensure policy coherence on the national level (vertical integration) and foster the take-up of Sustainable Urban Mobility Plans by cities (horizontal integration).

Linkages between local and national policies need to be identified, coordination mechanisms between institutions in charge of delivering on urban mobility policy and planning is required, and funding and financing mechanisms that embrace the concept of subsidiarity are key elements to deliver on jointly agreed policy objectives. This can help ensuring that local actions meet national climate and sustainable development objectives. An integrated policy and governance approach facilitates a consensus building process that defines system boundaries (i.e. relevant policy fields and actors), derives and ranks policy objectives, responsibilities and resources, identifies policy measures and establishes a review and evaluation process.

This thesis identified three critical interlinkages:

- Decarbonisation of the transport sector is not possible through isolated measures. A broad range of local and national actions are needed to bring the sectors on to low-carbon development path. An integrated policy and governance approach can help ensuring that local and national actions are complementary and mutually reinforcing.

- A holistic policy approach is needed to deliver on wider sustainable development objectives. Addressing a broader range of policy objectives can help forming coalitions and consensus among key political and societal actors. Coordinated national and local governance frameworks that help addressing a range of sustainable development objectives and ensure policy coherence.
- Consensus oriented institutions are needed to maintain a stable policy environment that enables the long-term transitions towards a low-carbon development path. Coordination mechanisms should aim to develop a consensus on key policy objectives, how to deliver on them and how to fund them.

5.1 Further research

Cities and transport play a crucial role in global decarbonisation efforts. The transition to low-carbon urban mobility cannot rely on technological innovation alone, it needs to be driven by a concerted political effort between the local and national policy levels. The role of political actors and institutions and the interaction with policies and innovations is generally well acknowledged in transition theories and the Multi-Level-Perspective on system innovations and transitions reflects this to some extent (Grin, Rotmans, and Schot 2010), but a closer focus of the interplay between policy design and the objectives and roles of different political actors would help to foster the policy relevance of transition theory. Identifying transition pathways considering the specificities of different policy and institutional environments can help guiding local, (state) and national policy, but also institutional theory can be enriched by further examples and quantifiable data on institutional characteristics from developing economies. Most of the institutional analysis has been focused on the national level, further research on the similarities and differences of institutional settings at the local level would be adding value to the existing literature. Further analysis will be needed on the causal relationship between government agenda setting and executive dominance and comparisons in developed and emerging economies, which would add further insights to the factors for success and failure in the uptake of sustainable mobility policies, both at the national and the local policy level.

Generalised assessments of institutional structures either at the local or at the national level will be able to prove some indications on the ability of countries or cities to deliver on the opportunities for co-benefits and generate coalitions. However, these assessments will always fall short of delivering reliable information on the feasibility of decarbonisation pathways. Hence, individual analyses on institutional structures, policy objectives of key actors and linkages to proposed policy packages would be needed at the local and national level for many country and cities to get a better picture on global decarbonisation targets.

The quantifiable extent to which co-benefits can be generated with an integrated policy approach varies significantly, in particular in areas such as air quality and energy security as there are influencing factors beyond the transport sector. Hence, policy integration also needs to go beyond sectoral boundaries which increases the complexity of the policy process even further, but also yields an even great potential for co-benefits, which could be the objective of studies on economy-wide decarbonisation pathways that take into account policy design and process aspects and go beyond econometric analyses.

6. Abstracts status of the papers

This section summarises the key messages of the papers developed for this thesis and provides information on the status of the publications and the role of the authors. The thesis is comprised of a set of ten papers focusing on the requirements for the transitions towards a low-carbon, sustainable transport system, an evaluation of the key policies and how they need to be integrated and an analysis of the governance and institutional factors that affect the policy implementation.

Decarbonisation scenarios and the role of urban mobility

The paper developed for this part of the thesis outlines the greenhouse gas emission reduction potential and shows the relevance of different policy levers .

Paper 1: Transport Pathways towards a 2 Degree Scenario

Fulton, L. Lah, O., Cuenot, F., 2013, Transport Pathways towards a 2 Degree Scenario, *Sustainability, Special Issue: Sustainable Cities* http://www.mdpi.com/2071-1050/5/5/1863

Abstract: The transport sector is the second largest and one of the fastest growing energy end-use sectors, representing 24% of global energy-related greenhouse gas emissions. The International Energy Agency has developed scenarios for the transport sector within the overall concept of mitigation pathways that would be required to limit global warming to 2 °C. This paper builds on these scenarios and illustrates various passenger travel-related strategies for achieving a 2° transport scenario, in particular looking at how much technology improvement is needed in the light of different changes in travel and modal shares in OECD and non-OECD countries. It finds that an integrated approach using all feasible policy options is likely to deliver the required emission reductions at least cost, and that stronger travel-related measures result in significantly lower technological requirements.

Keywords: transport; climate change; sustainability; energy

Status of the paper and role of the authors: The paper was published in the peer-reviewed (double blind) journal *Sustainability* (MDPI) and I contributed to the design of the analysis and co-wrote the paper in close cooperation with Lew Fulton (the first author). François Cuenot from the International Energy Agency contributed data.

The potential of co-benefits and its role as basis for coalitions

The papers developed for this part of the thesis identifies the potential synergies among political objectives and provides quantified examples of co-benefits that can serve as a basis for political coalitions.

Paper 2: Integrating global climate change mitigation goals with other sustainability objectives: a synthesis

von Stechow, C., D. McCollum, K. Riahi, J. C. Minx, E. Kriegler, D. P. van Vuuren, J. Jewell, C. Robledo, E. Hertwich, M. Tavoni, S. Mirasgedis, O. Lah, J. Roy, Y. Mulugetta, N. K. Dubash, J. Bollen, D. Ürge-Vorsatz, O. Edenhofer (2015). Integrating global climate change mitigation goals with other sustainability objectives: a synthesis, *Annual Review of Environment and Resources, Vol. 40, 363-394)*. https://doi.org/10.1146/annurev-environ-021113-095626

Abstract: Achieving a truly sustainable energy transition requires progress across multiple dimensions beyond climate change mitigation goals. This article reviews and synthesizes results from disparate strands of literature on the co-effects of mitigation to inform climate policy choices at different governance levels. The literature documents many potential co-benefits of mitigation for non-climate objectives, such as human health and energy security, but little is known about their overall welfare implications. Integrated model studies highlight that climate policies as part of well-designed policy packages reduce the overall cost of achieving multiple sustainability objectives. The incommensurability and uncertainties around the quantification of co-effects become, however, increasingly pervasive the more the perspective shifts from sectoral and local to economy wide and global, the more objectives are analyzed, and the more the results are expressed in economic rather than nonmonetary terms. Different strings of evidence highlight the role and importance of energy demand reductions for realizing synergies across multiple sustainability objectives.

Keywords: welfare-theoretical framework, multiple objectives, co-benefits, air quality, energy security, energy efficiency, energy demand reduction

Status of the paper and role of the authors: The paper was published in the peer-reviewed (double blind) journal Annual Review of Environment and Resources. This paper was developed by IPCC Lead Authors responsible for the co-benefits sections in the sector chapters. I contributed to the planning and design of the paper and provided the sectoral analysis for the transport sector.

Paper 3: Sustainable development synergies and their ability to create coalitions for low-carbon transport measures

Lah, O. (2016). Sustainable development synergies and their ability to create coalitions for low-carbon transport measures. Transportation Research Procedia, 25, 5088–5098. https://doi.org/10.1016/j.trpro.2017.05.495

Abstract: Many low-carbon transport strategies can help achieve other economic, social and environmental objectives. These include improving access to mobility, reducing traffic and parking congestion, saving consumers money, supporting economic development, increasing public health and safety, and reducing air and noise pollution. Based on Avoid-Shift-Improve approaches and case studies from Germany, Colombia, India and Singapore, this paper shows that low-carbon transport generates significant and quantifiable benefits that can create a basis for political and societal coalitions. Estimates suggest that currently available and cost effective measures can reduce transport Greenhouse Gas emissions by 40-50% compared to 2010. Yet, a number of barriers affect the optimal exploitation of this potential. Considering the possible economic, social and environmental benefits of sustainable transport, the shift towards a low-carbon pathway of this sector can be a win-win situation for climate protection and local development goals. This paper aims to make a contribution to understand these opportunities by highlighting the linkages between objectives, presenting case studies, facts and figures. The paper will also explore assessment methodologies and tools that can help practitioners to assess sustainable development benefits (SDB) and providing evidence for policy-makers to make more informed decisions on transport investments and polices.

Keywords: Climate change, sustainable transport, co-benefits

Status of the paper and role of the authors: The paper was published in the peer-reviewed (double blind) journal Transportation Research Procedia (Elsevier). The review process was carried out under the World Conference on Transport Research, WCTR, Shanghai 2016, where the paper was presented. This is a single-author paper.

Institutions at the local and national level and pathways towards an integrated, multilevel governance structure

The paper developed for this section focuses on the interplay between urban mobility policy objectives, the potential for co-benefits and the coalitions that can help delivering on those.

Paper 4: Continuity and Change: Dealing with Political Volatility to Advance Climate Change Mitigation Strategies—Examples from the Transport Sector

Lah, O. (2017). Continuity and Change: Dealing with Political Volatility to Advance Climate Change Mitigation Strategies—Examples from the Transport Sector. Sustainability, 9(6). https://doi.org/10.3390/su9060959´

Abstract: As the recent withdrawal of the United States from the Paris Agreement has shown, political volatility directly affects climate change mitigation policies, in particular in sectors, such as transport associated with long-term investments by individuals (vehicles) and by local and national governments (urban form and transport infrastructure and services). There is a large potential for cost-effective solutions to reduce greenhouse gas emissions and to improve the sustainability of the transport sector that is yet unexploited. Considering the cost-effectiveness and the potential for co-benefits, it is hard to understand why efficiency gains and CO_2 emission reductions in the transport sector are still lagging behind this potential. Particularly interesting is the fact that there is substantial difference among countries with relatively similar economic performances in the development of their transport CO_2 emissions over the past thirty years despite the fact that these countries had relatively similar access to efficient technologies and vehicles. This study explores some well-established political science theories on the particular example of climate change mitigation in the transport sector at the city and national level in order to identify some of the factors that could help explain the variations in success of policies and strategies in this sector. The analysis suggests that institutional arrangements that contribute to consensus building in the political process provide a high level of political and policy stability which is vital to long-term changes in energy end-use sectors that rely on long-term investments. However, there is no direct correlation between institutional structures, e.g., corporatism and success in reducing greenhouse gas emissions in the transport sector. Environmental objectives need to be built into the consensus-based policy structure before actual policy progress can be observed. This usually takes longer in consensus democracies than in politically more agile majoritarian policy environments, but the policy stability that builds on corporatist institutional structures is likely to experience changes over a longer-term, in this case to a shift towards low-carbon transport that endures.

Keywords: sustainable transport; policy implementation; governance; institutions

Status of the paper and role of the authors: The paper was published in the peer-reviewed (double blind) journal Sustainability (MDPI). This is a single-author paper.

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8. Papers

Paper 1: Transport Pathways towards a 2 Degree Scenario

Fulton, L., Lah, O., Cuenot, F., 2013. Transport Pathways for Light Duty Vehicles: Towards a 2° Scenario. Sustainability 5, 1863–1874. https://doi.org/10.3390/su5051863 (Open Access, final version)

Paper 2: Integrating global climate change mitigation goals with other sustainability objectives: a synthesis

von Stechow, C., McCollum, D., Riahi, K., Minx, J.C., Kriegler, E., van Vuuren, D.P., Jewell, J., Robledo-Abad, C., Hertwich, E., Tavoni, M., Mirasgedis, S., Lah, O., Roy, J., Mulugetta, Y., Dubash, N.K., Bollen, J., Ürge-Vorsatz, D., Edenhofer, O., 2015. Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. Annu. Rev. Environ. Resour. 40, 363–394. https://doi.org/10.1146/annurev-environ-021113-095626 (preprint)

Paper 3: Sustainable development synergies and their ability to create coalitions for low-carbon transport measures

Lah, O., 2017. Sustainable development synergies and their ability to create coalitions for low-carbon transport measures. Transportation Research Procedia 25, 5088–5098. https://doi.org/10.1016/j.trpro.2017.05.495 (Open Access, final version)

Paper 4: Continuity and Change: Dealing with Political Volatility to Advance Climate Change Mitigation Strategies

Lah, O., 2017. Continuity and Change: Dealing with Political Volatility to Advance Climate Change Mitigation Strategies—Examples from the Transport Sector. Sustainability 9. https://doi.org/10.3390/su9060959 (Open Access, final version)

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Article

Transport Pathways for Light Duty Vehicles: Towards a 2° Scenario

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Abstract: The transport sector is the second largest and one of the fastest growing energy end-use sectors, representing 24% of global energy-related greenhouse gas emissions. The International Energy Agency has developed scenarios for the transport sector within the overall concept of mitigation pathways that would be required to limit global warming to 2 °C. This paper builds on these scenarios and illustrates various passenger travel-related strategies for achieving a 2° transport scenario, in particular looking at how much technology improvement is needed in the light of different changes in travel and modal shares in OECD and non-OECD countries. It finds that an integrated approach using all feasible policy options is likely to deliver the required emission reductions at least cost, and that stronger travel-related measures result in significantly lower technological requirements.

Keywords: transport; climate change; sustainability; energy

1. Introduction

Transport currently accounts for about 14% of overall global greenhouse gas emissions and 24% of the global CO_2 emissions from fossil fuel combustion [1]. To move onto a track that could limit the global temperature increase to 2 °C compared to pre-industrial levels, transport must decarbonize substantially over the coming decades [2,3]. The International Energy Agency (IEA) has developed a set of scenarios for its Energy Technology Perspectives (ETP) 2012 with the aim of providing policy advice on sustainable energy pathways toward 2050. The ETP scenarios deviate from a 6 °C scenario, which represents the baseline, and explores pathways toward a 2 °C stabilization target. The IEA suggests that CO_2 emissions are likely to double by 2050 if current trends persist [1]. The ETP shows that the benefits of shifting towards a low-carbon economy outweigh the costs, stating that a "sustainable energy system will require USD 140 trillion in investments to 2050 but would generate undiscounted net savings of more than USD 60 trillion" from total fuel and other savings of about USD 200 trillion [1]. For transport, the incremental investments for advanced powertrains over the next four decades amount to 65 trillion (out of over USD 500 trillion in overall expenditures for the whole transport sector), resulting in net savings of over USD 50 trillion in reduced vehicle purchases, needed infrastructure and fuel costs. The additional co-benefits generated by more sustainable transport, such as improved safety and air quality and reduced travel time are not included in this calculation, which would make the cost-effectiveness of a shift towards sustainable transport even more compelling. This paper aims to test some of the ETP 2012 assumptions and will explore additional scenarios. In particular, it identifies the impacts of varying the contribution of different mitigation options for transport and takes some initial steps toward quantifying the cost impacts of different approaches.

2. Energy Technology Perspectives 2012: Scenarios and Assumptions

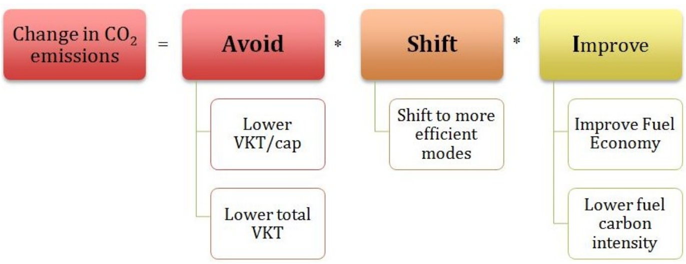
This section will explore some of the aspects behind the assumptions for the ETP 2012 scenarios and disaggregate the projected developments in OECD and non-OECD countries.

2.1. Avoid, Shift and Improve in the ETP 2012

In IEA ETP 2012, the 2-degree scenario (2DS) for transport is built upon a range of measures and changes in transport between 2009 and 2050 that reaches a CO_2 target consistent with a 2 °C stabilization pathway. A second scenario has also been developed for the ETP 2012, a 4° scenario (4DS), which assumes only a minor deviation from the baseline.

The ETP scenarios adopt the Avoid/Shift/Improve or A/S/I approach to decompose the assumed areas of emission reduction measures (Figure 1): *Avoid* (reduce travel Activity or reduce growth in activity) [3]; *Shift* (change travel Structure through shifts to different modes of travel), and *Improve* (lower vehicle energy Intensity and reduce Fuel carbon intensity). As the IEA ETP 2012 adopted this A/S/I classification, we will continue with this approach here.

Figure 1. Avoid/Shift/Improve (ASI) classification.



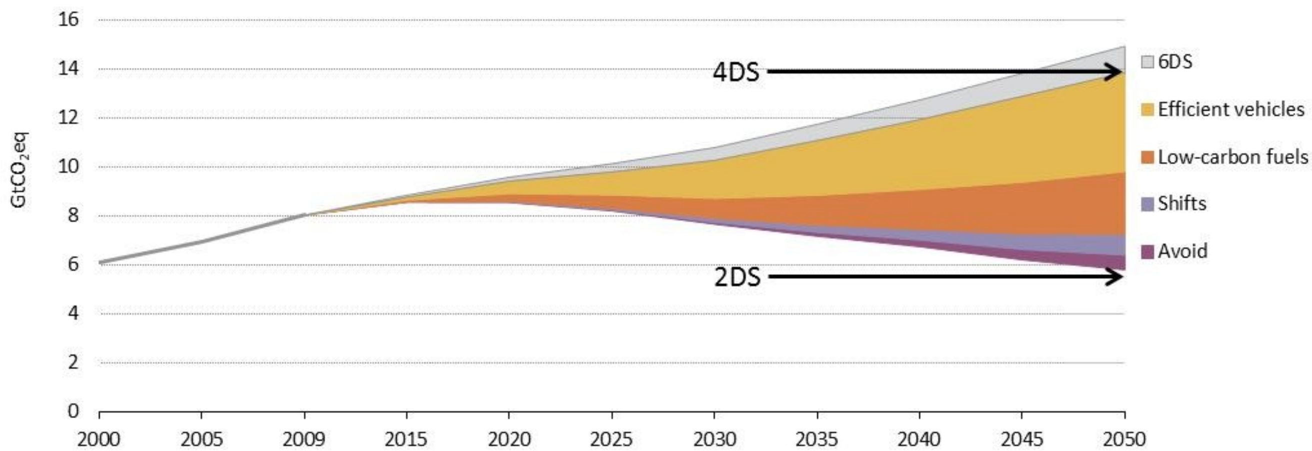
The underlying assumptions behind the Avoid/Shift/Improve (A/S/I) approach in the ETP 2012 2DS can be summarized as follows:

Improve (intensity/fuel): Most types of vehicles and modes have the potential for efficiency improvements in the range of 30–50% between 2010 and 2050; light-duty vehicles can achieve 50% through incremental improvements and adoption of electric hybridization (without considering plug-in vehicles). Advanced technologies such as plug-in electric and hydrogen vehicles could achieve more than 50% market share of new light duty vehicles and medium duty trucks by 2050; advanced, low-carbon biofuels may provide 30% of all transport fuel by 2050.

Avoid/Shift: by 2050, passenger-kilometres of travel in cars grow by 25% less in the 2° scenario than in 4° scenario (4DS). Around half of this reduction is shifted to more efficient modes (public transport, walking and cycling) and half is avoided by improved land-use and urban form that reduce trip-lengths.

As one of the key figures for transport in the ETP 2012 (Figure 2) indicates, compared to a baseline (6 °C) and a 4 °C scenario where well-to-wheel CO_2-eq emissions rise from about 8 Gt in 2009 to over 14 Gt in 2050, in the 2° scenario emissions peak at about 8.5 Gt in 2020, and then drop back to about 6 Gt by 2050. Reductions are achieved through a combination of changes in travel patterns (Avoid/Shift), and more efficient vehicles and low carbon fuels (Improve). However, as stated in ETP, "Avoid/Shift case contribution to lowering GHG emissions is modest when low-carbon technologies are widely implemented" [1].

Figure 2. Energy Technology Perspectives (ETP) results for global well-to-wheel greenhouse gas emissions mitigation potential from the transport sector for a 4° and a 2° scenario.



One problem with depicting CO_2 reductions in a wedge diagram is that improvements of one type (such as efficiency) leave less CO_2 to reduce via other means (such as modal shift), and allocation of CO_2 reductions in a combined scenario can be misleading. The avoid/shift reductions in Figure 2 appear small but this is partly due to the strong decarbonisation in all vehicle types, which (at least after 2030) leave relatively small possible reductions from modal shift. If strong decarbonisation of the transport sector occurs as in the 2DS, there is little incentive to undertake modal shift policies for purposes of CO_2 reduction, as all modes move to a similar well-to-wheel CO_2 emissions intensity (WTW gCO_2/pkm).

While from a pure climate change mitigation perspective vehicle efficiency and low-carbon fuels may provide the biggest potential, this does not fully reflect a broader sustainable transport perspective. A multimodal, low-carbon transport sector, which also aims to manage growth in travel demand and modal split may yield important benefits in air quality, traffic congestion, safety and overall societal mobility—and thus a higher level of socio-economic co-benefits and may also be more cost effective [4,5]. This paper focuses on CO_2 but this broader perspective must be kept in mind when assessing effectiveness of mitigation options.

A number of transport sector mitigation measures rely on well-established technologies and practices, e.g., shift to public and non-motorized transport and efficiency improvements of internal combustion engines. However, efficiency gains beyond a certain level require major technology shifts towards electric powertrains and/or hydrogen, which are associated with substantial uncertainties. Associated with even larger uncertainties are the assumptions on life-cycle carbon emission reductions from biofuels.

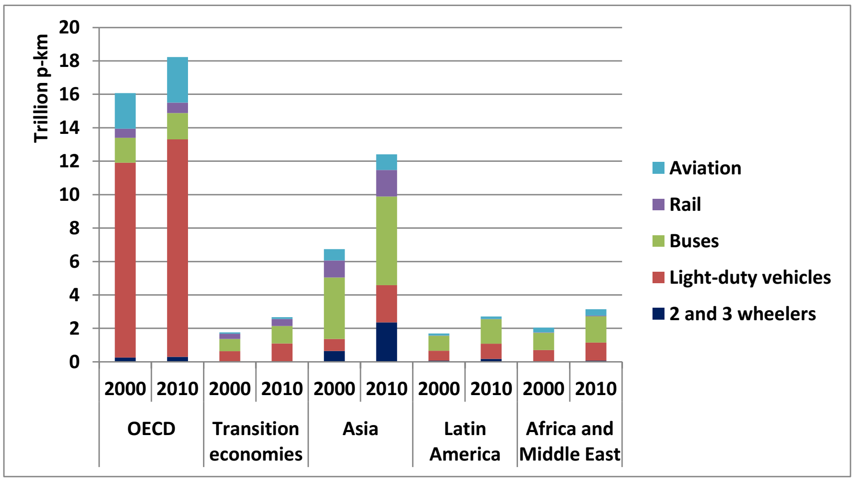
The primary goal of this paper is to show the relationship between the Improve elements with the Avoid and Shift strategies in the ETP 2DS scenario. Mainly for purposes of simplicity, the focus in the following analysis is kept on light-duty vehicles (LDVs). The private vehicle is by far the most energy intensive personal land transport mode; the importance of vehicle fuel economy for transport's overall productivity is heavily interrelated with overall travel patterns and modal choices (e.g., access to high quality and reliable public transport services). Hence the efficiency and fuels of LDV travel and the overall travel demand for light-duty vehicles provide useful indicators for the biggest source of transport CO_2 emissions and land transport energy efficiency more generally.

2.2. Regional Differences in the Scenarios for OECD and Non-OECD Countries

The scenarios developed for this paper disaggregate the ETP 2012 scenarios further to highlight the relationship between different CO_2 mitigation actions. Starting with the IEA ETP 2012 2-degree (2DS) scenario, we break out key A/S/I details and then create two alternative cases, principally varying the contribution from travel demand and modal share (Avoid/Shift) on the one hand, and fuel economy and the carbon intensity of energy carriers (both Improve options) on the other hand. In each case we reach the same overall CO_2 emission reduction target for 2050, using the same underlying conditions (e.g., income, population growth). Thus these cases also have the same carbon emissions per capita.

Baseline travel growth and the resulting CO_2 reduction potentials and trajectories for light duty vehicles differ substantially between OECD and non-OECD countries. Over the coming decades most growth in travel demand will come from non-OECD countries, although vehicle travel per capita in these countries will remain at a substantially below the OECD average even in 2050. This rapid growth of travel demand in non-OECD is already evident when looking at the developments throughout the past decade (Figure 3). Although the overall level of passenger travel (particularly car travel) is far higher in OECD than in non-OECD countries, travel is growing faster in non-OECD, particularly in Asia.

Figure 3. Modal distribution of total motorized passenger transport by region in 2000 and 2010.

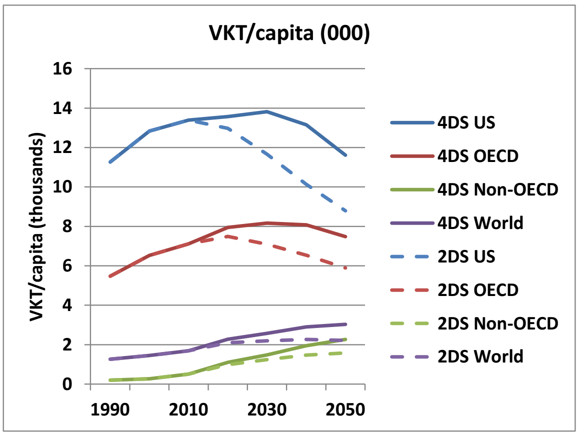


IEA, 2012, Mobility Model (MoMo) database.

Figure 3 also shows that modal share varies greatly between world regions, with light duty vehicles dominating personal transport in OECD countries, while public transport is still the most important travel mode in Asia, Latin America and Africa, even though its share is shrinking. Considering the rapid growth in travel demand, the key challenge for most developing countries is to sustain the share of low-carbon transport modes, while ensuring high levels of efficiency for the new vehicles entering the fleet. For OECD countries, vehicle fuel efficiency along with shifts towards public- and non-motorized transport are key [6,7].

Looking out to 2050, Figure 4 shows the passenger travel projection for light-duty vehicles in the ETP 2012 two-degree scenario (2DS) and also the ETP four-degree scenario (4DS). As shown, there is a large difference in vehicle travel between these scenarios, but an even bigger difference between OECD and non-OECD countries in either scenario. The United States is broken out (also included in the OECD average) to highlight the required changes the country with the highest level of car-travel. The US average is over 12,000 km per person per year in 2010, while the OECD average travel is only about 7,000 km per capita and travel in non-OECD is currently below 1,000 km per person per year.

Figure 4. Vehicle kilometres travelled (VKT) per capita in light-duty vehicles by region and scenario, 2010–2050 (IEA data).



The key point of Figure 4 is to show that in the 2DS case, car travel grows far less in both OECD and non-OECD countries, and in fact declines on a per-capita basis over most of the projection period. This reflects measures to cut travel growth and shift some of it away from cars toward public transport, walking and cycling. Even though the VKT per capita is set to substantially decrease in most OECD countries, global population is still set to increase to more than 9 billion by 2050 and travel demand growth in non-OECD countries is surging.

The VKT reductions in OECD countries and the reduced growth in non-OECD countries in Figure 4 appear to be substantial, yet this seems to have only a small influence on the overall CO2 emission reductions in 2050, as depicted in the ETP 2012 wedge diagram (Figure 2).

3. Disentangling the ETP 2012 Scenarios: The Roles of Avoid/Shift and Improve Measures in OECD and Non-OECD Countries

This section will build on the ETP 2012 scenario and will explore the results of the two sensitivity cases that have been developed to show the relevance of the required fuel switch and efficiency improvements under different travel growth and modal share projections in OECD and non-OECD countries. This will help highlighting the complementarity of Avoid/Shift and Improve measures for climate change mitigation strategies over the coming decades.

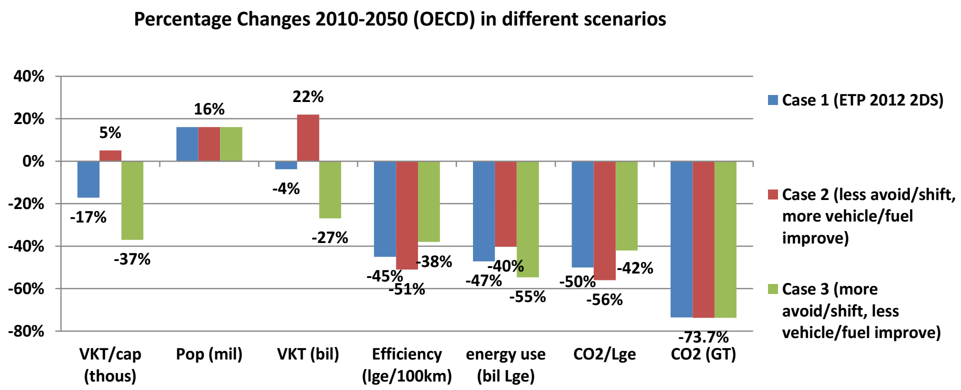
3.1. Three Different Pathways towards a 2° Goal: Two Sensitivity Cases Building on the ETP 2012 2° Scenario

Based on the ETP 2012 2° scenario (Case 1, ETP 2012 2DS) two sensitivity cases have been developed (Case 2, less avoid/shift, more vehicle/fuel improve, and Case 3, more avoid/shift, less vehicle/fuel improve) to disentangle the required fuel switch and efficiency gains changes in travel and determining the necessary changes in vehicles/fuels to reach a given CO_2 reduction target. For all three cases constant assumptions on population and economic growth have been used. This sensitivity analysis has been developed for OECD and non-OECD countries to highlight the different development pathways.

In the OECD countries the ETP 2012 2DS projection sees a 17% reduction in light-duty vehicle travel per capita between 2010 and 2050 (Figure 5). This assumes that even though the population grows, total travel in industrialized countries is decreasing by 4%, which would be a substantial deviation from the current path. This change in travel is accompanied by a 45% average improvement in vehicle efficiency (reduction in energy/km) to achieve a 47% reduction in energy use. To achieve the desired reduction of 73% (The emission reduction target of 73% has been adopted for the ETP 2012 to be in line with an emission reduction pathway for a 2° stabilization scenario as suggested by the IPCC [8].) in light vehicle well to wheel CO_2 emissions, the ETP 2DS case further assumes a 50% reduction in the carbon intensity of the energy (via shifts to electricity, hydrogen, and biofuels).

The sensitivity case 2 shows what would happen if the reality with regard to reduced travel and modal shift (avoid/shift) fall short of the assumptions made in the ETP 2DS case. The Case 2 uses the travel projections assumed for the ETP 4° scenario, which are a 5% growth per capita and 22% overall between 2010 and 2050. Under these conditions, additional efficiency gains and fuel carbon reductions are required to meet the CO_2 emission reduction target of 73% for the light vehicle fleet in OECD countries. As shown in Figure 5, this could be achieved by improving on-road vehicle efficiency (lower energy/km) by 51% instead of 45% over the 40-year period, combined with reducing fuel carbon intensity (emissions per unit energy) by a similar additional proportion, by 56% instead of 50%.

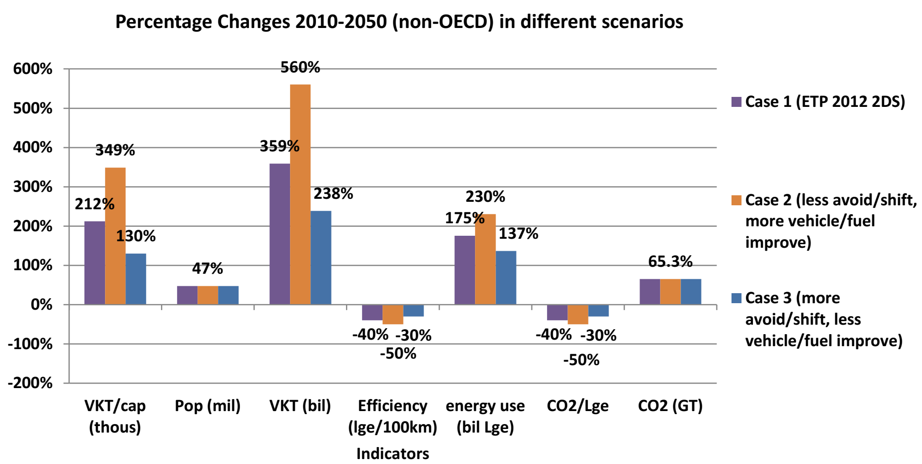
Figure 5. Light vehicle fleet scenarios until 2050 in OECD countries.



The other sensitivity case shows what happens if car travel per capita could be reduced by even more than the 2DS case. Case 3 shows the effects of additional reductions leading to a 37% drop of car travel between 2010 and 2050. While this would require very strong policies and investments to reduce travel and shift towards public transport and non-motorized transport, efficiency would only need to improve by 38% instead of 45% and a 42% drop in fuel carbon intensity instead of 50% compared to the 2DS case.

Figure 6 shows these same cases for non-OECD countries. The results are similar despite a very different underlying situation. In developing and emerging countries, light-vehicle travel per capita triples in 2DS case while fuel efficiency and carbon intensity both improve by 40%, leading to a net increase in CO_2 of 65% by 2050. Considering that emissions in non-OECD countries would more than tripling without any major additional mitigation strategies, this would be a substantial reduction from the baseline. The two sensitivity cases aim to achieve the same target via different approaches. Case 2 allows for travel growth, which means that efficiency and fuel carbon will have to improve by 50% instead of 40%. The lower growth in car travel achieved through sustained high levels of public and non-motorized transport in Case 3 requires lower efficiency and fuel switch, at 30% instead of 40%.

Figure 6. Light vehicle fleet scenarios until 2050 in non-OECD countries.



For both OECD and non-OECD countries, not achieving the car travel paths used for the 2DS case, would mean that vehicle fuel efficiency and fuel carbon intensity will have to be improved to levels that may be challenging, both from a technology and cost-effectiveness perspective [9]. However, the modal shifts and travel reductions assumed in Case 3 may be equally challenging, which clearly indicates that an integrated approach will be required that combines avoid, shift and improve measures.

3.2. The Implications of Different Travel Demand and Modal Share Assumptions on Vehicle Technologies and Fuels

Considerable analysis is needed of policy implications, private and social costs, and the wide range of impacts and sustainability implications of different pathways. However, the high level assessment of the three cases compared in this paper already provides some interesting insights on the relationship of avoid, shift and improve measures.

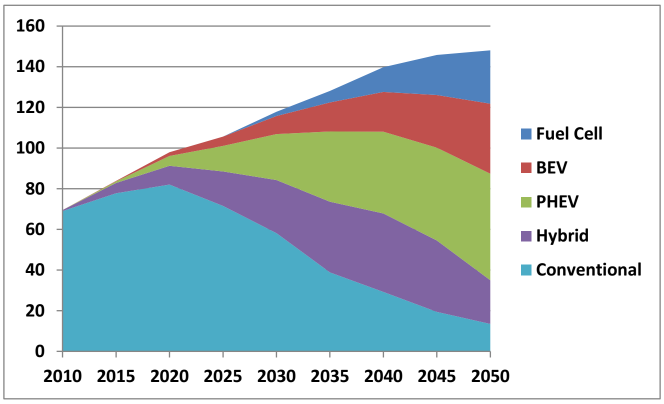
Comparing cases 2 and 3 (the high travel and low car travel sensitivity cases), the requirement for additional fuel efficiency improvements and reductions in vehicle stock energy intensity as explored in the previous section reach levels where cost-effectiveness may become challenging. The significant additional amount of efficiency gains of 13% in OECD countries and even 20% in non-OECD countries represents a range of fuel economy improvements that may become steadily more difficult and costlier. A number of studies have developed cost curves for light duty vehicle fuel economy (e.g., NRC, 2010, ICCT, 2011), summarized by the IEA in its Fuel Economy Roadmap [9]. It finds that, if undertaken today, it would cost an extra €4,000 (USD5,000) per vehicle to move from a 45% to a 60% improvement, compared to around €2,000 to reach the initial 45% improvement. This reflects the upward concavity of the cost curve and increasing marginal cost of technologies to improve fuel economy. The technologies that are deployed start with relatively low cost changes such as 4-valve HDI fuel injection, and eventually move toward adoption of hybridization and expensive light-weight materials. Efficiency improvements can also be achieved through a shift to plug-in vehicles (battery-electric vehicles, plug-in hybrid electric vehicles), likely to be even more efficient than advanced hybrids when running on electricity and electric motors. But the costs of these vehicles will be even higher than advanced conventional vehicles and hybrids, at least in the near term.

It should be noted, however, that over time the costs of advanced efficiency technologies and plug-in technologies will likely decrease, given technology advances and economies of scale, and by 2030 could be well less than the costs for current changes [9,10]. None-the-less, the cost of marginal efficiency improvements between 40 and 60% may remain be over €3,000 (USD4,000) in the near-medium term [9–11]. This is likely to hold for both OECD and non-OECD, since the technologies are likely to be similar.

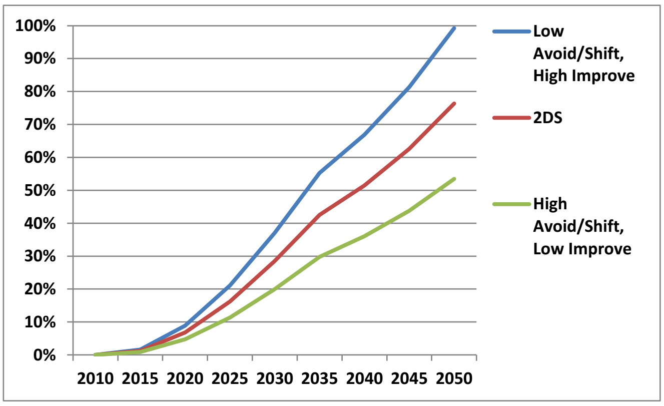
The CO_2 intensity of fuels can be improved through a combination of uptake of plug-in vehicles, fuel cell vehicles and their new fuels, electricity and hydrogen respectively [1,6]. Advanced biofuels can also play an important role in reducing average fuel carbon intensity. However, all of these technologies and fuels are quite expensive today and associated with a number of uncertainties, which may help to explain why they are not yet fully commercial, though sales of electric vehicles have increased rapidly in the past two years [1]. Attempting to estimate how the cost of deploying these new vehicles and fuels will change over the next two decades, and in particular how costs may change in the range of sales that reduces average CO_2 intensity from 40% to 60%, is quite speculative [9–11]. Hence, strategies that heavily rely on advanced technologies and fuels contain a higher level of risks and uncertainties.

Figure 7a,b illustrate the changes in sales and market shares of advanced technology vehicles that occur in 2DS case compared to the two sensitivity cases developed (Low Avoid/Shift, and High Avoid/Shift) through 2050. It shows how the sales share of these technologies would need to change in the higher and lower car travel cases to meet the combined CO_2 emission reduction target for both, OECD and non-OECD countries. In the ETP 2DS, new technology vehicles such as plug-in hybrid (PHEV), battery electric vehicle (BEV) and fuel cell vehicles (FCEV) will have to increase their market shares very rapidly after 2030 to achieve a high combined share by 2050 and provide both efficiency improvements and fuel carbon reductions (Figure 7a). Figure 7b shows these three plug-in vehicle types together in the three different cases; in the 2DS it can be seen that these reach over 75% market share in 2050, and even by 2035 they reach about 45% of global light-duty vehicles (LDV) sales. In the Low and High Avoid/Shift cases, the sales share ranges from 50% to 100% of new LDVs in 2050, and 30% to 60% in 2035. These are very significant differences, which suggests that the Low Avoid/Shift and High Improve case would require much faster market penetration rates, while the and High Avoid/Shift and Low Improve case would compensate for slower progress in technology uptake.

Figure 7. New technology light-duty vehicle (LDV) sales in 2-degree scenario (2DS) (**a**) and combined (battery electric vehicle (BEV) + plug-in hybrid vehicle (PHEV) + Fuel cell) sales share in three cases (**b**).



a

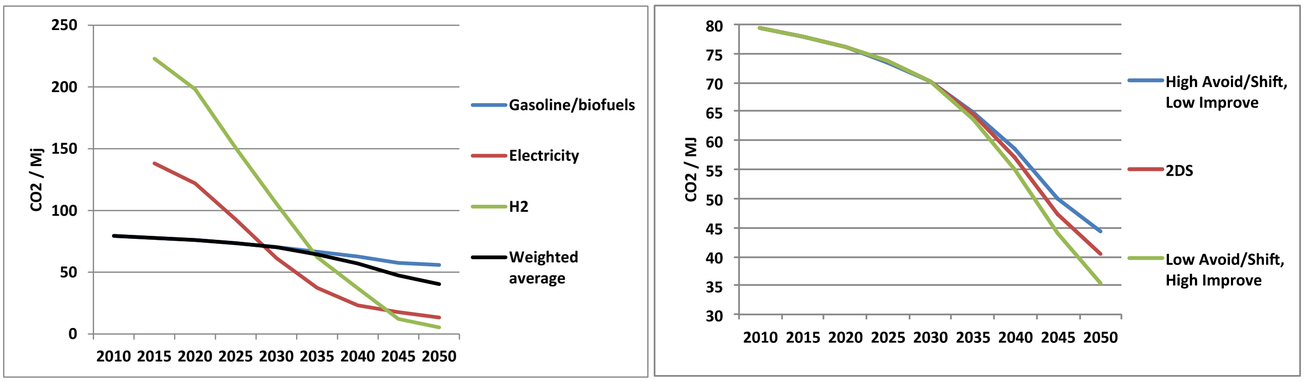


b

Figure 8a below shows the well-to-wheel (WTW) carbon intensity (CO_2 per MJ) of the major fuels in the 2DS case, along with the weighted average fuel intensity based on the consumption of the different fuels. This corresponds to the vehicle technology sales shares explored in Figure 7. Although biofuels help bend the curve for liquid fuels somewhat, the increasing use of electricity and hydrogen in plug-in and fuel cell vehicles serve to strongly decrease the average LDV fuel carbon intensity after 2035, when these vehicles and fuels have reached substantial market shares (Figure 8a). This is also shown in Figure 8b as the middle line, which clearly shows a drop in CO_2 g/MJ from 70 in 2030 to 40 in 2050, providing a direct reduction in CO_2 intensity of nearly 50%.

Figure 8b also shows the two alternative cases, and the effect of the additional advanced technology vehicles in the High Improve case, and the fewer vehicles in the Low Improve case. The difference in average fuel intensity ranges from 45 to 35 CO_2. An additional reduction in CO_2 intensity comes from on-going required increases in biofuel share. In the 2DS case, this reaches about 30% of the liquid fuels share, and is increased to about 40% in the Low Avoid/Shift and High Improve case in order to bring the overall fuel carbon intensity down to the target level (not reflected in this figure).

Figure 8. LDV Fuel Carbon Intensity in 2DS (**a**) and weighted average intensity in all three cases (**b**).



a **b**

While it is difficult to assess how the three cases compare with regard to their cost-effectiveness and technological and political feasibility over time, it becomes apparent that a combined approach as suggested in the 2DS case, potentially with an even stronger focus on Avoid/Shift measures may be required. A larger role for technology and fuels than suggested in the ETP 2012 2DS case may require a substantial boost in the transition toward low-carbon vehicles and fuels, which may become very challenging in terms of investment rates into new production systems and consumer acceptance of new types of vehicles and fuels. It will take additional analysis to better estimate the actual costs and benefits in these scenarios and attempt to quantify the level of policy stringency that may be needed to achieve them, but it seems clear that both sensitivity cases would require strong policy packages to foster modal shift, reduce travel demand and/or boost fuel efficiency and technology take-up, compared to a more balanced approach as explored in the IEA ETP 2012 2DS case.

4. Conclusions

The cases presented here test the validity of the light-duty vehicle fleet scenarios developed for the IEA Energy Technology Perspectives 2012. The sensitivity analysis indicates that a comprehensive approach to road passenger transport CO_2 emission reductions requires a mix of all available options, including measures to reduce travel demand and foster modal shifts (Avoid/Shift) and improvement in vehicle technology and fuels (Improve). However, they also suggest that if very strong efficiency improvements and fuel switch measures could be achieved, it is possible to meet CO_2 emission reduction targets without major changes in travel demand. Similarly, stronger shifts to low-carbon modes, such as public transport and non-motorized transport would require less effort with regard to low-carbon technology and fuel uptake.

This paper lays out some comparisons between different approaches and how changes in travel affect what is required in terms of efficiency and fuel changes. It has not attempted to quantitatively assess which of these approaches is more likely to succeed or which has the lowest societal cost. A more in depth analysis would be required to assess how fast sales of new technologies, such as plug-in and fuel cell vehicles can increase, and whether the penetration rates in the Low Avoid/Shift and High Improve case are feasible, at what cost, would help better evaluate the various options. However, the analysis already provides some indication that the costs and policy challenges to achieve this case could be substantial.

Similarly, more work is needed to understand whether the Avoid and Shift changes shown in the different cases are achievable, at what cost, and with what types of policies. It is likely that cutting LDV travel by about 30% in OECD, and cutting growth in LDV travel by nearly 2/3 in non-OECD countries as suggested in the High Avoid/Shift and Low Improve, will require major policy initiatives and massive investments in alternative modes of travel at the city and national level all over the world.

Though not the focus of this paper, it should be remembered as well that transport CO_2 mitigation strategies primarily focusing on fuels and technologies are not likely to deliver on the full potential of co-benefits. Efficiency improvements and most fuel switch options (e.g., electric vehicles, provided the electricity is derived from a low-carbon, low polluting power source) will affect local air quality positively. These measures are unlikely, however, to reduce congestion or improve safety and may even impact on accessibility and affordability. Hence, an integrated, multimodal climate change mitigation strategy for the transport sector is likely be more cost effective and will also generate a higher level of co-benefits, while reducing uncertainties associated with some advanced vehicle technologies.

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Conflict of Interest

The authors declare no conflict of interest.

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Integrating global climate change mitigation goals with other sustainability objectives: a synthesis

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Short title: Integrating multiple objectives
Keywords: Welfare-theoretical framework, multiple objectives, co-benefits, air quality, energy security, energy efficiency.

Abstract: Achieving a truly sustainable energy transition requires progress across multiple dimensions beyond climate change mitigation goals alone. To inform climate policy choices at different governance levels, this paper reviews and synthesizes results from disparate literature strands on the co-effects of mitigation. The literature documents a large potential for mitigation co-benefits for non-climate objectives such as human health and energy security, but little is known about the overall welfare effects. Integrated model studies highlight that climate policies as part of well-designed policy packages reduce the overall cost of achieving multiple sustainability objectives. The incommensurability and uncertainties around quantification of co-effects are increasingly pervasive the more the perspective shifts from sectoral and local to economy-wide and global; the more objectives are analyzed; and the more results are expressed in economic rather than non-monetary terms. Drawing on different strings of evidence highlights the role of energy efficiency for realizing synergies across multiple sustainability objectives.

Integrating global climate change mitigation goals with other sustainability objectives: a synthesis

1. Introduction

A large body of literature has looked at the challenge of meeting stringent climate targets (1–6). However, many argue that stringent climate change mitigation goals are a necessary, but insufficient condition for a sustainable energy transition (7). Other key sustainability objectives include air quality and health, the provision of affordable energy services for all, energy and food security as well as minimizing energy-related land and water use and biodiversity loss. Mitigation efforts should hence be assessed in a multi-objective framework (8–12) which would need to consider the energy transition as a multi-level governance challenge. On the one hand, climate change mitigation is a global commons problem that warrants a coordinated global response (13, 14). In fact, the integrated model literature has shown that achieving particular mitigation goals, such as the 2°C target, is most cost-effective if approached from a global perspective and entails high long-term global benefits at considerable short-term costs (15, 16). On the other hand, most climate policies are increasingly formulated at national and even sub-national levels (17–19). At these levels, many of the other non-climate objectives are often more salient as policy drivers. Since mitigation co-benefits hold the prospect of helping achieve some of these other objectives and reducing the short-term costs of climate policies that accrue on the local/national level, the concept has recently attracted increasing attention. Hence, for implementing a comprehensive energy strategy, tailored information on the interaction between mitigation and other sustainability objectives is required to guide choices within a multi-level governance framework ranging from the global to the national and sub-national levels.

Starting from the assessment of global integrated model results, the IPCC Working Group III contribution to the Fifth Assessment Report (WGIII AR5) highlights that there is no single, preferred portfolio of mitigation measures for cost-effectively meeting any specific temperature goal. Instead, there is flexibility in how a particular mitigation goal can be achieved: the timing of GHG emissions reductions, the choice of particular sets of low-carbon energy supply technologies and their upscaling requirements, among others, can substantially differ across scenarios, both globally and locally (1). Policymakers can increase the level of flexibility by enacting policies that help reduce energy demand (5, 20). The WGIII AR5 suggests that national and local policymakers can utilize this flexibility by choosing mitigation measures according to national/local circumstances and preferences, such as the level of socioeconomic and technological development, distributional aspects, risk perceptions and priority settings for non-climate objectives (7, 19, 21).

Although there is a wealth of relevant literature on synergies and tradeoffs across mitigation and non-climate objectives, evidence remains scattered across different sectoral studies, different research communities, and across different scales of analysis, which makes it generally inaccessible for decision-making. As with the rapid expansion of literature in climate science in general, there is a void of meaningful interpretation of the 'sum' of the individual sets of results (22, see also 23, 24, and 25 for bioenergy research). The benefits of integrating sectoral evidence with evidence from scenario studies have been highlighted in recent reviews (23, 26–29). Such an integrated perspective is highly relevant for decision-making because it advances the understanding of the practical implications of alternative climate policy choices for other human and policy dimensions (8, 10, 12, 30).

In this paper, we try to connect relevant strings of evidence on the interaction between mitigation and other sustainability objectives which is scattered across many different bodies of literature and different scales of analysis. By doing so, we generate new insights and identify robust evidence for policymakers – even for those places for which no scientific evidence is available directly.[1] This article focuses on a global perspective

[1] In practice, the stated rationale of a particular climate policy at the national or local level may not be restricted to mitigation and may be different in different contexts. In fact, mitigation is often considered the co-benefit of other policies primarily aimed at environmental, health and development policies (19). The aim of this paper is, however, less to illuminate the different drivers of implementing mitigation-related policies at the national or local level but it rather tries to synthesize existing

since it aims at making insights on the interaction across mitigation and non-climate objectives relevant for understanding the global energy transition challenges. The WGIII AR5 already made important progress in assessing this broad literature by i) providing both a welfare and a sustainable development (SD) framing for mitigation policies in a multi-objective context, ii) assessing the literature on co-effects of mitigation measures in different sectors, and iii) assessing the integrated model literature on co-effects on a global scale. But it only provided a limited synthesis which is divided across several chapters of the report, which hindered a comprehensive view with more far-reaching insights on this important topic. The authors of this paper further condense and expand the synthesis of this material by presenting the different chapters' results at one glance (see Tables 1 and 2), providing a comprehensive conceptual framework for synthesizing the relevant bodies of literature, analyzing the challenges to quantitative aggregation of co-effects, particularly on a global scale, presenting a way forward to usefully draw on existing strings of evidence, discussing the high-level insights gained from this grand synthesis, and pointing to a promising research agenda for multi-objective literature and its synthesis.

To that end, Section 2 provides a welfare-theoretical framework that will serve as an organizing device for the review and condensation of sectoral research results in Section 3 and of integrated model literature results in Section 4. These sections discuss the different aspects different communities have focused on in their analysis of the interaction across mitigation and multiple other objectives, pointing to the respective strengths as well as the caveats for quantitative synthesis. Section 4.3 critically discusses the extent to which integrated models are actually able to assess changes in welfare while Section 5 suggests one possible way forward to make multi-objective implications of climate policy choices more transparent by drawing on the respective strengths of these different communities. Although this approach does not eradicate the incommensurability in aggregation of various co-effects, particularly on a global scale, it deals with the uncertainties of the different sets of results in a more transparent way and makes them more accessible to decision makers who would like to understand how to maximize synergies and minimize tradeoffs across multiple objectives.

2. A conceptual framework for assessing the co-effects of mitigation

Despite a long-standing interest in the 'co-effects of mitigation' (see, e.g., 31), there is no commonly agreed terminology. For example, positive (negative) co-effects are referred to in the literature as 'co-benefits' or 'ancillary benefits' ('co-costs', 'ancillary costs' or 'tradeoffs'), but these terms have been defined differently across studies (see 11 for a review). This is largely because the same terms have been used to describe a range of effects based on different methodological approaches. To enable a structured review and condensation of the insights from different bodies of literature and to motivate our usage of terminology, we introduce here a conceptual welfare-theoretical framework.

Suppose social welfare W can be written as a function of different objectives z_i ($i = 1, \dots, m$); the attainment of each of those objectives is influenced by the deployment of a number of technological or other measures m_k ($k = 1, \dots, n$) which, in turn, are influenced by the implementation of a number of policies, p_l ($l = 1, \dots, o$). Now consider a marginal change dp_l in one or more policies. Building on the conceptual framework presented by Kolstad et al. (32), but highlighting the important role of the broad set of measures through which policies often impact objectives, the net effect on social welfare effect is given by:[2]

Equation 1. $$dW = \sum_{i=1}^{m} \sum_{k=1}^{n} \sum_{l=1}^{o} \frac{\partial W}{\partial z_i} \frac{\partial z_i}{\partial m_k} \frac{\partial m_k}{\partial p_l} dp_l$$

Based on these considerations, we define co-benefits (or adverse side-effects) as the positive (or negative) effects on an objective that is not directly targeted by a given policy ($\frac{\partial z_i}{\partial m_k} \frac{\partial m_k}{\partial p_l}$ for $l \neq i$), leaving aside the implications for social welfare (not multiplied by $\partial W / \partial z_i$, i.e. the value different individuals or society as a

evidence on the global implications for multiple objectives and social welfare if governments embark on alternative global mitigation pathways.

[2] Please note that spatial, temporal and distributional dimensions have been omitted from Equation 1 although they will be discussed where relevant. A discussion of changing governance conditions is beyond the scope of this paper.

whole attach to the co-effect). This differentiation between the non-monetary effect on a particular objective and the associated welfare effect is important because the overall magnitude is determined by the two effects in combination, which may also work in different directions (see Section 4.3). Moreover, co-effects are often reported in non-monetary or even qualitative terms only, because they are challenging to measure, quantify and monetize due to a variety of practical obstacles such as data availability (see, e.g., 11, 33, 34).

We apply this framework as a structuring device for the review and condensation of the literature, which can be roughly classified into three broad strands of literature. After a brief introduction to the main characteristics of these three literature strands, Figure 1 relates them to each other at one glance as well as to the most important terms and concepts that are used throughout this paper. It shows that the foci or system boundaries of the different literature strands are very different, with an increasing ambition of integrating the different related concepts from strand 1 to 3 – which implies an increasingly thin literature base.

Literature strand 1 – from climate change mitigation measures to multiple objectives ($\frac{\partial z_i}{\partial m_k}$): The first strand of literature links mitigation measures m_k $(k = 1, \dots, n)$ – defined here as "technologies, processes and practices that contribute to mitigation" (35) – to other sustainability objectives z_i $(i = 1, \dots, m)$. In particular, it characterizes these mitigation measures in terms of their multiple co-benefits and adverse side-effects for non-climate objectives, mostly in the context of specific sectors/applications and locations (see Section 3). Other co-effects accrue to stakeholders outside the sector/location (upstream, downstream or downwind). Such evidence can inform technology choices of national and local policymakers by highlighting potential co-effects of mitigation measures for other objectives. This task remains challenging, however, because the wealth of evidence is scattered across multiple research communities and studies, each dealing with specific aspects, sectors, locations, sometimes policies, and neglecting cross-sectoral and cross-regional interactions of policies, technology choices and the associated effects on social welfare.

Literature strand 2 - from climate policies to mitigation measures to multiple objectives ($\frac{\partial z_i}{\partial m_k}\frac{\partial m_k}{\partial p_1}$): The second strand of literature analyzes the implications of a stylized global climate policy p_1 (i.e. global mitigation goal) for other sustainability objectives z_i $(i = 2, \dots, m)$ via the deployment of cost-effective portfolios of mitigation measures m_k $(k = 1, \dots, n)$ and the resulting macroeconomic mitigation costs ($\frac{\partial W}{\partial z_1}$).

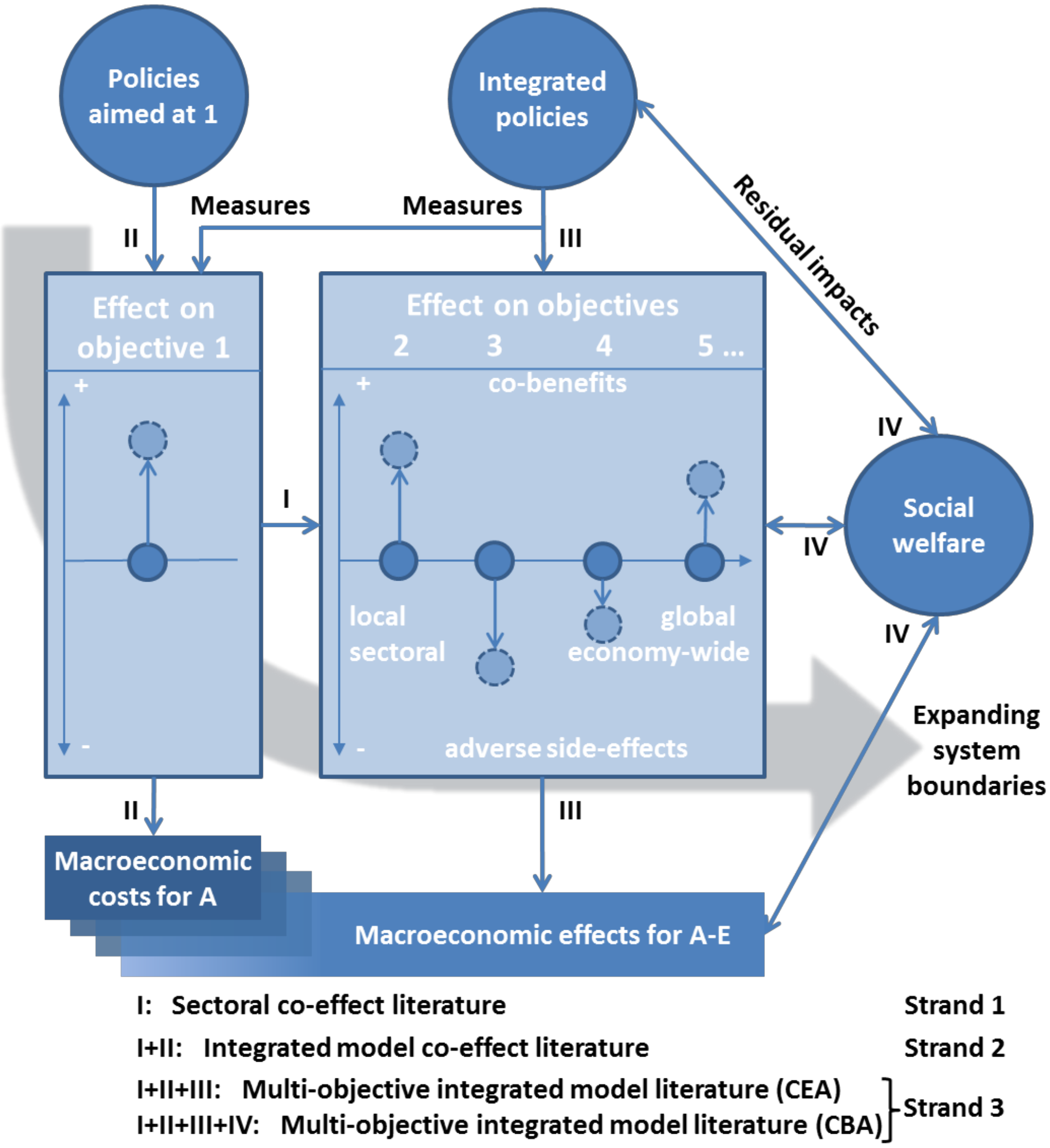

Figure 1: Schematic overview of important terms and concepts linked to the different literature strands on the interaction across mitigation, other objectives and social welfare, following Equation 1.

The analysis has been largely limited to co-effects of mitigation on only one other sustainability objective at a time – and in some cases vice versa (see Section 4.1). This body of research can be an important source of evidence for policymakers, potentially changing the incentive structure for global mitigation efforts, if near-term benefits for other objectives (e.g., local air quality) were taken into account more explicitly (34, 36–42). Yet, this strand focuses on the co-effects of mitigation pathways in non-monetary terms and does not consider interactions across climate and non-climate policies or the resulting macroeconomic effects (beyond aggregate mitigation costs).[3]

Literature strand 3 – from integrated policies to measures to objectives to welfare ($\frac{\partial W}{\partial z_i}\frac{\partial z_i}{\partial m_k}\frac{\partial m_k}{\partial p_l}$)*:* The third strand of literature adds another step by not only considering how integrated policies p_l ($l = 1, \ldots, o$) via different measures m_k ($k = 1, \ldots, n$) contribute to multiple objectives z_i ($i = 1, \ldots, m$), but also analyses their respective macroeconomic effects ($\frac{\partial W}{\partial z_i}$). To analyze the aggregated importance of the synergies and tradeoffs

[3] Barker et al. (43) reviews studies that apply CGE models for evaluating the welfare impacts of mitigation vis-à-vis non-climate policies, but with a focus on specific regions and policies (e.g. Chile and China); they are thus not suitable for drawing lessons for a global scale and longer time horizons.

among multiple objectives resulting from alternative policy packages on a global scale, different integrated models have sought to extend their system boundaries to embrace a multi-objective perspective. Since welfare effects are only significant in second-best environments (i.e. if there are multiple externalities which are not fully internalized, see Section 4.2), the existing studies look at a smaller set of objectives than the other literature strands to deal with rising complexity (see Section 4.3). While one modelling approach compares many different future mitigation scenarios based on different combinations of policies to achieve different levels of multiple energy policy objectives (cost-effectiveness analysis, CEA), another modelling approach equalizes marginal costs (including residual impacts) and benefits (including avoided impacts) to determine socially optimal policy stringencies (cost-benefit analysis, CBA). Due to major conceptual challenges in integrating several objectives in a decision framework, this evidence base is still in its infancy (7, 8, 32, 44, 45).

3. Sectoral research results on the co-effects of mitigation measures

This section provides a qualitative meta-analysis of the many existing studies on mitigation co-effects from the sector-specific research assessed in WGIII AR5, in order to expand its high-level findings and the associated implications for multi-objective decision-making. The section also identifies the most important caveats that are associated with the quantification and global aggregation of co-effects – often referring to literature on air pollution because it is the most thoroughly researched co-effect (11, 34, 39).

The qualitative meta-analysis in Table 1 on potential co-effects of sectoral mitigation measures for a wide range of sustainability objectives builds on several hundred studies that were published after the WGIII AR4 (46) and assessed in the different sector chapters of the WGIII AR5 (47). Although the underlying studies were often conducted for locally specific circumstances, the potential for such effects in one place often implies that they are possible or even likely in other places with similar circumstances. While some studies are able to draw on existing data for some of the sectoral measures (particularly bioenergy), most studies on co-effects are forward-looking since many mitigation measures are not yet implemented for various reasons. The extent to which any of these effects will eventually materialize also depends on other factors, such as the scale, scope, and pace of implementation of the mitigation measures, which are not discussed in detail here. In the Supporting Material (SM), the reader can find condensed information on the co-effects from this table in the context of the respective sector. Two broad messages that are globally relevant for decision-making can be derived from this meta-analysis:

(i) For mitigation measures on the demand side, the potential co-benefits outweigh the risks; on the supply-side, the balance depends to a larger degree on the specific measure (1). This implies that measures to reduce sectoral energy demand are a robust strategy across multiple objectives but that the overall co-effects of fuel switching are not as clear-cut (see below). In these cases, the number of potential positive vs. negative effects is not necessarily a good indication for the net effect on welfare because some large effects in terms of the change of non-monetary indicators may have very small welfare effects – and vice versa (see Section 4.3).

(ii) Multi-objective decision-making on climate change mitigation can build on a wealth of evidence on different co-effects for many policy-relevant objectives. In fact, the scientific literature covers the co-effects of most sectoral mitigation measures for objectives like energy security and reduced health and ecosystem impacts. This is, however, not the case for all objectives: some effects seem to be rather idiosyncratic to specific (groups of) measures as shown in the last column of Table 1, highlighting the question of how to compare those different effects. If no arrow is shown, this can either imply that an effect is unlikely to materialize or that no scientific literature is (yet) available on this effect.

Table 1: The wealth of evidence from sectoral research on the potential co-effects of (groups of) sectoral mitigation measures on additional objectives; green arrows: potential co-benefits; orange arrows: potential adverse side-effects; smaller arrows: small-scale effects by comparison; blue shaded cells: potential effects outside the location of implementation; based on a qualitative meta-analysis of the

sectoral literature on non-monetary indicators for co-effects in the WGIII AR5 sector chapters on energy supply (20), the transport sector (48), the buildings sector (49), the industry sector (50), and for bioenergy (51). Due to space constraints, the table focuses on the effects for which a considerable amount of studies exists. To facilitate a structured overview, the mitigation measures on the demand side and the associated co-effects are classified into three broad strategies: (i) fuel switching to low-carbon energy carriers/fuels; (ii) technical energy efficiency improvements and (iii) energy demand reduction through other means (e.g., behavioral/structural changes) – largely following Edenhofer et al. (9). The co-effects for the different sustainability objectives are classified along the three SD pillars – economic, social, environmental (see Fleurbaey et al. (7) on the relation between multiple objectives and SD). Whereas some objectives can be regarded as ultimate endpoints (e.g., health), others are intermediate endpoints (e.g. water pollution), following the availability of information.

		Sectoral mitigation measures	Economic			Social			Environmental			Other objectives
			Energy security	Sectoral	Local/sectoral	Reduced health	Thermal	Safety/	Reduced	Reduced water	Reduced land	
Low-carbon energy supply	(replacing coal)	Nuclear	↑ [a]		↑	↑↓		↓	↑↓			Proliferation, nuclear waste
		Non-combustion renewables	↑		↑	↑			↑↓	↑↓		(Off-grid) energy access; Increased resource mining
		CO_2 capture & storage (CCS)			↑↓	↓		↓	↓	↓		Long-term monitoring of CO_2
		Bioenergy with CCS; (excl. co-effects of bioenergy)				↓		↓	↓	↓		Long-term monitoring of CO_2
		Bioenergy[b]	↑		↑↓	↑↓			↓[c]	↓	↓	Food security and equity in land tenure
Transport		Fuel switching	↑			↑[d]		↑	↑↓			Technical spill-overs to DCs
		Technical energy efficiency	↑			↑		↑	↑			
		Urban form/modal shift[e]	↑	↑	↑↓	↑		↑	↑		↑	Equitable mobility access
		Energy demand reduction	↑	↑		↑			↑↓		↑	Reduced urban congestion
Buildings		Fuel switching	↑		↑	↑			↑			Reduced fuel poverty
		Technical energy efficiency[f]	↑	↑	↑	↑↓	↑	↑	↑	↑		Reduced fuel poverty
		Energy demand reduction[g]	↑			↑			↑			
Industry		Fuel switching (incl. CCS)		↑		↑	↑		↑	↑		Increased competitiveness
		Technical energy efficiency	↑	↑	↑	↑	↑	↑	↑	↑		Technological spillovers
		Material efficiency			↑	↑		↑	↑			Reduced resource mining

[a] The co-benefit relates to reduced exposure to fuel price volatility; the concentration of the nuclear supply chain may, however, lead to long-term stresses (52); [b] The co-effects of bioenergy heavily

depend on the development context and the scale of the intervention. Other AFOLU measures are not included in this table because these are not directly related to energy transition (see 25, 51, 53 for an overview); [c] this is mainly valid for large-scale monocultures; [d] excluding diesel; [e] Land use planning can create the underlying conditions for co-located higher employment and residential densities that are necessary to support the use of public transport (see 18) [f] including efficient equipment as well as insulation interventions; [g] based mainly on behavioral changes.

It is, however, difficult to gain more than qualitative insights for policymaking in one place, if the quantitative evidence is based on locally specific circumstances, policies and assumptions from another. For example, the net effect of fuel switching on other objectives depends to what extent the benefits of switching away from high-carbon energy carriers dominate the context-specific balance of co-effects due to the increased supply of low-carbon energy carriers. The net effect also depends on how individual measures are implemented, affecting the degree to which each unit of low-carbon energy actually replaces one unit of high-carbon energy (54). Many studies discuss the example of biofuel deployment and its effect on total global fuel consumption but do not agree on the quantitative importance (e.g., 55, 56). In the same way, energy efficiency measures in the energy end-use sectors may not necessarily lead to the possible energy demand reductions due to rebound effects – which also differ across different locations (49, 57). In fact, a multitude of changes (e.g. in climate and non-climate policies, energy prices as well as energy supply and demand due to technological and behavioral change) makes any comprehensive analysis highly complex and estimations of these rebound effects vary widely (20, 48, 58). To address this challenge of context-specific circumstances in Table 1, the underlying assumption of the first part of the table that each unit of low-carbon energy supply replaces one unit of coal (instead of a locally specific energy mix) is a required specification to establish a baseline against which the lower-carbon energy supply technologies can be evaluated with respect to other objectives.

This implies that any quantifiable results reported in the literature depend largely on the system boundaries chosen for the analysis of individual studies. In contrast to the cross-regional, cross-sectoral mitigation perspective adopted by the integrated models discussed in Sections 4 and 5, sectoral research on the co-effects often focuses on a particular place/country. This allows the research to take into account locally specific detail, which in turn is useful for informing national policy priorities and processes, but less useful as a basis for generalized results. The diverging foci can partly be explained by the fact that mitigation effects are independent of the place of GHG emission reductions while many of the co-effects are most salient as policy drivers at the local scale (19, 39, 59).[4]

Moving beyond technological aspects, the empirical projections for co-effects of individual sectoral studies also depend on explicit or implicit assumptions on the effectiveness of existing or planned non-climate policies at the national and local level that target the additional objectives directly, i.e. the projected baseline developments in the absence of climate policies (33, 41, 58, 63, 64). For example, the effects of mitigation measures on air pollution will usually differ between wealthier and poorer countries due to more stringent air quality policies in richer places and, hence, a lower base of pollutants squeezing the potential health gains (33, 39, 60, 62, 65, 66). The extent to which co-effects will materialize also depends on geographical characteristics – even within a specific country, such as differences across rural and urban contexts – and socioeconomic circumstances that cannot be shaped by policies, at least in the near to medium term, such as different indoor/outdoor activity patterns and the concentration of population which impact the associated exposure to air pollution (28, 33, 43, 67)

Despite these caveats in quantifying the co-effects of mitigation policies already in non-monetary terms many researchers have gone one step further by monetizing them, building on economic valuation techniques that

[4] The most notable exception are emissions of non-GHG air pollutants which are reduced along with GHG emissions reductions when fossil fuel combustion is avoided. Their analysis also draws on regional and global models (see, e.g., 41, 60–62) because the impacts of many air pollutants are not confined to the place of emission. See section 4.1 for a discussion of their climate effects.

are used in research fields such as health and environmental economics (11, 32, 67). Some of the studies on monetized health co-benefits through air quality improvements, for example, cover a wide range of estimates: \$2-840 per ton of CO_2 saved (see 39 for an overview, 62 for the upper estimates). This is due to, inter alia, consideration of diverse locations, mitigation and air quality policies, pollutants, impact channels, economic sectors, time horizons, and valuation techniques (see, e.g., 33, 39, 43, 58, 68).

In conclusion, many of the qualitative results for the various co-effects of mitigation measures derived in the context of one location are critical for decision-making in that location, and can also be helpful for decision makers elsewhere to gain an overview of the potential effects of the many available sectoral mitigation measures. At the same time, any quantitative aggregation, particularly on a global scale, of sectoral research results on co-effects beyond the qualitative meta-analysis presented above remains challenging due to the incommensurability in results across effects, sectors and locations – despite the vast amount of literature that has developed recently. This is, however, a prerequisite for a detailed understanding of the importance of synergies and tradeoffs across mitigation and the multiple other relevant objectives. The next section will thus discuss quantitative results from integrated models on this interaction, building on a unified framework of analysis with respect to future global climate policy and a number of harmonized exogenous key parameters across models (see SM) – making their results at the global level more comparable and accessible to decision makers – but at the expense of the rich sectoral details presented above.

4. Integrated model results on the interaction across mitigation and other objectives

The results on the interaction across mitigation and other sustainability objectives from integrated model studies assessed in the WGIII AR5 (1) are further condensed and discussed in this section to expand on the high-level findings and the associated implications for multi-objective decision-making. One important advantage of this literature is that the deployment projections capture cross-regional and cross-sectoral interactions of mitigation measures.[5] Based on the methodological insights on the co-effects of specific objectives from the sectoral literature (see Section 3), the integrated models have expanded their system boundaries to analyze the interactions across global mitigation goals and additional objectives in one research set-up, such as air quality and its health implications, energy security, energy access, as well as minimizing energy-related biodiversity loss and water and land use. While the majority of these studies focus on the co-effects of mitigation pathways on one other objective, or vice versa, in non-monetary terms (see Section 4.1), a few recent analyses have looked at the interaction across multiple objectives simultaneously, in some cases even taking welfare effects into account (see section 4.2). A thorough analysis of such welfare effects with numerical models requires a consistent formulation of policy and counterfactual baseline scenarios. Section 4.3 critically discusses these issues as well as the associated cost metrics used in integrated models to convey information on macroeconomic and welfare impacts.

4.1. Integrated model results on the co-effects of mitigation pathways

In the integrated model literature, there is increasing attention to the interaction between mitigation and additional objectives (10, 70). Table 2 offers a condensed overview of those studies looking at (i) the co-effects of different mitigation pathways and, (ii) the reverse direction, i.e., the effect on climate change if, e.g., air quality policies are pursued (as indicated by the arrows in the 2nd column).

An increasing body of literature has explored the linkages between air pollutant and climate policies (see 71, and 72 for a review). These studies indicate significant mitigation co-benefits for a number of different pollutant emissions – up to 50/35/30%/22% reductions by 2030 of SO_2, NO_x, $PM_{2.5}$, and Hg emissions or concentrations against baseline scenarios, respectively (10, 41, 73, 74).[6] At present, only a limited number of

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[5] To keep model complexity manageable, however, this strand of literature typically does not consider detailed policy instruments but rather projects effects of stylized policies – leaving aside the potential interaction between different mitigation policy instruments on different governance levels (19, 69).

[6] Due to the fact that the deployment projections for the portfolio of measures are uncertain with respect to the role of individual measures (even for a particular mitigation goal, such as the 2°C target) and that different models show different results (see SM), the ranges for these results are relatively large (see Figure S.2 for BC and SO_2 emissions).

global integrated models are able to analyze these effects in some detail. The current versions of these models typically estimate the physical air pollution co-benefits of technological changes motivated by mitigation activities (66); in some cases, air quality and human health impacts are also calculated (41). However, explicit representations of air pollution control costs are for the most part not included. What some of the scenarios do consider are clearly specified policy packages for air pollution control, finding that the co-benefits of mitigation depend on the stringency of current and planned air pollution legislation (e.g., 38, 72) (cf. Section 3). Other studies have meanwhile analyzed the reverse mechanism: the impacts of air pollution control measures on the global climate. A key point here is that many of the air pollutants also impact radiative forcing as they form aerosols or act as precursors of aerosols or GHGs, though there is high uncertainty in the estimations (36, 66, 75–78). Studies focusing on the co-benefits of air pollution policies for mitigation show that such actions can potentially reduce net radiative forcing and midterm temperature change by up to 0.2 °C by 2030, but only under somewhat debatable assumptions, such as limited or no improvements in the control of air pollutants that cool the Earth (e.g., SO_2, NO_x) (61, 72, 78). The current science indicates that such climate benefits decrease with increasing mitigation efforts and, more generally, depend greatly on which air pollutants are reduced and to what extent. This is because emissions of SO_2 and NO_x mask global warming due to their cooling effect, whereas emissions of black carbon and tropospheric ozone precursors contribute positively to radiative forcing (58, 75). Several studies go further by noting that reductions in short-lived climate pollutants do not buy substantial time for CO_2 emissions reductions but can act as complementary strategies to concerted mitigation efforts (72, 79, 80). Air pollution policies that are not focused on the co-benefits for mitigation could even exacerbate global warming (66).

A growing body of literature focuses on the energy security implications of climate change mitigation scenarios. From the perspective of energy sovereignty (or risks arising from foreign actors), most of the literature finds that energy trade and imports decline as a result of mitigation (10, 81–85); however, the bulk of this co-effect emerges after 2030, since mitigation limits domestic coal deployment which counterbalances the increase in domestic renewables (86). In addition, the increased sovereignty of major importing nations likely implies a drop in energy export revenues for the Middle East, former Soviet Union and possibly the United States (87–92).[7] Moreover, the geographic diversity of production has been found to increase as fossil fuels are phased out of the system (81, 91).

[7] Though a few studies argue that if cost of unconventional oil were high enough, conventional oil producers may actually benefit from climate policies because this market structure would increase the marginal price of oil (93–95).

Table 2: Overview of integrated model literature results on interactions across mitigation and other sustainability objectives on a global scale as reviewed in Clarke et al. (1), Sections 6.3.5 and 6.6; colored arrows show global mitigation co-effects on additional sustainability objectives; green arrows: co-benefit; orange arrows: adverse side-effect; smaller arrow: small-scale effect by comparison. Studies that looked at multiple objectives simultaneously are discussed in section 4.2 while there results are also included in Table 2 for completeness.

Direction of analysis between objectives			Indicators used most prominently	Direction of co-effects	Scale of co-effects	Key determinant(s) for the size of the co-effects	Most relevant references
Mitigation	→	**Air pollution and health**	SO_2, NO_x, $PM_{2.5}$, Hg emissions or concentrations	↓	2030: up to 50/35/30/22% reductions	Stringency of current/planned air pollution regulation, ratio of abated warming vs cooling air pollutants	(10, 36, 41, 61, 66, 72–75, 78, 96)
	←		Midterm global °C change	↓↑	2030: fraction of 1°C in both directions (effect low after 2050)		
	→ →	**Energy security**	Electricity diversity Import dependence Cumulative oil extraction	↑ ↑↓ ↓	2050: 13–36 % increase 2050: 10–70% decrease[a] 2050: 2–36% decrease	Energy resource endowment, type of policies pursued, energy supply restrictions & current and future usage	(10, 81, 83, 84, 86, 88, 90, 97)
	←		GHG emissions	↑	> CO_2 emissions vs baseline		
	→	**Energy access**[b]	People with modern energy access, GJ per capita	↑↓	**?** (off-grid RE access vs higher energy prices)	Type of fuel used by the poor and policies to support switch to modern energy services	(10, 41, 70, 98–101)
	←		GHG & short-lived climate pollutant emissions (SLCP)	↑↓	**?** (more GHGs/less SLCPs)		
	→	**Biodiversity loss**	Loss in mean species abundance (MSA)	↓↑	2050: halving MSA loss (direct and co-effect)	Land use policies and policies for re/afforestation & bioenergy	(70)
	←		CO_2 emissions from land use	↓	2050: lower CO_2 emissions	Ecosystems protection policies	
	→	**Land use impact**	Million hectares in global land use change	↑	Higher land use change vs baseline (high variance across models)	Land use policies, incentives for re-afforestation/bioenergy, soil quality, yield growth	(102–110)
	→	**Water use impact**	number of people in severely water-stressed regions	↓↑	2050: -8–3% (most studies: small reduction) (direct and co-effect)	Implementation practice of water-intensive mitigation options (e.g. bioenergy, afforestation)	(70, 111–114)

[a] Interregional energy trade is used in the underlying studies as a global proxy for regional import dependence. [b] Energy access here refers to basic needs for clean, reliable and affordable energy services and should not be confused with the increased demand for energy services that, at least historically, has been driven by broader economic growth (1).

The upside of lower extraction rates is fewer concerns over resource scarcity and the related price volatility (81, 86, 115). The literature also finds that mitigation leads to higher resilience from diversification of energy sources in transport and electricity (10, 81, 83, 86). What is missing from the limited scenario literature on the linkages between energy security and mitigation is, for instance, a broader treatment of robustness concerns related to systemic failures from discontinuities and shocks (116) and a more systematic analysis of the climate implications of energy security-targeted policies than has been done previously (38, 97).
The impact of climate policy on energy access depends strongly on the actual implementation. While the transition from traditional to modern energy could become somewhat more expensive if GHG emissions would be priced universally, staged implementation of climate policies or dedicated policy schemes could lead to very different results (70). In Least Developed Countries with higher potential for off-grid technologies, scenario studies have shown that the deployment of renewable energy can help to promote access to clean, reliable, and affordable energy services (99, 101).
The impact of policies promoting energy access on climate change are projected to be very small (70, 117). As energy consumption of the world's poorest is very low and modern energy carriers can be used much more efficiently than traditional ones, studies have shown that there is negligible impact on global CO_2 emissions over baseline developments, even if traditional biomass is completely replaced by fossil fuels (100, 118).[8] Moreover, the use of modern energy also reduces emissions of BC, further reducing the net impact on climate (36, 61, 75).
The interactions between climate policy and biodiversity are complex and beset with increased uncertainty from lack of knowledge regarding detailed functioning of complex ecosystems. The impact of climate policy on biodiversity depends in particular on the net impact of avoided climate change (and associated changes in air pollution) and the possible impacts of mitigation measures such as the use bioenergy and forestry-related measures (impact here depends on the specific measure). PBL (70) shows that unless bioenergy is regulated, the negative impacts might in the next decades dominate over the positive ones. In the opposite direction, policies to preserve biodiversity could lead to a reduction of CO_2 emissions from land use, if they lead to a larger forest area at the global scale (70). This not only depends on local policies to protect specific ecosystems, but also on land-use policies in different areas of the world in general (given the potential impacts on food trade).
The relationships between land use and climate policy is complex as there are several, very uncertain relationships and different policies can have very different impacts. For instance, mitigation scenarios tend to use a large amount of bioenergy. Models show that this can significantly influence land use or land tenure as land is needed for bioenergy production, potentially leading to a reduction of natural areas (and associated GHG sinks and/or less area for food production). The exact impact depends on assumptions and modelled impacts on (induced) yield changes, dietary patterns, trade policies, land policy and other GHG policies. The latter could, for instance, lead to an incentive not to increase (or even decrease) natural area. At the moment, most integrated models capture only some of these relationships, and the net impact is difficult to assess given the uncertainties involved (23, 26, 28, 51, 70, 106, 109, 110).[9] Most studies agree that, in net, it is the important to account for the adverse side-effects of large-scale use of afforestation and bioenergy, in particular for food security and land tenure concerns (see 25, 53, 104, 106, and 122 for a more in-depth discussion and assessment of many other SD implications).[10] This is why many scenarios in the literature explicitly consider futures with

[8] Pachauri et al. (100) argue that achieving universal energy access could even reduce global GHG emissions if assuming that 20% of traditional biomass is unsustainably harvested today and hence adds to current net GHG emissions.
[9] Under the heading of water-land-energy nexus, however, local trade-offs are analyzed by a growing research community (e.g., 119, 120, 121).
[10] One recent model intercomparison (the first for agro-economic models) found that the effect of lignocellulosic bioenergy deployment rising to about 100 EJ by 2050 on food prices is significantly lower (5% higher prices on average across models) than the potential effects induced by climate impacts on crop yields (25% higher prices on average across models) (123). Since these effects are closely related to land-use impacts, they are not separately shown in Table 2.

limited supplies of biomass for bioenergy purposes; while this may lead to higher mitigation costs in total, the SD risks could be lower (124).

A few studies have looked at the relationship between climate policy and water use. Mitigation reduces water use for fossil-fuel power plants (114; see also SM), but could increase water use for bioenergy production (112, 125; see also SM). Mitigation will also influence the precipitation and evaporation changes associated with climate change, but these are very uncertain (126). Yet, given the current uncertainties, it is challenging to conclude anything on the net impacts at the moment.

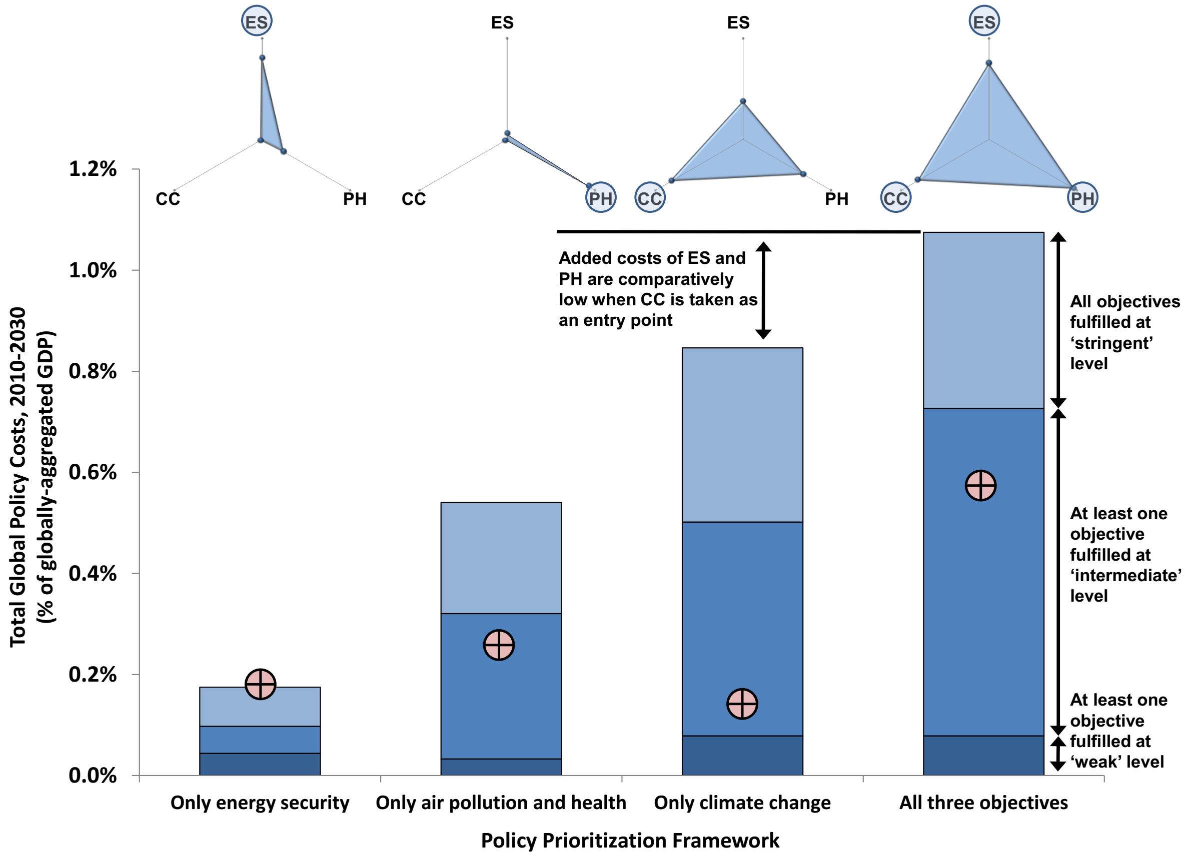
Taken together, the overall evidence on the implications of stringent mitigation goals on other objectives – often from multi-model scenario results – is very relevant for multi-objective decision-making. For instance, the integrated model literature confirms the insights from more sectoral studies (condensed in a qualitative way in Table 1) that the co-effects of mitigation goals on air quality and energy security via the many sectoral mitigation measures are positive and often projected to be substantial. At the same time, this synergy is less clear or entirely reversed for the mitigation benefits of policies primarily targeted at air quality or energy security. The majority of the model studies, however, have only explored the co-effects of mitigation on a single additional objective – or vice versa. The next section discusses the recent body of literature of strand 3, which takes a more comprehensive and holistic perspective in order to explore the interactions between multiple objectives and how to reach them simultaneously with integrated policies.

4.2. Integrated model results on integrated policies for multiple objectives

Some of the models thus further broadened the scope of their model tools to analyze multiple objectives simultaneously in an integrated way: Bollen et al. (97), the Global Energy Assessment (GEA) (10, 38, 127), Akimoto et al. (111), and PBL (70).[11] The former two studies quantify key interactions in economic terms on a global scale which is why they will be discussed in more detail in this section. As outlined by Edenhofer et al. (27) and in Section 4.3, analysis of integrated policies and their effect of multiple objectives on macroeconomic costs or welfare metrics implies consideration of multiple externalities – either explicitly or implicitly.

Bollen et al. (97) develop a set of scenarios using a social welfare optimization approach to assess the costs and benefits (both market and external) of climate, air pollution, and energy security policies, either in isolation or in an integrated way (i.e. a CBA, see pink circles in Figure 2). The GEA (127) focuses on the same subset of energy policy objectives but instead uses a set of normative policy targets (implicitly assuming a second-best environment, i.e. that pre-existing externalities are not sufficiently internalized) and a large ensemble of scenarios to determine ranges of costs for policy packages of varying stringency and form (i.e. a cost-effectiveness analysis, see blue-shaded bars in Figure 2 and the table below for explaining the three stringency levels for each objective). For both sets of scenarios, the figure shows global policy costs as a percentage of globally-aggregated GDP between 2010 and 2030 of pursuing one of the three energy policy objectives in isolation (the three leftmost bars/circles) or all three objectives simultaneously with integrated policies (rightmost bar/circle). For a discussion of the different welfare measures used by the two studies, please refer to Section 4.3.

[11] Although the literature on Low-Carbon Society pathways is able to consider multiple sustainability objectives in an integrated way, the models are calibrated to national scales only which is why they are not discussed here (128–132).



Fulfillment	Climate change mitigation (CC) [CO_2-equivalent (CO_2eq) concentration ranges in 2100]	Air pollution and health (PH) [%-reduction in global health impacts from baseline, 2030]	Energy security (ES) [global primary energy trade (EJ/yr), 2030]
Stringent	**< 465 ppm CO_2-eq**	**>80%**	**<120**
Intermediate	**465-700 ppm CO_2-eq**	**25% – 80%**	**120 – 140**
Weak	**> 700 ppm CO_2-eq**	**<25%**	**>140**

Figure 2: Costs of achieving three energy policy objectives for different policy prioritization frameworks. For McCollum et al. (127) [blue bars], policy costs are derived from an ensemble of >600 scenarios and represent the net financial requirements (cumulative discounted energy-system and pollution-control investments, variable, operations and maintenance costs) over and above baseline energy-system development, which itself is estimated at 2.1% of global GDP. For Bollen et al. (97) [pink circles], policy costs are derived from a set of four distinct scenarios and are calculated as GDP losses (cumulative discounted) relative to a no-policy baseline. Triangular schematics summarize the performance of scenarios from McCollum et al. (127) that achieve 'stringent' fulfilment only for the objective(s) targeted under the corresponding policy frameworks (axis values normalized from 0 to 1 based on the full range of scenario ensemble outcomes). Sources: Riahi et al. (10), McCollum et al. (127), Bollen et al. (97).

Both studies find substantial synergies across the different objectives. McCollum et al. (127) show that global policy cost reductions can materialize – particularly in the near term – if multiple objectives are pursued with integrated policies rather than in isolation. Note, for example, that the sum of the costs represented by the three leftmost bars is much greater than the costs represented by the rightmost bar.[12] These cost synergies come about, for example, through reduced financial requirements for end-of-pipe air pollution control equipment and imported fossil fuels in a decarbonized energy system (see Table 2). Other near-to-mid-term synergistic effects of mitigation activities, also identified by Bollen et al. (97) include improved air quality (hence, lower health impacts) and enhanced energy security through fuel diversification by lowering the reliance on oil and gas demand and imports. As many of these synergies come about through energy and carbon intensity reductions, climate policy may be seen as a strategic entry point for reaping these benefits. It should be mentioned, however, that the co-benefits of stringent climate policies for energy security, air quality and health, respectively, will be much less pronounced if future policies for air pollution and energy security are more aggressive than currently planned as discussed in Section 3 (see 41, 72, and 96 for a detailed discussion of the implications of different air pollution control stringencies).

The scenario studies presented in this section are the most comprehensive efforts to date to integrate many of the steps from the welfare-theoretical framework presented in Section 2 while still being able to show conclusive quantitative results on a global scale. At the same time, these studies also show the limits of integrating all these aspects in a single framework of analysis since they have to reduce the scope of analysis at each step compared to other literature strands, thus highlighting the value of each individual strand:

i) In order to keep model complexity manageable, these two studies focus on a smaller set of (energy policy) objectives, compared to the objectives considered in the sectoral research (literature strand 1 and Table 1) and even compared to model results on co-effects (literature strand 2 and Table 2).

ii) Since these studies are each based on single models, respectively, the entire uncertainty range of deployment projections (see SM) – and the associated co-effects (as evidenced by the wide ranges from literature strand 2 in Table 2) cannot be fully considered.

iii) Since determination of 'optimal levels' of multiple objectives is prone to assumptions and value choices and largely hypothetical for non-market goods, this small set of studies that analyze macroeconomic implications across multiple objectives needs to reduce the complexity of the task by resorting to a range of simplifying assumptions. McCollum et al. (38), for instance, avoid explicit analysis of externalities and determination of welfare optima by considering a set of three possible stringency levels of policy targets from the political arena, circumventing the (locally) contested nature of the priority levels attached to many objectives. In contrast, Bollen et al. (97) choose a relationship between income and the value of statistical life as well as specific parameters for the penalty function for energy security deficiencies and for the climate change damage function – all of which predetermine the priority setting across the analyzed objectives; yet, despite the sensitivity analysis conducted, the choice of these values/parameters/functions does not cover the wide range of estimates available in the relevant literature.

The analysis of even more objectives relevant for multi-objective decision-making in the future would require consideration of the attached priorities along with the locally specific policies, their non-climate and climate effects and their implications for macroeconomics costs and welfare. To this end, Section 5 will present a complementary approach, which usefully juxtaposes sectoral research and integrated model results. But before that, the next section critically discusses to what degree the integrated assessment of costs, benefits and co-effects of mitigation can be embedded in a welfare framework, and how this depends on the modelling approach.

4.3. Critical discussion of policy costs and welfare effects in integrated models

In Section 2, co-benefits and adverse side effects were introduced as part of a welfare-theoretic framework. We will show here how the analysis of co-effects in integrated models can be related to this framework. Such models are dynamic numerical tools that explore the impact of transformational policies on the coupled

[12] Similar findings have been made for regional assessments of the economic implications of co-benefits (60, 133, 134) but the literature reviewed here is the first to evaluate these effects on a global scale.

energy-economy-environment system over a longer period of time (see SM for more details). By definition, such policies lead to non-marginal changes in economic activity and social welfare. The related economic costs and welfare effects of a policy are usually measured against a counterfactual business-as-usual case which is used as a point of reference or baseline for the analysis. Integrated models come in different types (see Table S.1 in the SM), and thus also have different capabilities to measure economic costs and welfare effects of policy changes. Two dimensions are relevant here: (i) the coverage of policy impact channels – both in terms of their economic costs and their benefits for societal objectives – and (ii) the degree to which (changes in) welfare can be measured.

Concerning coverage of policy impact channels, most models provide estimates of the direct economic costs of climate policies measured, e.g., in terms of reduction in household consumption or economic output (2; see discussion below). A small, but increasing number of models is also capable of capturing the direct costs of additional policies aimed at other, non-climate, objectives (see 38 in Section 4.2). Only a subset of models directly include the economic benefits of policy intervention in terms of reduced climate damages (135–137, see 8 for a discussion). A full welfare analysis of costs, benefits, and co-effects of climate policy would require capturing the benefits and adverse effects of the whole policy portfolio on all relevant objectives and thus the modelling of all impact channels through which the set of policies may alter the objectives (see 97 in Section 4.2). Such a complete cost-benefit analysis (e.g., following Equation 1) involves a series of heavily contested value judgments, is associated with a whole array of (additional) uncertainties in the valuation process, and hence remains a huge challenge – both analytically as well as empirically (cf. 8, 45). Those models that only capture policy costs are used for CEA estimating the costs of reaching a set of pre-defined objective levels, e.g. long term climate targets (feature II in Figure 1) or targets for other objectives (feature III in Figure 1). Those models that additionally capture the policy benefits and residual impacts can also be used in a CBA mode to identify welfare maximizing policies (feature IV in Figure 1).

Figure S.3 in the SM shows how this welfare effect can be decomposed into a policy cost and benefit component and how the range of cost and welfare estimates emerging in CEA and CBA applications, as well as climate damage estimates relate to each other. For example, the policy costs in a multi-objective setting in the case of McCollum et al. (127) are estimated by a CEA, considering the policy benefits in physical terms only (e.g., health benefits), but not in economic terms. In contrast, Bollen et al. (97) include the disutility of air pollution, climate change, and energy insecurity in their study. A thorough understanding of how cost and benefit estimates relate to a social welfare approach is essential for a meaningful comparison of costs and benefits to assess overall welfare changes. Nevertheless, information about the individual components of welfare changes shown in Figure S.3 is also highly useful to evaluate policy tradeoffs. Such information can be deduced from an analysis of subsystems, consequently includes a smaller set of uncertainties and assumptions, and is based on models with better system representation. For example, policy cost estimates based on CEA do not need to make assumptions about climate damages that are still highly uncertain, particularly on a global level (see 21 for a discussion).

A second source of difference between cost estimates of integrated models is related to the degree to which welfare can be measured. Partial equilibrium models can only explore economic impacts on the sectors that are represented in the model. They usually express policy costs in terms of changes to consumer and producer surplus. Estimates of welfare changes require a general equilibrium framework that can capture the macroeconomic impacts of policies and changes to other objectives (see Table S.1 in the SM). Monetary measures of welfare change in general equilibrium frameworks include ‘equivalent variation’ and ‘compensating variation’, which describe how income would need to change to keep households just as well off after the implementation of a policy as before. As these are quite difficult to calculate and communicate, proxy measures for welfare changes such as changes in household consumption are used more frequently in integrated models (1). Changes in GDP are also a commonly used metric, although GDP is a less satisfactory measure of welfare changes, because it only captures economic output, not the welfare benefit it generates (45).

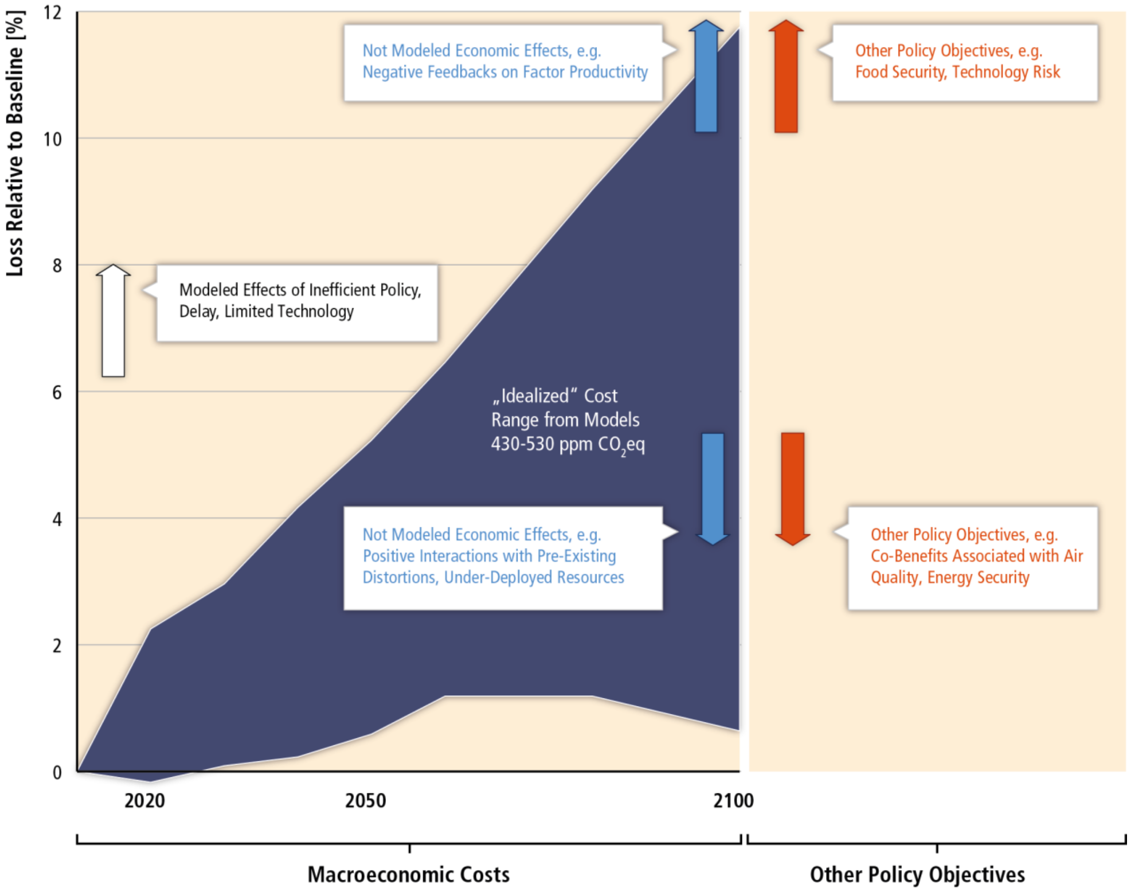


Figure 3: Stylized representation of mitigation cost impacts of considerations usually outside of those considered by integrated models, such as co-effects. The plotted cost range refers to the percentage loss relative to baseline scenarios across models for cost-effective scenarios reaching 430-530 ppm CO_2eq (25^{th}-75^{th} percentiles), adapted from Krey et al. (138).

The introduction of a baseline scenario against which the welfare impact of a policy is measured gives rise to the notion of idealized ("first-best") and non-idealized ("second-best") policy environments (cf. 138). An idealized policy environment is such that only one policy problem relating to a single objective exists, while all other objectives are already achieved at their optimal levels in the baseline scenario (economically speaking, all externalities are already fully internalized). Economic theory stipulates that an idealized ("first-best") policy consisting of ubiquitous Pigouvian pricing of environmentally damaging activities is optimal. In the case of mitigation, the idealized policy corresponds to comprehensive uniform GHG pricing in all sectors and regions, rising over time at a rate that reflects the cost increase of the next available unit of GHG emissions reduction. This is a useful analytical benchmark, included in most integrated modeling studies. However, co-effects do not have any value for society in such an idealized setting, since the value of co-effects depends on the degree of internalization of existing externalities (32). Those need hence to be studied in non-idealized environments characterized by deviation from the optimal levels in more than one objective. In such circumstances, first-best policies may no longer be optimal (cf. 139).[13] For example, if a climate policy can adversely affect other objectives, overall mitigation costs can be higher, but if co-benefits dominate, mitigation costs can be lower or possibly negative, even before factoring in the direct benefits of reducing climate change

[13] In some cases, climate policy could even lead to welfare losses if an already internalized externality was over-corrected (32) or interacted with pre-existing inefficiencies in a welfare-degrading way (140, 141, also cf. literature on the "double dividend", e.g., 142, 143).

(see Figure 3). It is an empirical question how large the value of co-effects will be – a major research challenge for the next generation of climate policy assessments.

An even bigger challenge is an integrated perspective across mitigation and adaptation. Although integrated models were originally developed and are still used to prescribe optimal policy, and thus included impacts and adaptation in addition to mitigation, the vast majority of scenarios reviewed in the IPCC were based on CEA rather than CBA and had a narrow focus on mitigation. This is mostly due to the uncertainty in estimating impacts and adaptation, and their dependence on the geographical scale (see SM). Yet, mitigation, adaptation and damages are highly interconnected, and joint assessments are receiving renewed interest (144). Few integrated studies have quantified the competition between mitigation and adaptation in terms of allocation of investments (145, 146). Others have looked into the implications of including adaptation strategies on equity in international climate policy (147, 148). In all cases, mitigation and adaptation strategies are found to be complements, but with potentially important repercussion on mitigation costs and strategies, especially in terms of regional differences.

5. Untapped potential for further synthesis of existing research

The review and condensation of literature on the co-effects of mitigation in Sections 3 and 4 shows that interesting and important insights can be gained from the different literature strands. Across these strands, there is, however, a tradeoff between the number of objectives analyzed in a study and its ability to present quantitative results – mainly due to the challenges of linking results from the integrated model literature, on the one hand, and those from the sectoral literature, on the other hand. Recent attempts to tackle this analytical separation from within the integrated model literature (Section 4.2) have improved the integrated understanding but are limited in scope, because studies need to find the right balance in handling complexity, providing transparency and computational limitations. This section suggests a complementary kind of synthesis, juxtaposing (i) quantitative evidence from a wider set of mitigation scenarios consistent with the 2°C target from integrated models and (ii) qualitative evidence on potential co-effects of mitigation measures on a wider set of multiple sustainability objectives from sectoral research. While such synthesis also faces limitations, it is able to draw on the respective strengths of the somewhat disparate bodies of research: (i) the ability of the different integrated models to take into account cross-regional and cross-sectoral interactions of mitigation measures and (ii) the ability of the sectoral studies, taken together, to take into account co-effects on a wider set of sustainability objectives and at a more disaggregate, detailed level.

In this context, Table 3 presents the different sets of results in such a way that they 'speak to each other' in order to increase the understanding of relevant co-effects for global mitigation pathways choices. The table draws on data for energy supply and demand projections (in primary and final energy terms, respectively) that are presented by a bigger group of integrated models for different sets of scenarios (from the WGIII AR5 Scenario Database).[14] Ranges of scenario results are shown for those indicators which can be linked directly to the groups of mitigation measures for which co-effects are presented. Whereas integrated models usually include all relevant energy supply technologies, the number of sectoral end-use measures far exceeds the models' current limitations of complexity. For each demand sector, the table hence focuses on the range of projections for total sectoral energy demand and for those high-carbon energy carriers that are most widely used today and whose reduction is linked most directly to the co-benefits presented on the right side; it also shows the median of projections for sectoral demand for electricity and bioenergy which are the most important low-carbon energy carriers (see SM). To show the effect of climate policies on the energy supply and demand projections, the table shows baseline vs mitigation scenarios consistent with the 2°C target (as an illustration) – both for standard (black ranges) and for low-energy intensity (lowEI) assumptions (blue ranges) in which the rate of increase in energy intensity (EI) improvement is either consistent with or greater relative to historical developments, respectively. The table thus allows linking the co-effects of the sectoral mitigation

[14] https://secure.iiasa.ac.at/web-apps/ene/AR5DB

measures to the projected changes in crucial energy indicators. Even though the ranges are often wide, the changes in the median projections consistently show the following:

i. higher ambition for EI reductions in baseline scenarios (i.e. without targeted climate policies) will lead to reduced demand and supply of energy carriers in all sectors against baseline – implying a high number of potential co-benefits, particularly due to reduced impacts of those energy carriers which are associated with the largest adverse side-effects (oil, traditional biomass and coal, see SM). Yet, relying on high ambition for EI alone, i.e. without dedicated climate policy, will fall short of achieving the 2°C target (1) as it will only slow the growing oil and coal demand.
ii. projections for mitigation scenarios with standard EI assumptions imply demand reductions against baseline and today's levels of oil and coal but also require an increased demand for biofuels and electricity from low-carbon sources. The balance of the local co-effects primarily depends on how and where the additional bioenergy is produced and which low-carbon electricity supply technologies will be deployed where to satisfy the additional electricity demand (Section 3 and SM).
iii. higher ambition for EI reductions in mitigation scenarios will lead to the lowest demand for all fossil-based energy carriers shown in Table 3 and lessen the additional supply of low-carbon electricity and bioenergy supply in comparison to mitigation scenarios with standard EI assumptions. Maximizing synergies and minimizing tradeoffs with additional sustainability objectives hence requires that climate (and non-climate) policies be chosen in such a way that certain adverse side-effects of bioenergy production are either avoided or carefully managed (23–25, 28, 51, and the section on bioenergy supply in the SM, 53, 124) and low-carbon but risky energy supply technologies (e.g., nuclear and CCS) are deployed how and where they imply the lowest adverse side-effects (see 20, 149, and the section on energy supply in the SM).

This synthesis offers the opportunity to usefully draw on different strings of evidence from the somewhat disparate bodies of literature at one glance and potentially increases the understanding of the implications of mitigation policy choices. Yet, the table does neither offer quantitative results on the net global co-effects, nor their impact on overall social welfare. To mitigate this shortcoming and better adapt these findings to the specific circumstances, this exercise could be repeated for those disaggregated scales that are still supported by the scenarios studies (up to about two dozen world regions). This would give decision makers the opportunity to interpret the results against the background of regional priority settings, circumventing some of the challenges of welfare accounting discussed in Section 4.3.

6. Conclusion and outlook

Based on a conceptual analytical framework, the review and condensation of the WGIII AR5 results in this paper shows that the different bodies of co-effects literature have focused on different aspects of the interaction across climate change mitigation and other sustainability objectives. All literature strands considered independently have remained partial. It also reveals that quantification and aggregation of co-effects is challenging because of the incommensurability and uncertainties of results that are all the more pervasive the more

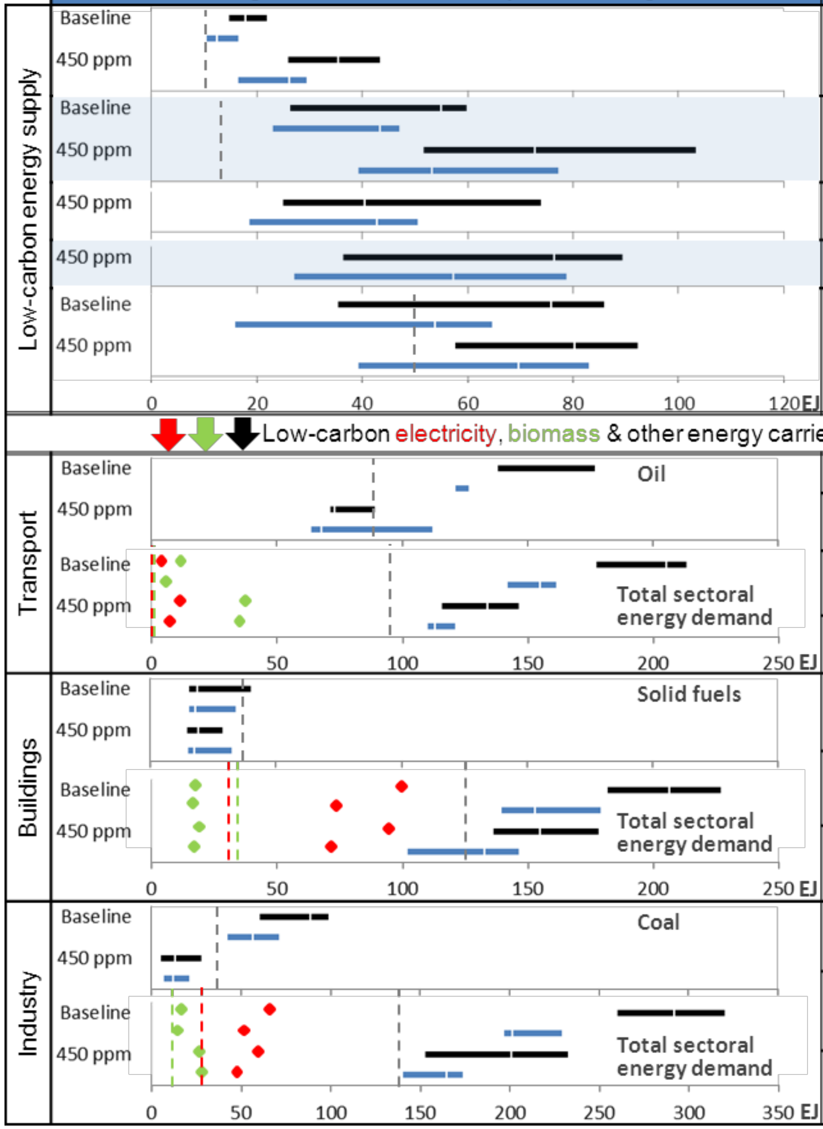
i. the perspective shifts from sectoral and local to economy-wide and global;
ii. more objectives are taken into account in the analysis; and
iii. the results are expressed in economic rather than non-monetary terms

Despite the growing insights on the co-effects of mitigation measures and recent efforts to conduct more integrated research, there are still substantial tradeoffs between the number of objectives analyzed and the ability to present quantitative results, particularly for overall welfare implications, as well as between capturing synergies and tradeoffs across different levels to inform global coordination and providing context-specific information necessary for local/sectoral policy-making:

While *literature strand 1* is able to analyze the effect on many objectives at a high degree of sectoral detail and its meta-analysis in Table 1 points to the important role of energy efficiency improvements, the associated results are very challenging to aggregate, particularly in monetary terms and on a global level. One reason is that they do not take into account cross-sectoral or cross-regional interactions – a prerequisite for cost-effective mitigation. While *literature strand 2* develops a better understanding of cost-effective mitigation pathways with respect to their implications for global co-effects in quantitative terms, revealing how large co-benefits can be for energy security and air quality metrics, it only analyzes a limited number of objectives. *Literature strand 3* finally offers important insights into the welfare implications of pursuing three energy policy objectives either simultaneously or in isolation and reveals that climate policy is a good entry point to realize synergies across those objectives. But the number of objectives analyzed is even smaller as is the ability to reflect the full range of uncertainty across different models.

Table 3: Scenario results from integrated models consistent with a 2°C target for different energy supply and demand indicators and the potential co-effects of (groups of) sectoral mitigation measures on additional sustainability objectives; green arrows: co-benefit; orange arrows: adverse side-effect; smaller arrow: small effect by comparison.

Integrated model results (25^{th}-75^{th} percentiles and median) for energy supply (in Primary Energy) and sectoral energy demand (in Final Energy) in 2050 for baseline vs mitigation (450 ppm CO_2eq) and conventional (black) vs low (blue) energy intensity scenarios; dashed lines indicate median 2010 levels in all scenarios; only scenarios with immediate mitigation and full availability of technologies are shown.



Low-carbon electricity, biomass & other energy carriers (diamonds display medians for those indicators for which ranges are not shown)

Sector	Sectoral mitigation (groups of) measures in energy supply and energy end-use sectors	Economic: Energy security	Economic: Sectoral productivity	Economic: Local/sectoral Employment	Social: Reduced health impact	Social: Comfort, working conditions	Social: Safety/disaster resilience	Environmental: Reduced ecosystem impact	Environmental: Reduced water use/pollution	Environmental: Reduced land use	Other objectives
Low-carbon energy supply	Nuclear (replacing coal)	↑		↑	↓↑		↓	↑↓			Proliferation, nuclear waste
Low-carbon energy supply	Renewable (excl. bioenergy) (replacing coal)	↑		↑	↑			↑↓	↑↓		(Off-grid) energy access Reduced resource mining
Low-carbon energy supply	Coal with CCS (replacing coal)			↑↓	↓		↓	↓	↓		Long-term monitoring of carbon dioxide
Low-carbon energy supply	BECCS (replacing coal)				↓		↓	↓	↓		
Low-carbon energy supply	Bioenergy (without CCS)	↑		↑↓	↑↓			↓	↓	↓	Food security and equity in land tenure
Transport	Fuel switching	↑			↑		↓	↑↓			Technological spill-overs
Transport	Technical energy efficiency	↑			↑		↑	↑			
Transport	Urban form/modal shift	↑	↑	↑↓	↑		↑	↑		↑	Equitable mobility access
Transport	Energy demand reduction via other means	↑	↑		↑			↑↓		↑	Reduced urban congestion
Buildings	Fuel switching	↑		↑	↑			↑			Reduced fuel poverty
Buildings	Technical energy efficiency	↑	↑	↑	↑↓	↑	↑	↑	↑		
Buildings	Energy demand reduction via other means	↑			↑			↑			
Industry	Fuel switching		↑		↑	↑		↑	↑		Increased competitiveness
Industry	Technical energy efficiency	↑	↑	↑	↑	↑	↑	↑	↑		Technological spillovers
Industry	Material efficiency			↑	↑		↑	↑			Reduced resource mining

To relax this tradeoff to some extent, we present a way forward to usefully draw on the existing strings of scientific evidence building on the respective strengths of the different communities without integration in a common modelling framework. Section 5 brings together in one table (i) quantitative evidence on the future energy supply and demand in different sectors from a wider set of mitigation scenarios consistent with the 2°C target and (ii) qualitative evidence on co-effects of mitigation measures on a wider set of sustainability objectives from sectoral studies. Although this approach does not eradicate the pervasive incommensurability and uncertainties, it makes them more transparent and accessible to decision makers. This synthesis tool allows decision makers to gain a better overview of and to extract high-level insights into the complex interactions across multiple objectives, revealing the following:

i. mitigation pathways consistent with the 2°C target lead to a whole range of potential co-benefits and lower risks by reducing the use of fossil fuels and traditional biomass against baseline developments (and often current use) while higher demand for low-carbon energy carriers might increase supply-side risks in specific local circumstances;
ii. faster-than-historical EI reductions lead to potential co-benefits and reduced risks in all sectors, irrespective of the scale of targeted global mitigation efforts. Combining these with stringent mitigation efforts leads to higher co-benefits and lower risks compared to mitigation pathways with standard EI reductions by reducing the demand for and increasing the flexibility of choosing among alternative mitigation measures. This allows better management of mitigation risks on the supply side associated with the upscaling of low-carbon energy technologies and bioenergy supply.

The good news is that most risks on the supply side – increasing with more stringent mitigation goals – occur at the local scale and can be managed locally (except, perhaps, food security and proliferation risks). This means that no additional global cooperation beyond mitigation action might be needed to manage mitigation risks. Decision makers at the local/national level can exploit the increasing amount of knowledge and the flexibility implied by the large ranges from mitigation scenarios (see SM) to choose mitigation policies and measures according to their priorities for sustainability objectives beyond mitigation. On the basis of existing literature, however, it is not possible to analyze the potential deployment of these (sub-)national measures for achieving multiple objectives and their global mitigation effects in an integrated way, and vice versa – at least not for more than a small number of energy objectives (see Section 4.2). And despite a better understanding of the potential co-effects of different sets of mitigation pathways for a broader set of objectives (presented in Section 5), scientific evidence thus far only offers limited guidance for decision makers that seek to understand under which conditions and at which level synergies across multiple objectives can actually be realized and tradeoffs avoided. Future research could advance the understanding of these complex interactions in three possible ways:

First, given that the trend is toward increased national level climate legislation and policy, and international cooperation is also increasingly focused on leveraging and enhancing these national measures, greater attention to consolidating and summarizing co-effects at the national scale would be particularly helpful. Similarly, there has been a proliferation of sub-national decision-making on climate issues, while other SD objectives (e.g., urban air quality) are almost exclusively handled at this level. To serve these needs, future research should develop a multi-dimensional typology of co-effects beyond the classification into sectors, local or global effects and SD aspects presented in Table 1. This could then be used to target the specific types of challenges associated with the realization of synergies and avoidance of tradeoffs to more specifically target co-effects that map to decision-making jurisdictions, such as cities, states/provinces and nation states. For example, the typology could differentiate more explicitly between co-effects that accrue locally and are primarily driven by local decisions (e.g., mobility access), those that accrue locally but are primarily driven by decisions taken within the broader region (e.g., local agricultural yield gains through methane mitigation elsewhere), and those that accrue globally but are primarily driven by decisions taken locally (e.g., technological spillovers). Other dimensions could include distributional, geographical or timing aspects (i.e., which societal groups or stakeholders are most affected where at what point in time). This would be useful for research that could choose the most appropriate methods, models and system boundaries as well as for the political process that could focus on the most salient aspects of the interactions across multiple objectives.

Second, such a typology could be useful for a broader modelling strategy that could draw on the strengths of different methods by combining global integrated models (which take into account cross-sectoral and cross-regional interactions) with national and sub-national models (which are more spatially disaggregated and may have greater technological and socio-demographic detail and heterogeneity). While it may be too much to expect the hard-coupling of these different tools, careful analyses within the framework of internally consistent scenario studies could permit a better accounting of national/local circumstances and preferences (along with their aggregate global/regional consequences), such as the level of socio-economic and technological development, distributional aspects, risk perceptions and priority settings for non-climate objectives.

Third, from a risk-management perspective, it is particularly important to differentiate between risks that can be managed locally (e.g., landscape impacts) and risks that can build up globally (e.g. food security and proliferation risks). Future research could draw on the recent advances of integrated modeling with respect to more elaborate real-world assumptions for mitigation pathways, taking into account delayed and fragmented global mitigation efforts as well as limited availability of mitigation technologies. Understanding the risk tradeoffs across multiple objectives for alternative mitigation pathways would be an important contribution to a better-informed decision-making process at both global and national/local levels.

Since many authors have argued for a more integrated policy approach to advance mitigation and additional SD objectives (e.g., 7, 8, 27, 37, 39, 41, 42), partly dissolving the analytical separation between the different sets of scientific evidence as done in this paper is highly relevant for climate and sustainability policy choices. Better knowledge on the potential synergies and tradeoffs across multiple objectives improves the understanding of this ends-means interdependency and may, according to Edenhofer & Kowarsch (30), even encourage decision makers to adapt existing priority settings to release political gridlocks, e.g. in international climate policy (cf. 150).

Acknowledgements

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Supporting Material

Dealing with uncertainty in integrated model studies

The integrated model results presented in Sections 4 and 5 derive from large-scale numerical models that identify the globally most cost-effective portfolios of mitigation measures, e.g., for a given atmospheric CO_2-equivalent (CO_2eq) concentration or carbon budget, for all world regions. To that end, they integrate insights from different disciplines and draw on models of both biogeophysical and human processes over long time horizons (8, 29, 151). To circumvent climate system uncertainties with respect to the temperature response due to a given emission scenario, integrated models usually calculate mitigation scenarios for meeting different atmospheric CO_2eq concentrations or carbon budgets. The uncertainty reflected in their results due to the diversity of modelling approaches with respect to structural as well as parametric differences (5) is hence distinct from the uncertainty of the exact change in the global mean surface temperature due to different emission scenarios (see Section 6.3.2.6 in 1). The model community regularly organizes model intercomparison projects in which efforts have been made to harmonize key input parameters and to make model outputs comparable (2, 5, 15, 152–154). Partly owing to this coordinated research agenda, the results from the different modelling teams have been an important contribution to the WGIII ARs (e.g., 1, 155, 156). Another reason is that CBA is contested in climate economics due to a variety of reasons, one of them being the challenge to adequately account for 'fat tail' probability distributions of high-impact climate damages, as discussed in Edenhofer et al. (8). There are, of course, a number of drawbacks associated with the global approach taken by the models. For example, many non-technical measures including behavioral changes or modal shift are usually not represented in detail by integrated models (157). In some circumstances, MCA approaches might instead be chosen to make synergies and tradeoffs across different objectives transparent without valuation in monetary terms (38, 158–160).

Although the deployment projections from the integrated model literature for the portfolio of measures are consistent with a particular mitigation goal, such as a given atmospheric CO_2eq concentration, they are uncertain with respect to the role of individual measures. This is illustrated by Figure S.1 which shows results from mitigation scenarios leading to an atmospheric concentration of 430-530 ppm CO_2eq in 2100, i.e. with an at least 66% chance of not exceeding the 2°C target. The figure does show, however, how the two main mitigation strategies, energy demand reduction and switching to lower-carbon fuels, interact on a global scale (see also Sections 3 and 5): the required upscaling of low-carbon energy supply technologies for meeting a stringent mitigation goal is significantly lower for future scenarios in which the total final energy demand is low. Reducing energy demand (against baselin) is increasingly seen as a low-cost mitigation strategy within the integrated model literature (e.g., 5, 154, 161). This is also why the model teams have constructed low-EI pathways in addition to the conventional 'scenarios families' (i.e. scenarios where some political and/or technological aspects are constrained allowing comparison across models for similar sets of assumptions). In that way, it is possible to analyze implicitly how different energy demand patterns (e.g., through behavioral changes in energy service, food and material consumption) in the future can impact mitigation efforts in terms of timing, costs and effects on the rest of the energy system. Since the cost-effective mitigation potential of energy efficiency improvements declines, however, with increasing decarburization of the supply side, they need to be realized in the short to medium term if targeted at mitigation (157).

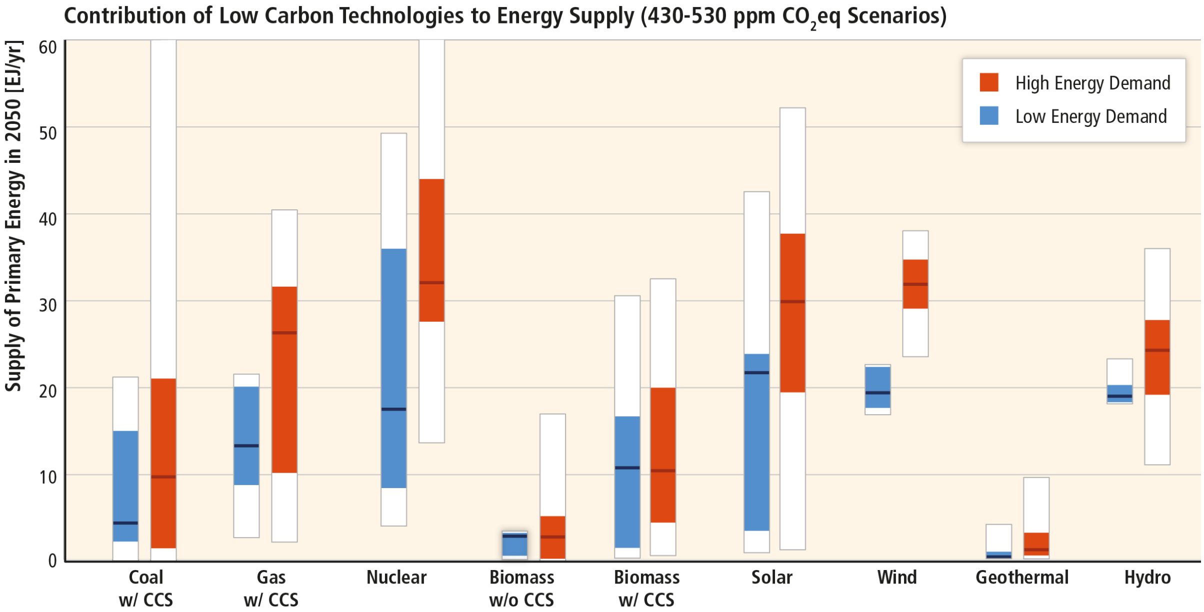

Figure S.1: Deployment of energy supply technologies in 2050 for mitigation scenarios reaching 430-530 ppm CO_2-equivalent (CO_2eq) concentration in 2100, differentiating between low- and high-energy demand scenarios. Blue (red) bars show the deployment range with <20% growth of final energy in 2050 compared to 2010 (>20% growth of final energy in 2050 compared to 2010). For each technology, the full deployment range, the interquartile and the median are displayed (adapted from 20).

Figure S.2 provides an illustrative example for the co-benefit of mitigation goals (consistent with the 2°C target) for air pollutant emissions. It shows the spatial distribution of the current human exposure to PM_{10} pollution in 3200 cities, as well as the ranges of co-benefits for two key air pollutants (SO_2 and BC) from a large number of scenarios from the WGIII AR5 scenario database. Despite relatively large uncertainties (partly owing to parametric and structural differences across integrated models, see above), the co-benefits are robust against a wide range of integrated models that quantified the climate-pollution interactions.

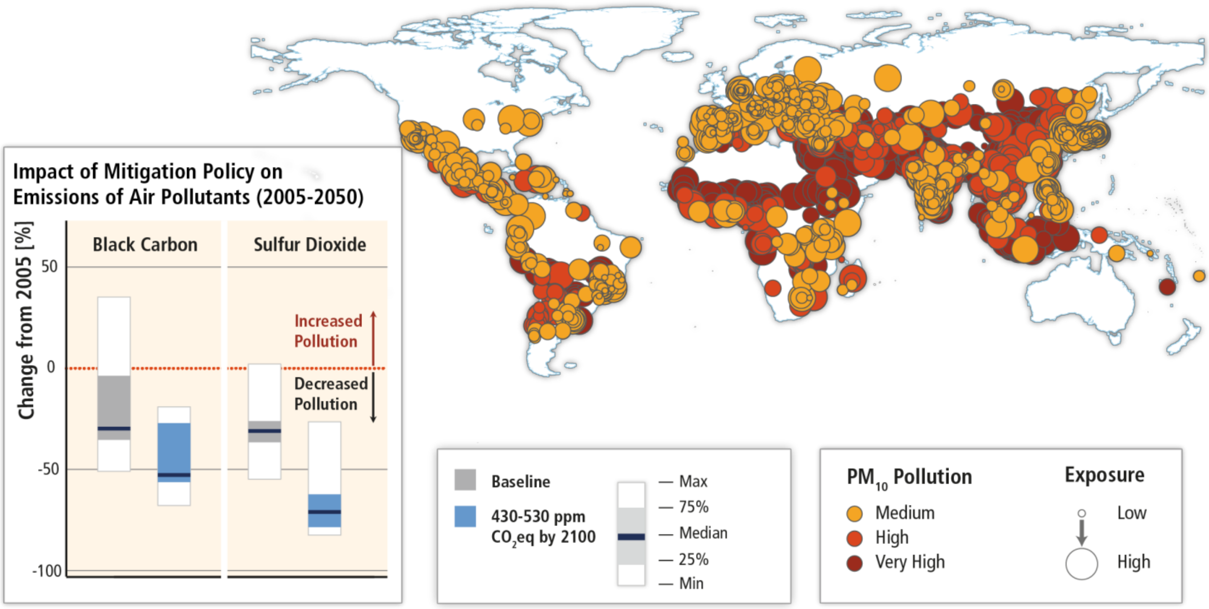

Figure S.2: Human risk exposure to PM_{10} pollution in 3200 cities worldwide (adapted from 18, data from 162) and co-benefits of stringent mitigation policies for air quality in scenarios reaching concentrations of 430-530 ppm CO_2eq in 2100 (adapted from 1).

A conceptualization of welfare metrics in integrated model studies

To conceptualize the diverse set of cost information from integrated models in a welfare framework, it is useful to rewrite the social welfare function from Section 2 as $W(z_i^* - D_1(\boldsymbol{p}), \ldots, z_m^* - D_m(\boldsymbol{p}), c(\boldsymbol{p}))$, where the objective z_i is described as the combination of some ideal level z_i^* in the counterfactual case of a non-existing policy problem, e.g., an undamaged environment, and the adverse impact D_i on the objective z_i under some set of given policies $\boldsymbol{p}$. In addition, we add household consumption c that may be directly affected by the policy implementation as a further element of the welfare function. The counterfactual reference case without policy intervention is then characterized by welfare W_R for some reference policy $\boldsymbol{p}_R$, and the total welfare gain of a policy intervention $d\boldsymbol{p} = \boldsymbol{p} - \boldsymbol{p}_R$ is given by $G = W_p - W_R$. Thus, the welfare differentials shown in Figure S.3 could be based on direct welfare, welfare equivalent consumption metrics, direct consumption, economic output and partial equilibrium measures depending on the model.

$W_p = W(z^*_1\text{-}D_1(p), \ldots, z^*_m\text{-}D_m(p), c(p))$
$W_R = W(z^*_1\text{-}D_1(p_R), \ldots, z^*_m\text{-}D_m(p_R), c(p_R))$
$W_{Rp} = W(z^*_1\text{-}D_1(p_R), \ldots, z^*_m\text{-}D_m(p_R), c(p))$
$W^*_p = W(z^*_1, \ldots, z^*_m, c(p))$
$W^*_R = W(z^*_1, \ldots, z^*_m, c(p_R))$

Damages (in reference case): $D^*_R = W^*_R - W_R$
Damages (in policy case): $D^*_p = W^*_p - W_p$
Policy costs (CEA without damages): $C^* = W^*_R - W^*_p$
Policy costs (at reference damages): $C = W_R - W_{Rp}$
Policy benefits: $B = W_p - W_{Rp}$

Welfare gain from policy intervention: $G = W_p - W_R$
Residual welfare loss of policy problem: $L = W^*_R - W_p$

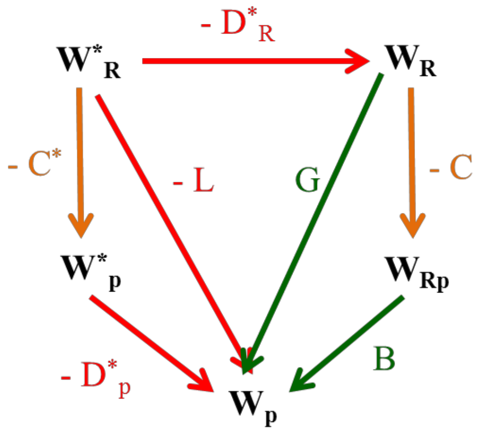

Figure S.3: Relevant welfare measures, and associated cost and benefit metris, for transformational policy analysis with integrated models.

In order to provide an overview of the types of integrated models on which the literature builds that is reviewed and condensed in Sections 4 and 5, Table S.1 provides key characteristics of a representive set of six different integrated models with a special focus on the differences discussed in Section 4.3:

(i) the coverage of policy impact channels is represented by the columns ‘System boundaries’ and ‘Non-climate sustainability objectives covered’;

(ii) the degree to which (changes in) welfare can be measured is represented by the columns ‘Model type’, ‘Metric for climate change mitigation costs’, and ‘Costs for other objectives covered’.

One aspect not covered by the above conceptualization is the interrelation between climate change mitigation and poverty eradication beyond access to basic energy needs. Generally, current integrated models are lacking the presentation of the poor and their economic and social development. Conversely, climate policies are expected to have repercussions for development and poverty (163, 164). For example, higher energy prices could delay structural changes and the build-up of physical infrastructure (98, 165). The subset of integrated models which include an economic feedback capture some of these dynamics, although in most models economic growth is largely exogenous and stems mostly from labor productivity changes. Further endogenization of economic growth and linkage to poverty and climate change is an important avenue of future research.

Table S.1: Key characteristics and representation of multiple objectives and costs for selected global integrated modelling frameworks

Model name	Model type	Metric for climate change mitigation costs	System boundaries	Non-climate sustainability objectives covered	Costs for other objectives covered
IMAGE	Energy system partial equilibrium model –recursive dynamic, simulation	Energy system cost mark-up, Area under marginal abatement cost curve	Energy, land-use change, agriculture, climate, hydrology, some adaptation (not comprehensive)	Energy access, food, water, air pollution, biodiversity loss, energy security	Food production costs, energy access investments and subsidies, energy system costs for improving energy security
GCAM		Energy system cost mark-up, Area under marginal abatement cost curve	Energy, land-use change, agriculture, forestry, climate, hydrology, some adaptation (not comprehensive)	Energy access, food, water, air pollution, energy security	Food production costs, energy system costs for improving energy security
MESSAGE-GLOBIOM	Systems engineering energy system model coupled with macroeconomic generable equilibrium model – perfect foresight, optimization	GDP & Consumption loss, Energy system cost mark-up, Area under marginal abatement cost curve	Energy, land-use change, agriculture, forestry, climate, water for irrigation and energy, some adaptation (mainly in the agriculture sector)	Energy access, food, water, air pollution/health, energy security	Food production costs, energy access investments and subsidies, air pollution control costs (ex-post), energy system costs for improving energy security
REMIND-MAgPIE	Optimal growth generable equilibrium model – perfect foresight, optimization	Welfare change, GDP & Consumption loss, Energy system cost mark-up	Energy, land-use change, agriculture, climate, air pollution, hydrology, some adaptation of land use (not comprehensive)	Water, air pollution, energy security	Energy system costs for improving energy security, adaptation costs
WITCH-GLOBIOM		Welfare change, GDP & Consumption loss, Energy system cost mark-up	Energy, aggregated land-use change, agriculture, forestry, climate, climate damages and adaptation	Food, air pollution, energy security, adaptation	Food production costs, energy system costs for improving energy security
GEM-E3	Computable Generable Equilibrium model – recursive dynamic, optimization	Welfare change, GDP & Consumption loss, Equivalent variation	Energy, climate, air pollution, adaptation, labor markets	Air pollution, energy security, employment, impact on competitiveness	Energy system costs for improving energy security

Literature review of co-effects of mitigation measures in specific sectors

Energy supply

The energy supply sector is characterized by a chain of processes, comprising energy extraction, conversion, storage, transmission, and distribution processes. It is by far the largest contributor to GHG emissions, accounting for about 35% of the total anthropogenic GHG emissions at 144 $GtCO_2$/yr in 2010 (20). Between 2000 and 2010, their growth in the global energy supply sector increased to 3.1% per year, compared to the previous decade's levels of 1.7% – largely fuelled by higher energy demand associated with rapid economic growth in emerging economies and an increase of the share of coal in the global fuel mix (58, 166).

As outlined in Bruckner et al. (20), multiple options exist to reduce energy supply sector GHG emissions. These include energy efficiency improvements and fugitive emission reductions in fuel extraction as well as efficiency improvements in energy conversion, transmission, and distribution systems; fossil fuel switching; and low-GHG energy supply technologies such as renewable energy (RE), nuclear power, and fossil fuel and bioenergy use with carbon dioxide capture and storage (CCS/BECCS). The implementation of these options can lead to a range of co-benefits and adverse side-effects that would have an influence on investment decisions, individual behavior as well as policy directions (20, 167). The large variation that exists across and within regions in terms of the nature and composition of the co-effects can be explained by differences in resource endowments, renewable energy potential, economic structure, development pathways and priorities, etc.

Since changing the energy sector is at the heart of all climate change mitigation scenarios, there are always energy security co-effects from mitigation. Most energy security analysis focuses on short-term evaluation of static energy systems and even in the short-term, the meaning of energy security is contested (52, 168–170). The most general definition, which is applicable under radical energy system transformations is low vulnerability of vital energy systems (171), since both vulnerabilities and vital energy systems can change under mitigation scenarios (83). This definition also facilitates the identification of vital energy systems for different actors such as reliability of energy imports for importers (security of supply) and energy export revenues for energy exporters (security of demand) (172). The explicit separation of vital energy systems and vulnerabilities also helps identify distinct perspectives on risks and resilience capacities of energy systems. There are three commonly recognized perspectives on energy security: two focus on risks (sovereignty threats from foreign actors and robustness risks from critical infrastructure or resource constraints) and the third focuses on the resilience capacity, which is commonly measured by the diversity of an energy system (173). In general, the increase in renewables under mitigation scenarios leads to lower energy imports (81–85) and higher resilience from greater energy system diversity (10, 81, 83, 86), but the scant literature has yet to develop a full analysis of the robustness impacts of scaling up renewables.

Another co-effect in the energy supply sector associated with climate policies is the effect they would have on employment. According to Cai et al. (174), the increased share of renewables in China generated over 470,000 net job gains in 2010. Studies by Lehr et al. (175) and Ruiz-Romero et al. (176) for Germany and Spain, respectively, also indicated over 500,000 people would be employed in the renewable energy supply sector in each country by 2030. Employment generation is not limited to the renewables sector. It also extends to nuclear power generation and CCS where safe-guarding jobs in the fossil-fuel industry is seen to be the main employment co-benefit (177, 178). However, it is also important to recognize that mitigation measures could come at a high cost when seen as unit of public investment against the number of jobs created. A study by Frondel et al. (179) has calculated that the cost per job created in the PV sector in Germany could be as high as €175,000, indicating that the viability of the industry is dependent on the level and continuity of public support (180).

Differences in access to modern energy supply across regions partly explain the wide disparity in economic and social development, both within and between countries. More than 1.3 billion people worldwide, especially in sub-Saharan Africa and developing Asia lack access to electricity and over 2.7 to 3 million people are estimated to lack modern fuels for heating and cooking (100, 181). Whilst improvements in energy access do not need to entail significant changes in GHG emissions (see Section 4.1), multiple co-benefits could be obtained. In a number of developing countries such as India, Brazil, Nepal and parts of Africa, renewable energy deployment has been shown to stimulate local economic development (182, 183). Educational benefits and enhanced support for income generation are some of the specific benefits observed in large parts of the developing world (184–186). At the same time, the effect of climate policies on energy prices and, by extension, energy access aspirations is not as clear and depends importantly on the specific circumstances within countries and devolved jurisdictions, such as the type of fuel used by different income groups, the distribution of the revenues through, e.g. a carbon tax and effectiveness of pro-poor interventions (187). Hence, regulators have an important role to play so that climate policies do not become a burden on low-income households and communities (20).

Combustion-related emissions from the energy supply sector cause significant and widespread human health and ecological impacts and depend on the height of the smoke stack, the type of fuel used, the scrubber technology installed, the downwind population concentration as well as the background pollution from other sources (see Section 3). Ambient air pollution of some 80% of the world's population is estimated to exceed the World Health Organization (WHO) recommended levels of $10ng/m^3$ for $PM_{2.5}$ (41) and to cause about 3.2 million of premature deaths each year (Lim et al., 2012). SO_2 and NO_x are implicated in acidification of fresh water and soils as well as threatening biodiversity (188, 189). Coal is an important source of mercury and other toxic metals, which could be reduced significantly through a range of pollution control technologies. Moreover, extraction and transport of fossil fuels, particularly coal, have high occupational impacts and accident rates (190). Replacing coal with cleaner fuels is hence associated with a wide range of co-benefits (20, 191).

However, ecological and health impacts are not limited to fossil fuels, but also extend to renewable and nuclear systems. These impacts are in areas of land use, water use and pollution, effect on ecosystems, and impacts associated with mining and material processing. Hertwich et al. (192) compared indicators for pollution-related health and ecological effects of fossil fuel and renewable power technologies, taking into account life-cycle emissions and thus accounting for emissions from material and fuel production, manufacturing, operation and decommissioning. They found that although wind power, photovoltaics, concentrating solar power and some hydropower plants require more materials than coal and gas fired power plants, the pollution-related indicators are generally significantly lower for these renewable power technologies. Even modern supercritical coal power plants and natural gas combined-cycle plants with state-of-the-art pollution control equipment cause more PM exposure and freshwater ecotoxicity per kWh electricity produced than any of the renewable power technologies investigated (see Figure S.4). For freshwater eutrophication, natural gas performed on par with renewable technologies, but it caused more marine eutrophication. The implementation of a range of renewables as foreseen in mitigation scenarios would stabilize or reduce all investigated pollution-related environmental and human health indicators, while a baseline scenario would increase these indicators (192). For impacts related to habitat change, see below.

Health effects associated to radioactive material handling have preoccupied healthcare professionals as some epidemiological studies show an increase in childhood leukemia of populations living within 5 km of nuclear power plants (193–195).

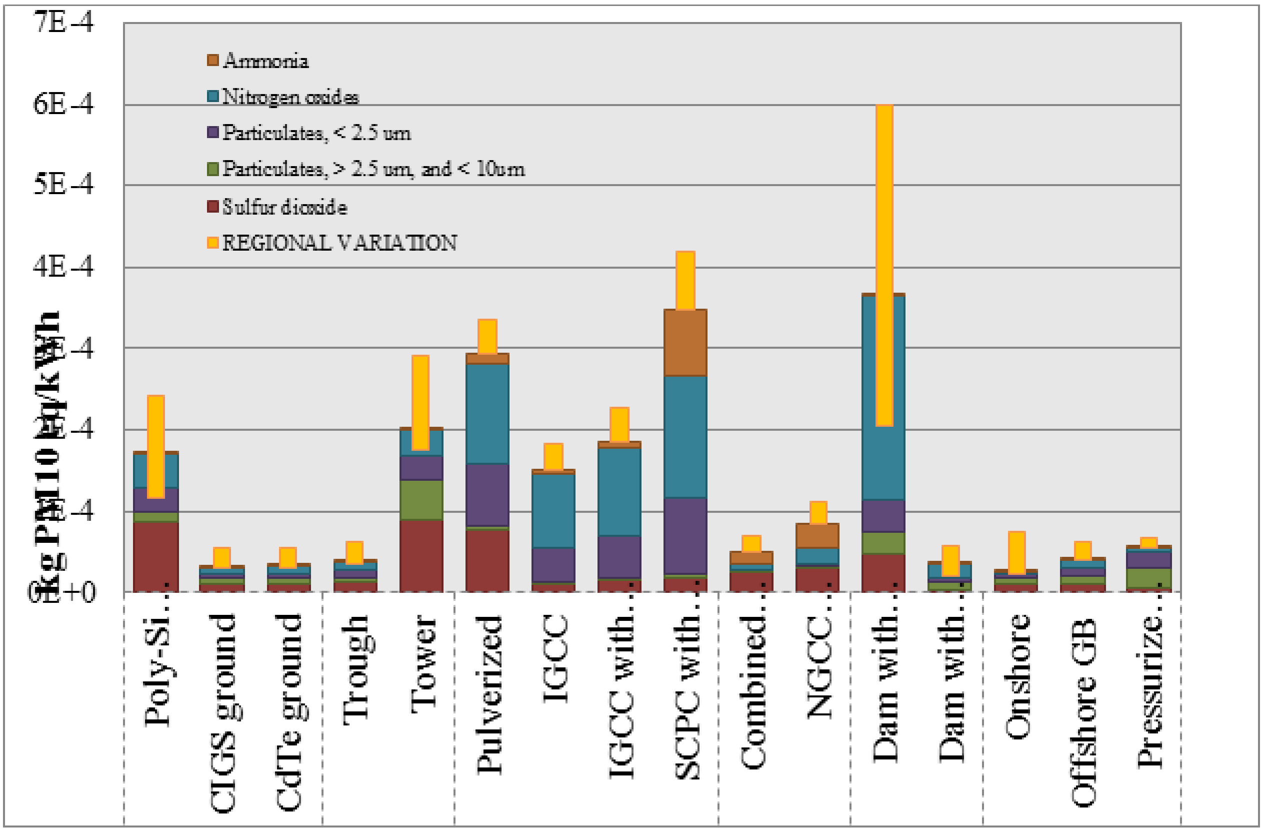

Figure S.4 Human health impact from PM exposure resulting from air pollution caused in the production of 1 kWh of electricity with various technologies (192) as evaluated using the lifecycle impact assessment method ReCiPe (http://www.lcia-recipe.net), presented in units of kg PM_{10}-equivalents (PM_{10}-eq) as suggested by van Zelm et al. (196).[15] Figure credit: Thomas Gibon, NTNU.

The capture and storage of CO_2 from fossil fuel and biomass combustion are mitigation measures that are important in most mitigation scenarios investigated by the WGIII AR5 (20). Even though a wide range of technologies have been investigated, the process of CO_2 capture and storage requires 16-44% of additional energy (198), thereby increasing the fuel requirements and associated environmental impacts. On the other hand, CO_2 capture requires a pure gas stream, reducing some air pollution from the power plant. Investigating different CCS technologies, Hertwich et al. (192) find that CCS increases the life-cycle indicators for PM, toxicity and eutrophication by 5-60% compared to state-of-the-art coal and gas power plants. CCS doubles the demand for metals. For the case of biomass co-firing with coal, Schakel et al. (199) find that impacts from the biomass supply chain are comparable to those of coal production and that combustion-related pollution is also comparable, so that BECCS, while providing net negative GHG emissions, results in similar pollution-related health and ecological impacts as coal power with CCS.

Renewable energy systems are also in focus because they lead to habitat change, leading to biodiversity loss. For wind power, collisions of birds and bats with wind power plants are an important concern (200–202). It is clear that wind power plants reduce survival rates of some species, but there are disagreements as to whether these impacts are significant and how they compare to other threats to the same species (203, 204). For hydropower, dams clearly impact freshwater species by disrupting the free flow of water, affecting flooding and nutrient deposition, leading to a deepening of the channel, and acting as a migration barrier (205–207).

[15] When presenting a set of results in a common metric (e.g. DALY, or PM_{10}, see Figure S.4), the relative weight of different effects varies with the choice of that metric because many assumptions and value choices along the impact chain have to made. For example, for estimation of environmental and health impacts, e.g., drawing on life-cycle impact assessment approaches, modelers need to decide for either mid-point or end-point approaches to weigh the disparate environmental and health impacts (33, 34, 191, 197). Comparing the health impacts of alternative electricity supply technologies is hence sensitive to the chosen metric of comparison (20, 28).

Not all dams are used for hydropower and some hydropower plants may have positive impacts on freshwater species as well, and some impacts may at least be partially mitigated. For both hydropower and wind power, site selection, project design and mitigation of ecological impacts are important topics. Even though habitat change-related impacts of renewable energy sources can be clearly identified, it is not clear how these impacts compare with the ecological impacts of fossil fuel extraction, transport and use. Land use associated with coal mining is substantial and larger on a per kWh basis than that of most non-biomass renewable energy systems (192). Consumptive water use of hydropower and concentrating solar power is significant while that of photovoltaics and wind energy is small (208). The cooling water use of thermal power plants, whether they are operated with coal, nuclear or geothermal energy, can cause ecological impacts (209). Methods to compare such impacts are currently under development, but more work, taking into account site-specific impacts of populations of realized or prospective projects, is needed to allow a comparison of the ecological impacts of different energy scenarios.

Bioenergy supply

Bioenergy mitigation options include energy resources as dedicated agricultural and/or forestry plantations, optimal forest harvesting, forest and agriculture residues or organic waste. A further mitigation option in this sector is given by reducing traditional biomass demand and/or increasing efficiency of bioenergy technologies (51, 124). Due to the different bioenergy sources as well as to the specificities of the areas where bioenergy is produced development impacts from bioenergy and its qualification as co-benefit or potential adverse side-effect are context, pace and size-specific (51, 53, 210, 211).

The specific interaction between environmental, social, institutional and technological factors with a given biomass resource and its size is what determines the development impacts in a given region. Further, co-benefits and potential adverse side-effects do not necessarily overlap, neither geographically nor socially (212–214). Thus generalizations (global statements) of development impacts from a given bioenergy source is very difficult. Scientific studies since 2007 have looked at development impacts at five dimensions: institutional, social, environmental, economic and technological (see Table S.2).

The main potential co-benefits seem to be related to access to energy services and impacts on the economy, job creation and improvement of local resilience (215–219). The main potential adverse side-effects of bioenergy include competition on arable land (220) and consequent impact on food security, displacement of communities and economic activities, creation of a driver of deforestation, impacts on biodiversity, water and soil or increment in vulnerability to climate change (124, 210, 215, 216, 221–230). Research on indirect effects (e.g. those on consumption due to increased income) is only starting (231–234) and preliminary conclusions are not yet generalizable.

Labelling, certification and other information-based instruments are seen as option to promote 'sustainable' biofuels (110, 211). Nevertheless, certification approaches have been scrutinized and challenged on the basis of a lack of legitimacy in their design, inherent design weaknesses (235), and a deficient on-the-ground implementation (236, 237), rendering them inadequate substitutes for effective territorial policy frameworks.

For many bioenergy options and almost all regions there is still a knowledge gap between top down models based on rough estimations and bottom-up studies looking at specific impacts on specific contexts (see, e.g., 23, 24–26).

Institutional	Social	Environmental	Economic	Technological
May contribute to energy security (reduce dependency on fossil fuels) (+)	Land use competition implying risks, e.g., to food security (except for bioenergy derived from residues, wastes or by-products) (-) Some agroforestry plantation can	Biofuel plantations can promote deforestation and/or forest degradation (-)	Increase in economic activity and income diversification (+)	Can promote technology development and/or facilitate technology transfer (+)

	contribute to food security whole producing biomass resources (+)			
Impacts on land tenure for local stakeholders (+/-, however mostly negative)	Increasing (+) or decreasing (-) existing conflicts or social discomfort	Increase in use of fertilizers with negative impacts on soil and water	Increase (+) or decrease (-) of market opportunities	Increasing infrastructure coverage (+) while reduced access to infrastructure might increase marginalization (-)
Cross-sectoral coordination (+) or clashes (-) between forest sector, agriculture, energy and/or mining	Impacts on traditional practices (+/-)	Large scale bioenergy crops can have negative impacts on soil quality, water pollution and biodiversity	Contribution to the changes in prices of feedstock (+/-)	High-tech and/or mechanization might reduce labor demand (-) or promote capacity building (+)
Impacts on labor rights across the value chain (+/-)	Displacement of small-scale farmers by big scale producers (-)	Displacement of activities or other land uses (+/-, however mostly negative)	May promote concentration of income and /or increase poverty (-)	High dependence on technology transfer and/or technology acceptance (+/-)
Promotion of participative mechanisms for small scale producers (+/-)	Promote capacity building and new skills (+)	Installing bioenergy plantations on degraded land can have positive impacts on soil and biodiversity	Bioenergy from waste and residues might create socio-economic benefits with reduced non-environmental risks (+)	
	Gender impacts (+/-)		Price uncertainty (+/-)	
	Health impacts from bioenergy production (+/-, however mostly negative)		Employment creation (+)	

Table S.2: Major development impacts reported from bioenergy supply (based on 24, 25, 51, 122).

Urban transport

Transport is relatively unique among the energy end-use sectors as it depends on petroleum products to 94%, with natural gas, biofuels and electricity making up the small rest (48). However, the modes with which people and freight are transported vary greatly with regard to their energy intensity, ranging from walking and cycling to shared modes, such as public transport to car and truck based road transportation, rail, waterborne transport and aviation. The choice of modes, technologies and fuels influences heavily the potential externalities of passenger and freight transport. Air quality, safety, energy efficiency, access to mobility services and other factors that are considered to be co-benefits of sustainable transport measures from a climate change perspective are in fact often the driving factors for policy intervention, in particular on the local level.

As transport relies almost entirely on petroleum products, energy security is a major issue for the sector (52, 238, 239). While there is hence a direct link between energy security and mitigation actions that all reduce fuel consumption, potential co-benefits for other objectives differ across the types of action. For example, fuel switching and propulsion technology based options, such as biofuels and electrification can potentially result in co-benefits for energy security, depending on the fuel stock or electricity source (83, 240, 241). These strategies, however, do not yield the potential to generate as many co-benefits for other objectives as many demand-side measures do (242). For example, fuel efficiency, shift to more efficient transport modes and compact urban design can improve energy security (52, 169, 243) as well as access to mobility services and reduce transport costs, which affects positively productivity and social inclusion (244, 245) and provide better access to jobs, markets and social services (246–248).

Mitigation actions that relieve congestions are also a potential generator for additional co-benefits, providing that the reduced congestion does not induce additional traffic.[16] For congestion relieve measures to be effective a combination of solutions is vital to avoid tradeoffs and induce additional travel; for example, 'Intelligent Transport Systems' and traffic management systems should be accompanied by strategies to shift to lower-carbon modes, such as walking, cycling and public transport. Technology and fuel-based measures are unlikely to impact congestion levels and traffic flows, indicating that these actions should also be part of a wider, more comprehensive strategy (254, 255).

Another major factor where climate change mitigation actions can have positive synergies with other objectives is related to the various health impacts of transport activities, such as air pollution, noise, vibration and road safety. Well over one million people are killed in road accidents globally each year, 91% of which occur in low and middle-income countries (256). Reducing car-based transport can have an immediate effect on road safety (257–260). Comparing the multiple health and safety effects of increased physical activity through walking and cycling often implying higher exposure to air pollution is slightly more complicated (260, 261), but considered to be positive overall (258, 259). Again, a combined approach, for example in conjunction with fuel or technology switch for the public transport and taxi fleets, access restriction for road freight carriers and incentives for more efficient and lower-carbon motorized transport can ensure that air quality is improved to reduce exposure to air pollutants while using active modes of transport (262).

Biofuels for transportation as replacement for petroleum products are associated with several uncertainties, not only with regard to their ability to contribute to GHG emission reductions, but also to their air quality and health impacts (51). For example, replacing fossil-based transport fuels with biofuels may reduce carbon monoxide and hydrocarbon emissions, but increase NOx emissions (28). This is likely to change, however with more advanced biofuels (263). Similarly the potential contribution of electric mobility to local air quality improvements depends on the source of the electricity generation and the location of power plants in a city (264).

There is a lack of studies managing to provide a comprehensive picture on the costs, benefits and potential adverse side-effects and co-benefits of sustainable transport measures across a range of options and beyond specific case studies. Some of those case studies are widely used as examples of the potential for co-benefits and synergies (e.g., 250, 260, 261, 265). Measuring the co-benefits and adverse side-effects of sustainable transport measures is currently not carried out in a consistent manner as different studies/countries apply different metrics and values, e.g. value of a statistical life vs. DALY/QALY or value of travel time, and are hence challenging to aggregate globally. Some effects are barely assessed at all, such as quality of life in cities, but can be very crucial for the success of a sustainable urban mobility policy (see also 18 for a spatial planing perspective on transit and accessibility).

Buildings

The buildings sector is characterized by the utilization of a diverse array of energy sources, technologies and practices, which provide a number of energy services, namely thermal comfort, refrigeration, illumination, communication and entertainment, sanitation and hygiene, nutrition, etc. The technologies and practices widely used today in the buildings sector rely, directly or indirectly, on the usage of various energy carriers,

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[16] Time lost in traffic was valued at 1.2% of GDP in the UK (249); 3.4% in Dakar, Senegal; 3.3% to 5.3% in Beijing, China (250); 1% to 6% in Bangkok, Thailand (251) and up to 10% in Lima, Peru with daily travel times of almost four hours (252, 253).

such as solid fuels (3%), petroleum products (13%), natural gas (24%), combustible renewable energy sources (31%) as well as electricity (29%) and are to a large extent responsible for a number of negative impacts to the environment and public health. Specifically:

- In developing countries inefficient combustion of traditional solid fuels used by about 2.6 billion people worldwide (181), mainly biomass and coal, in households produces gaseous and particulate emissions (known as products of incomplete combustion, PICs), which result in significant health impacts, particularly for women and children who spend longer periods at home (266–268). Indoor air pollution from the use of biomass and coal was responsible for about 3.5 million premature deaths in 2010 (269).
- A significant part of the population in both developed and developing countries lives in households with inadequate insulation, ventilation and heating systems; the resulting indoor conditions are associated with respiratory diseases, allergies, asthma, etc., (21, 270). Of particular importance is fuel poverty, which is associated with excess mortality and morbidity effects, depression and anxiety. It is estimated that over 10% to as much as 40% of excess winter deaths in temperate countries is related to inadequate indoor temperatures (271, 272).
- The consumption of fossil fuels either directly in households or indirectly through electricity and heat generation is associated with the degradation of outdoor air quality, resulting in: (i) increased mortality and morbidity, particularly in developing countries and big cities (269, 273, 274); and (ii) additional stresses on natural and anthropogenic ecosystems (20, 275).

The implementation of energy efficiency measures in the buildings sectors, including fuel switching to electricity that is increasingly decarbonized, improves indoor and outdoor conditions resulting in significant co-benefits for public health and the environment. For example, the associated health and environmental benefits attributed to reduced outdoor air pollution are of the order of 8-22% of the value of energy savings in developed countries (276, 277), and even higher in developing countries. Monetized co-benefits associated with fuel poverty alleviation make up over 30% of the total benefits of energy efficiency investments (271, 278). Bruce et al. (279) found that the healthy years gained per US$2010 million spent in implementing interventions aiming at reducing indoor air pollution range between 700 and 79,500 depending on the world region and the type of intervention implemented. On the other hand, the implementation of energy efficiency technologies in the building sectors is associated with limited risks emanating mostly from health problems caused by airtight buildings with insufficient ventilation (‘sick building syndrome’) and the use of sub-standard energy efficiency technologies due to in-situ toxic chemicals (280, 281).

Apart from health and environmental improvements, an increasing number of studies show that greater use of renewables and energy efficiency technologies in the building sectors result in positive economic effects through job creation, economic growth, increase of income and reduced needs for capital stock in the energy sector (282–284); these conclusions, however, have been criticized for the accounting methods used, whereas objections have been raised over the overall efficacy of using public funds for implementing energy projects instead of other less labor-intensive activities (285). A review of the literature on quantifications of the employment effects of energy efficiency measures in the buildings sector conducted in the context of WGIII AR5, point out that the implementation of mitigation measures in buildings in the developed economies generates on average 13 (with a range of 0.7 and 35.5) job-years per $ million spent (49). Monetization of employment effects for integrating them in social CBA is possible through the implementation of either the adjusted reservation wage gain approach or the adjusted earnings gain approach (286). A recent application of the latter showed that the employment benefits associated with the exploitation of energy saving technologies in the Greek building stock reach 10-24% of the energy costs savings attributed to the implementation of these interventions throughout their entire lifetime, increased up to 45% in economies with high unemployment rates (287). In addition, energy-related renovations of buildings improve workplace productivity by 1-9% or even higher for specific activities or case studies as evidenced by a meta-analysis of several studies undertaken in the context of WGIII AR5 (in 49, see 270, 280, 288).

Other co-benefits associated with the implementation of energy efficiency measures in the buildings sector comprise improved energy security, increased comfort due to better control of indoor conditions and the reduction of outdoor noise, increased safety, enhancement of urban biodiversity, reduction of the heat island effect, improved values for real estate and enhanced ability to rent (18, 49).

It should also be noted that most of the aforementioned co-benefits are also expected from fuel switching to electricity that is increasingly decarbonized. Increased use of electricity in the building sector is projected in both baseline and mitigation scenarios elaborated (49); however, the magnitude of the associated health and environmental benefits are related to the nature of electricity generation (see above).

Despite the unequivocal progress in quantifying the co-benefits of energy efficiency measures there are only a limited number of studies that incorporate such benefits into social CBA; using common metrics and monetization could facilitate their integration into decision-making processes. In most cases the quantified co-benefits (in physical or monetary terms) of energy efficiency are expressed per million investments in energy-saving interventions or per unit of energy saved by the implementation of such interventions (11). However, the utilization of these indices in different case studies is not easy as the mitigation potential per intervention and the other underlying assumptions may differ significantly from country to country or even within a given country. Finally, while these metrics do not lend themselves to cross-sectoral analysis, they can be very policy-relevant in specific policy settings.

Industry

The industry sector processes a wide array of materials, products and services with the production of chemicals and petrochemicals, iron and steel, cement, pulp and paper, and aluminum usually accounting for most of the sector's energy consumption in many countries. Approximately three quarters of industrial energy is used to create materials from ores, oil or biomass, with the remaining quarter used in the downstream manufacturing and construction sectors that convert materials to products. In 2010, the industry sector contributed to GHG emissions by direct combustion of carbon-based fuels (5.27 $GtCO_2$) and indirectly through purchasing electricity and steam (5.25 $GtCO_2$), as well as by chemical reactions in industrial processes (2.59 $GtCO_2$). In 2008, 42% of industrial energy supply was derived from coal and oil, 20% from gas, and the remainder from electricity and direct use of renewable energy sources (50) with coal mining and combustion having the highest number of fatalities and negative impacts on health and the environment in downwind locations, respectively (Smith et al., 2014; Bruckner et al., 2014).

Despite high reductions in energy intensity in developed economies and major structural changes in developed countries during 1995–2008 (289), potential still exists for deployment of best available technologies to deliver products with low energy intensity in many countries where they are not in use. While the technical potential of energy efficiency measures in industry is estimated to be up to 25%, additional reductions of up to 20% in energy intensity may potentially be realized through innovation before approaching technological limits in some energy-intensive industries (50, 290). Up to 30% of emission reduction in industry in 2050 will occur by CCS according to IEA (291). Finally, cross-country investment in mitigation technologies can enhance positive technological spillovers in host countries although this depends on additional technology policies (292–294). However, to attain stringent mitigation goals in industry options like material use efficiency, low-carbon fuel use, decarbonized electricity use, demand reductions in other sectors (e.g., food) that lead to reduced demand for industrial products have important role to play as well.

Besides reductions in GHG emissions technical energy efficiency measures have resulted in less fossil fuel use per ton of production and hence productivity growth at the company level (295–298) and less import of fossil fuel with less exposure to price and supply shocks (52) to generate employment and income through expansion of new appliance design sector, fiscal deficit reduction etc. (178, 299–303). Reduced fossil fuel burning leads to reduced local impacts on ecosystems through less mining activity for, e.g., coal and waste disposal liability (304, 305). There is wide consensus in the literature on local air pollution reduction benefits from energy efficiency measures in industries (303, 306, 307), such as positive health effects, increased safety and work conditions, and improved job satisfaction (178, 299, 308).

Fuel switching options in the industry sector imply local air pollution reduction (303, 306, 307, 309) associated with health benefits (68, 310) and reduced ecosystem impacts (311). Companies individually gain from mitigation efforts from enhanced economic competitiveness, water conservation and reputation/public image building with shareholders (312).

Saving on materials by enhancing efficiency in use will enhance competitiveness (313). Industrial clusters and parks enhance resource sharing which lead to additional societal gains (314, 315), with reducing in need for virgin materials. Demand reduction for industrial product by adopting new diverse lifestyles (128, 149, 316, 317), dietary changes (51, 318, 319) and sufficiency goals can result in multiple benefits related to climate as well as health.

The scientific literature is identifying multiple benefits of many individual mitigation measures but the limited number of studies that quantify such benefits in comparable metrics across studies and countries makes them difficult to include in policy implementation (e.g., CBA). Weighing and aggregating these multiple benefits that accrue to various societal stakeholders is hence difficult for national policy maker, such as for energy intensity reductions in terms of i) savings in the national import bill due to less import of coal or oil or ii) health damage cost reduction to individual households living near industrial units from reduced air pollution measured in terms of sick days reduction or valued at wage loss.

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Acronyms and definitions

All acronym and definitions are adapted from Allwood et al. (35):

Adverse side-effects: The potential negative effects that a policy/measure aimed at one objective might have on other objectives, without yet evaluating the net effect on social welfare.

Aerosol: A suspension of airborne solid (primary PM) or liquid particles (secondary PM from gaseous precursors) that may influence climate in several ways.

Bioenergy and Carbon Dioxide Capture and Storage (BECCS): The application CCS technology to bioenergy conversion processes. Depending on the total lifecycle emissions, BECCS has the potential for net CO_2 removal from the atmosphere.

Traditional biomass: Biomass (e.g., fuelwood, charcoal, agricultural residues, animal dung) used with 'traditional' technologies such as open fires for cooking, rustic kilns and ovens for small industries.

Black carbon (BC): Aerosol species, also called soot, mostly formed by incomplete fuel combustion and has a warming effect by absorbing heat into the atmosphere.

Carbon dioxide (CO_2): A naturally occurring gas and by-product of burning fossil fuels and biomass, of land use changes and of industrial processes – the principal anthropogenic GHG.

Carbon Dioxide Capture and Storage (CCS): A process in which CO_2 from industrial and energy-related sources is captured, conditioned, compressed, and transported to a storage location for long-term isolation from the atmosphere.

CO_2-equivalent concentration (CO_2eq): The concentration of CO_2 that would cause the same radiative forcing as a given mixture of GHGs, aerosols, and surface albedo changes.

Co-benefits: The potential positive effects that a policy/measure aimed at one objective might have on other objectives, without yet evaluating the net effect on social welfare.

Cost-effectiveness analysis (CEA): A tool based on constrained optimization for comparing policies designed to meet a prespecified target.

Cost-benefit analysis (CBA): Monetary measurement of all negative and positive impacts associated with a given policy.

Greenhouse gas (GHG): Gaseous constituents of the atmosphere (natural and anthropogenic), absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted, e.g., by the earth's surface.

Mitigation (of climate change): Reducing the sources or enhancing the sinks of GHGs; often includes reducing other substances which contribute directly or indirectly to limiting climate change, e.g., PM emissions.

Mitigation measures are technologies, processes or practices that contribute to mitigation.

Nitrogen oxides (NO_x): Any of several oxides of nitrogen.

Particulate matter (PM): Very small solid particles from solid fuel combustion; have adverse health effects (particularly < 10 nanometers, PM_{10}) and can directly alter the radiation balance.

Precursors: Atmospheric compounds that have an effect on GHG or aerosol concentrations by taking part in physical or chemical processes regulating their production or destruction rates.

Radiative forcing: The change in the net radiative flux (in Wm^{-2}) at the tropopause due to a change in an external driver of climate change, e.g., changing CO_2 concentrations.

Short-lived climate pollutant (SLCP): Air pollutant emissions that have a warming influence on climate and have a relatively short lifetime in the atmosphere (a few days to a few decades).

Sink: Any process, activity or mechanism that removes a GHG, an aerosol, or a precursor of a GHG or aerosol from theatmosphere.

Sulphur dioxide (SO_2)

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Sustainable development synergies and their ability to create coalitions for low-carbon transport measures

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Abstract

Many low-carbon transport strategies can help achieve other economic, social and environmental objectives. These include improving access to mobility, reducing traffic and parking congestion, saving consumers money, supporting economic development, increasing public health and safety, and reducing air and noise pollution. Based on Avoid-Shift-Improve approaches and case studies from Germany, Colombia, India and Singapore, this paper shows that low-carbon transport generates significant and quantifiable benefits that can create a basis for political and societal coalitions.

Estimates suggest that currently available and cost effective measures can reduce transport Greenhouse Gas emissions by 40-50% compared to 2010. Yet, a number of barriers affect the optimal exploitation of this potential. Considering the possible economic, social and environmental benefits of sustainable transport, the shift towards a low-carbon pathway of this sector can be a win-win situation for climate protection and local development goals. This paper aims to make a contribution to understand these opportunities by highlighting the linkages between objectives, presenting case studies, facts and figures. The paper will also explore assessment methodologies and tools that can help practitioners to assess sustainable development benefits (SDB) and providing evidence for policy-makers to make more informed decisions on transport investments and polices.

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Keywords: Climate change; sustainable transport; co-benefits.

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From co-benefits to sustainable development benefits

With regard to the terminology, this paper evolves from using the well-established term *co-benefit* that describes positive side-effects of climate change mitigation actions, towards using the term *sustainable development benefits* to highlight the fact that diverse environmental, economic and social impacts are equally important from a societal perspective. The paper also explores the risks and uncertainties of some impacts of mitigation measures that may lead to trade-offs and negative side-effects. This aim will help to inform priority-setting for decision makers.

From a climate change mitigation perspective, the term *co-benefits* may make sense, as for example safety or air quality improvements are a (positive) by-product of the primary objective. However, from a wider political perspective it would be wiser to refer to these effects as *sustainable development benefits.* This will give a clear indication on the equal importance of all pillars of sustainable development and may facilitate coalition building between sector ministries and stakeholders from the environmental field, such as the environment ministries and NGOs. As the relevant sector institutions (e.g. the transport ministry or local transport departments) may have other primary policy objectives, such as improving air quality, access or safety it is important to emphasize and measure social, economic and environmental benefits of climate change mitigation measures beyond the greenhouse gas emission reductions in order to motivate actors from these groups by showing the synergies in goal achievement and the benefits a given mitigation action will have in terms of the ministry's priorities. While of course, political and institutional structures are very different from country to country and equally on the local level, some of the key priorities and perspectives of institutions are likely to be somewhat similar depending on the mandate of the institution. Similarly, policy objectives will be different for various institutional actors. However, generating the highest potential level of synergies is likely to have a positive impact on the potential to form coalitions that can support the take-up of a specific policy measure or packages of measures (Nemet et al. 2010; Grubler et al. 2012).

Low-carbon transport as enabler for sustainable transport policy coalitions

This paper analyses synergies between low-carbon transport strategies and other economic, social and environmental objectives, as these can substantially increase the measure´s cost-effectiveness and help build political support for their implementation. Low-carbon transport measures, by avoiding trips, reducing demand, shift to low-carbon modes and improving vehicle efficiency can help achieve various further planning objectives including reduced traffic and parking congestion, public infrastructure and service cost savings, consumer savings and affordability (savings targeting lower-income households), increased safety and security, improved mobility options for non-drivers (and therefore reduced chauffeuring burdens for motorists), and improved public fitness and health, in addition to their pollution emission reductions. Sector officials and many other stakeholders place a high value on these benefits, which creates opportunities for join forces to support their implementation. This paper explores the linkages between climate change and typical policy objectives of key stakeholders and political actors.

1. Identify synergies to other sustainable development objectives

Low-carbon transport strategies that – in addition to reducing Greenhouse Gas (GHG) emissions - help achieve further economic, social and environmental policy objectives, can have a far more extensive overall impact on sustainable development and count with more political support, than mitigation measures that solely focus on the reduction of GHG emissions (Eckermann et al. 2013). Only a few studies have actually examined the total cost of transport including congestion, air pollution, accidents, and noise, and therefore the total potential benefits of policies and programs that reduce these negative impacts. One example of the results of an estimation of positive impacts are the overall reductions of transport expenditures of a balanced sustainable transport policy in a 2 Degree Pathway that were assessed by the International Energy Agency of being up to USD 70 trillion by 2050 (IEA 2012a). In another example from the local level, the combined benefits were assessed for Beijing to be between 7.5% to 15% of GDP annually (Creutzig and He, 2009).

When preparing arguments for a transport climate change mitigation measure it may help thinking about additional benefits that may be high on the agenda of important policy actors and stakeholders. Energy security, transport access and affordability, air quality, health and safety are all powerful policy objectives that need to be taken into account when designing integrated climate change mitigation strategies and Nationally Appropriate Mitigation Actions (NAMAs) that are geared towards a high level of synergies and co-benefits. The following section provides a short overview with some key messages related to each major sustainable development benefit (based on IPCC 2014):

Access and mobility are vital for individuals and businesses. Many transportation emission reduction strategies also reduce costs by improving affordable travel options including walking, cycling, ridesharing and public transit, and by creating more compact communities with shorter travel distances. Households living in automobile-dependent communities often spend 15-20% of their household budget on motor vehicles, but only 5-10% if they are located in more accessible and multi-modal communities (Isalou, Litman, and Shahmoradi 2014; D Mahadevia, Joshi, and Datey 2013).

Air quality is another major issue to which low-carbon transport can make a positive contribution by reducing vehicle engine emissions such as sulphur oxides (SOx), nitrous oxides (NOx), carbon monoxide (CO), hydrocarbons (HC), volatile organic compounds (VOC), toxic metals, and particulate matter (PM), the finer particles of which can cause cardiovascular, pulmonary and respiratory diseases.

Noise pollution affects individual health and quality of life. Noise is second only to air pollution in the impact it has on human health, creating hearing loss, heart disease, learning problems in children and sleep disturbance. In Europe alone noise generated by traffic is linked to more than 50,000 premature deaths every year (T&E 2008).

Congestion is a major issue in many urban areas and creates substantial economic cost. For example, it accounts for around 1.2% of GDP as measured in the UK ; 3.4% in Dakar, Senegal and 4% in Metro Manila, Philippines (Carisma and Lowder 2007); 3.3% to 5.3% in Beijing, China (Creutzig and He 2009); 1% to 6% in Bangkok, Thailand (World Bank 2002) and up to 10% in Lima, Peru (Kunieda and Gauthier 2007). Re-allocating space from roads and parking to more people centred-activities can further significantly improve the **quality of live** in cities.

Employment and economic impacts relate to a number of direct and indirect effects of sustainable transport, such as direct employment opportunities, e.g. in public transport or improved access to jobs and markets. Improved reliability of travel times for both people and freight can also contribute substantially to the attractiveness of cities and the ease of doing business.

Energy security is a key policy objective on the national level and transport plays a major role in this due to its almost complete dependence on petroleum products. Low-carbon transport can improve energy security for individuals, businesses and national economies (Shakya and Shrestha 2011; Leiby 2007). By improving affordable transport options, such as walking, cycling and public transit, low-carbon mobility also improves overall accessibility (people's ability to reach desired services and activities), particularly for physically and economically disadvantaged groups, as well as commuters, tourists and businesses (Boschmann 2011; Sietchiping, Permezel, and Ngomsi 2012; David Banister 2011).

Public health benefits result from more active transport (cycling and walking). This is increasingly important due to increasingly sedentary lifestyles and resulting health problems such as diabetes. Although these modes incur risks, these tend to be offset by their health benefits, particularly if cities improve active transport conditions (David Rojas-Rueda, de Nazelle, et al. 2011; Rabl and de Nazelle 2012a). While some strategies towards modal shifts will have a direct mitigation effect, others such as the introduction of environmental zones may cause trade-offs, as they may ban efficiency, but polluting Diesel vehicles or re-direct traffic, which may increase trip length.

Road safety is also a major transport policy objective that many integrated climate change mitigation strategies can help achieve. Road accidents are estimated to kill around 1.27 million and injure between 20 to 50 million annually, mostly in developing countries (WHO 2011).

The IPCC (2014) pointed out that an integrated approach that addresses transport activity, structure, intensity and fuels is required for a transition towards a 2°C stabilisation pathway as well as generating sustainable development benefits (Table 1). Different types of mitigation actions tend to bring along different impacts and benefits. Policy makers interested in the implementation of mitigation actions and looking for specific *co-benefits* should take this into consideration when selecting and prioritizing mitigation actions for implementation. Mitigation actions in the transport sector can be grouped roughly into three categories. Strategies that **avoid** total motor vehicle travel, e.g. by creating more compact, multimodal communities, and providing incentives for travellers to **shift** from automobile to more resource-efficient modes (walking, cycling, ridesharing, public transit, telecommunications that substitute for physical travel, and delivery services) tend to provide the greatest total benefits, reflecting the high costs (both, internal and external) of motor vehicle travel and the road and parking facilities it requires. **Improving** motor vehicle fuel efficiency and shifting to alternative fuels, on the other hand, provides fewer co-benefits. Table 1 gives an overview of the three categories and the respective development benefits they bring along.

Table 1 A high-level overview of mitigation strategies and their potential economic, social and environmental co-benefits (based on IPCC, 2014)

Intervention level	**Emission reduction approach**	Sustainable development benefits (and risks for trade-offs)		
		Economic	**Social**	**Environmental**
Activity	***Avoid*** Reduce total vehicle travel by reduced trip distances e.g. by developing more compact, mixed communities and telework.	Reduced traffic and parking congestion (6,7). Road and parking cost savings Consumer savings Energy security (1,2). More efficient freight distribution (14). Reduced stormwater management costs	Improved access and mobility, particularly for non-drivers, which improves their economic opportunities and productivity (9) Affordability (savings for lower-income households) Accident reductions	Ecosystem and health benefits due to reduced local air pollution (20). Reduced land consumption (7, 9). Potential risk of damage to vulnerable ecosystems from shifts to new and shorter routes (15,16).
Structure	***Shift*** to low-carbon transport modes, such as public transport, walking and cycling	Improved productivity due to reduced urban congestion and travel times across all modes (6,7). Improved energy security (1,2).	More equitable mobility access and safety, particularly in developing countries (8). Reduced accident rates from improved walking and cycling conditions, and shifts from automobile to public transit (7,11). Total accidents can increase if extra safety measures for cyclists are not introduced (22).	Ecosystem and health benefits due to reduced local air pollution (20).

			Reduced exposure to air pollution (7). Health benefits from shifts to active transport modes (7,12).	
Intensity	***Improve*** the efficiency of the vehicle fleet and use	Reduced transport costs for businesses (4,5). Improved energy security (1,2).	Reduced fuel cost for individuals and transport operators (1,2). Health benefits due to reduced urban air pollution (20).	Ecosystem and biodiversity benefits due to reduced urban air pollution (20).
Fuels	***Reduce*** the carbon content of fuels and energy carriers	Some measures may reduce the costs for businesses; others may increase (4). Improved energy security (reduction of oil dependency) (1,2). Reduce trade imbalance for oil-importing countries (3).	Lower exposure to oil price volatility risks (1,2). Electric and fuel cell powered vehicles give air quality improvements (13,20) and noise reduction (10) Potential increase in accidents due to electric vehicles (2-wheelers, cars, buses, trucks) being silent at low speeds (24). CNG and biofuels have mixed health benefits (19,20). A shift to diesel can improve efficiency, but tends to increase air pollution (23).	Electric and fuel cell vehicles Air quality improvements (13,20). Biofuels: Potential adverse effects on biodiversity, water and nitrification (24). Potential issues associated with sustainable supply of biofuels (21). Unsustainable mining of resources for technologies e.g. batteries and fuel cell (17,18).

References: 1: (Greene 2010); 2: (Costantini et al. 2007); 3:(Kaufmann, R.K., Dees, S., Karadeloglou, P., Sánchez 2004); 4: (Boschmann 2011); 5: (Sietchiping, Permezel, and Ngomsi 2012); 6: (Cuenot, Fulton, and Staub 2012, Lah 2014); 7: (Creutzig, Mühlhoff, and Römer 2012); 8: (David Banister 2008); 9: (D. Banister 2008; Geurs and van Wee 2004); 10: (Creutzig and He 2009); 11: (Tiwari and Jain 2012); 12: (Rojas-Rueda et al. 2011); 13: (Sathaye et al. 2011); 14: (Olsson and Woxenius 2012); 15: (Garneau et al. 2009); 16: (Wassmann 2011); 17: Eliseeva and Bünzli 2011; 18: Massari and Ruberti 2013; 19: (Takeshita 2012); 20: (Kahn Ribeiro et al. 2012). 21: (IEA 2011a), 22: (Woodcock et al. 2009) , 23: (Schipper and Fulton 2012), 24: (Sims et al. 2014,)

2. Measure combination to maximise synergies

Decision making on transport policy and infrastructure investments is as complex as the sector itself. Rarely ever will a single measure achieve comprehensive climate change impacts and also generate economic, social and environmental benefits. Many policy and planning decisions have synergistic effects, meaning that their impacts are larger if implemented together. It is therefore generally best to implement and evaluate integrated programs rather than individual strategies. For example, by itself a public transit improvement may cause minimal reductions in individual motorized travel, and associated benefits such as congestion reductions, consumer savings and reduced pollution emissions. However, the same measure may prove very effective and beneficial if implemented with complementary incentives, such as efficient road and parking pricing, so travellers have both **push and pull incentives** to shift from automobile to transit. In fact, the most effective programs tend to include a combination of qualitative improvements to alternative modes (walking, cycling, ridesharing and public transit services), incentives to discourage carbon-intensive modes (e.g. by efficient road, parking and fuel pricing; marketing programs for mobility management and the reduction of commuting trips ; road space reallocation to favour resource-efficient modes), plus integrated transport planning and land use development, which creates more compact, mixed and better connected communities with less need to travel.

A vital benefit of the combination of measures is the ability of integrated packages to deliver synergies and minimise rebound effects. For example, the introduction of fuel efficiency standards for light duty vehicles may improve the efficiency of the overall fleet, but may also induce additional travel as fuel costs decrease for the individual users. This effect refers to the tendency for total demand for energy decrease less than expected after efficiency improvements are introduced, due to the resultant decrease in the cost of energy services (Sorrell 2010; Gillingham et al. 2013, Lah 2014). Ignoring or underestimating this effect whilst planning policies may lead to inaccurate forecasts and unrealistic expectations of the outcomes, which, in turn, lead to significant errors in the calculations of policies' payback periods (WEC 2008, IPCC 2014). The expected rebound effect is around 0-12% for household appliances such as fridges and washing machines and lighting, while it is up to 20% in industrial processes and 10-30% for road transport (IEA 1998, 2013). The higher the potential rebound effect and also the wider the range of possible take-back, the greater the uncertainty of a policy's cost effectiveness and its effect upon energy efficiency (Ruzzenenti and Basosi 2008).

A number of studies emphasize that an integrated approach is vital to reduce transport-sector greenhouse gas emissions cost-effectively (IPCC 2014, Figueroa Meza et al. 2014). While emissions reductions can be achieved through several means, such as modal shift, efficiency gains and reduced transport activity, it is apparent that the combination of measures is a key success factor to maximise synergies and reduce rebound effects. For example, overall travel demand reduction and modal shifts would need to be substantially stronger if not accompanied by efficiency improvements within the vehicle fleet and vice-versa (Figueroa Meza et al. 2014; Fulton, Lah, and Cuenot 2013). Vital element for this strategy is a policy package as summarised in the table below.

Table 2: Elements of a multi-modal, multi-level sustainable transport package

Examples measures	Complementarity of measures
National measures - Fuel tax - Vehicle fuel efficiency regulation - Vehicle tax based on fuel efficiency and/or CO2 emissions	- Vehicles standards and regulations ensure the supply of efficient vehicles and taxation helps steering the consumer behaviour - Fuel tax encourages more efficient use of vehicles, which helps minimising rebound effects that might occur if individuals and businesses drive more or not as efficient as they would have driving a vehicles with lower efficiency standards
Local measures - Compact city design and integrated planning - Provision of public transport, walking and cycling infrastructure and services - Road User Charging, parking pricing, access restrictions, registration restrictions and number plate auctions, eco-driving schemes, urban logistics	- Compact and policy-centric planning enable short trips and the provision of model alternatives provides affordable access - Complementary measures at the local level help managing travel demand and can generate funds that can be re-distributed to fund low-carbon transport modes

3. Veto players and coalitions for the implementation of sustainable mobility measures

Transport is a complex and multifaceted activity. Policy interventions in this sector can have unintended consequences, positive and negative as they rarely only affect one objective, for example air quality measures may affect fuel efficiency negatively or biofuels may have land-use change implications. Linking and packaging policies is therefore vital to generate synergies and co-benefits between measures. This provides a basis for coalitions that can align different veto players. An integrated policy approach can help to overcome implementation barriers, minimize rebound effects and create the basis for coalitions among key political actors and societal stakeholders.

It is sometimes claimed that transport is the hardest sector to decarbonise (ECMT 2007; IEA 2011c). However, cities, regions and countries around the world are successfully implementing polices and projects which provide substantial emission reductions in addition to other benefits. While currently implemented measures cannot by themselves achieve the established emission reduction targets, they can make important contributions. According to a recent IPCC Assessment Report, only an integrated approach can achieve the levels of reduction needed to shift to a 2°C pathway. This is true not only for the achievement of emission reduction goals, but also for the fulfilment of other sustainable development goals. Reductions in traffic and parking congestion, increased energy security and traffic safety, affordability of transport services, public fitness and health, economic productivity, mitigation of climate change, and the reduction of local air pollution are positive impacts of transport policy that can help motivate people, businesses and communities to implement **comprehensive policies and integrated transport** programs to reduce transport greenhouse gas emissions and generate sustainable development benefits. Different people, groups and institutions may have different priorities, for example, some may be motivated by economic objectives and others by social equity or environmental objectives. The diverse benefits offered by a comprehensive or integrated measure can help build broad community support. The nature of integrated sustainable, low-carbon transport policies is that they address several objectives simultaneously, which generates synergies and helps creating coalitions.

The political and institutional context in which policies are being pursued is a vital factor for the success or failure of implementation (Jänicke 1992). Institutional aspects such as the presence of absence of a environment ministry at the national or environment department on the local level and their respective role in the process as well as the legal power, budget and political influence are likely to have an effect on the implementation of (primarily) climate related transport measures. (Jänicke 2002).

Vital for the success of long-term policy and infrastructure decisions is support from diverse political actors, stakeholders and the public. A societal perspective and the incorporation of sustainable development objectives is a vital step in forging coalitions and building public support. Policy and infrastructure measures and the combination thereof are an important element in generating sustainable development benefits with low-carbon transport as they provide the content of a low-carbon transport strategy. But vital for the success of the take-up and implementation of measures is the policy environment – the context in which decisions are made (Justen et al. 2014). This context includes not only socio-economic, but also political aspects, taking into account the institutional structures of countries. The combination of policies and policy objectives can help building coalitions, but can also increase the risk of the failure of the package if one measure faces strong opposition, which, however, can be overcome if the process is managed carefully (Sørensen, Hedgaard, et al. 2014). A core element of success is the involvement at an early stage of potential veto players and the incorporation of their policy objectives in the agenda setting (Tsebelis and Garrett 1996).

Veto players are political actors who have a distinctive role in the policy process and put a hold to an initiative. Typical veto players are finance ministries and parliaments with legislative prerogatives. This is a substantially different role from **stakeholders**, who have a vested interested in a particular policy process, but do not have the (legal) power stop it. However, both groups need to be involved in the process to successfully implement a measure. **Public participation** can help ensuring durability and support beyond political parties. There is a causal relationship between policy objectives, agenda setting, institutional structures and policy outcomes (Tsebelis 2002, Lijphart 1984). The synergies explored in this paper provide a basis for the inclusion of veto players into the policy process, which is vital for the uptake of sustainable mobility policies. The table below aims to apply the veto players' approach to coalition formation to identify the links between policy objectives and policy actors (Table 1). This aims to highlight that politics and the policy environment play an important role in the uptake of policy measures.

Table 1: Coalition building - examples of potential linkages between climate and other sustainable development policy objectives and actors

Climate change mitigation approach and objective	**Economic implications and actors**	**Social implications and actors**	**Environmental implications and actors**
Avoid vehicle travel by reduced trip distances e.g. by developing more compact, mixed communities and telework.	Reduced congestion: *Local authorities (v)* ↑ More efficient freight distribution: *Businesses and associations* ↑ *Economic development ministry (v)* ↑	Improved access and mobility *Social development ministry* ↑ Accident reductions *Health Ministry* ↑	Reduced land consumption *Local planning authority (v)* →
Shift to low-carbon transport modes, such as public transport, walking and cycling	Improved productivity due to reduced urban congestion and travel times across all modes *Local authorities (v)* ↑	Reduced exposure to air pollution Health benefits from shifts to active transport modes *Local authorities (v)* ↑	Ecosystem benefits due to reduced local air pollution. *Local environmental department & national ministry* ↑
Improve the efficiency of the vehicle fleet and use	Reduced transport costs for businesses and individuals *Local authorities (v)* and Economic and Social development ministries ↑	Health benefits due to reduced urban air pollution *Health Ministry* ↑	Ecosystem and biodiversity benefits due to reduced urban air pollution *Local authorities (v)* ↑
Reduce the carbon content of fuels and energy carriers	Improved energy security *Economic development Ministry* ↑ Reduce trade imbalance for oil-importing countries *Finance Ministry (v)* ↑	A shift to diesel can improve efficiency, but tends to increase air pollution *Health and Environment Ministries (v?)* ↓	Potential adverse effects of biofuels on biodiversity and land-use *Environment and agriculture (v)* ↓

The selection is not exhaustive and depends on the policy environment. Key: positive ↑ negative ↓ uncertain →, (v) potential Veto Player

Conclusion

Considering that significant and diverse benefits can be gained from policies and projects that increase transport system efficiency, their uptake is far lower than economically justified. Shifting to a low-carbon development pathway requires substantial transport sector reforms. Many of these are options that provide significant economic, social and environmental co-benefits and so can conserve energy and reduce emissions at low or event negative costs. Because of their significant and diverse benefits, they offer opportunities to build coalitions involving many different stakeholders with various interests. This can help build support and strengthen the political case for the shift towards a low-carbon mobility pathway. Successful strategies need to be integrated across policy areas, regions and levels of government. One way of incorporating objectives of key players and include them in the process is to establish a cross-cutting working group (first in the department and then across departments and then across levels or government and including key business and civil society players). The table below provides some examples of linkages between climate change mitigation approaches, their linkages to some economic, social and environmental implications and examples of potential veto players and stakeholders. This matrix is mainly an illustrative example and needs to be amended for the specific context.

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Continuity and Change: Dealing with Political Volatility to Advance Climate Change Mitigation Strategies—Examples from the Transport Sector

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Abstract: As the recent withdrawal of the United States from the Paris Agreement has shown, political volatility directly affects climate change mitigation policies, in particular in sectors, such as transport associated with long-term investments by individuals (vehicles) and by local and national governments (urban form and transport infrastructure and services). There is a large potential for cost-effective solutions to reduce greenhouse gas emissions and to improve the sustainability of the transport sector that is yet unexploited. Considering the cost-effectiveness and the potential for co-benefits, it is hard to understand why efficiency gains and CO_2 emission reductions in the transport sector are still lagging behind this potential. Particularly interesting is the fact that there is substantial difference among countries with relatively similar economic performances in the development of their transport CO_2 emissions over the past thirty years despite the fact that these countries had relatively similar access to efficient technologies and vehicles. This study aims to explore some well-established political science theories on the particular example of climate change mitigation in the transport sector in order to identify some of the factors that could help explain the variations in success of policies and strategies in this sector. The analysis suggests that institutional arrangements that contribute to consensus building in the political process provide a high level of political and policy stability which is vital to long-term changes in energy end-use sectors that rely on long-term investments. However, there is no direct correlation between institutional structures, e.g., corporatism and success in reducing greenhouse gas emissions in the transport sector. Environmental objectives need to be built into the consensus-based policy structure before actual policy progress can be observed. This usually takes longer in consensus democracies than in politically more agile majoritarian policy environments, but the policy stability that builds on corporatist institutional structures is likely to experience changes over a longer-term, in this case to a shift towards low-carbon transport that endures.

Keywords: sustainable transport; policy implementation; governance; institutions

1. Introduction

Recent years have seen several drastic climate policy shifts in a number of countries, most notably the dismantling of climate policies implemented by the Obama administration in the United States by the Trump administration. Similar drastic policy changes led by conservative governments in Australia, Canada, New Zealand, and the United Kingdom show a pattern of political volatility that is inherent to the political and institutional structure of so-called majoritarian countries, which refers to democratic systems that are characterized by a two-party minimal majority political system. This paper will aim to shed some light on the relationship between political and institutional structures and climate policy outcomes.

The transport sector accounts for about 14% of global CO_2 emissions and it combines a number of other interesting factors. It is a key subject of energy security concerns, a major contributor to local air pollution, creates substantial road safety issues, and traffic congestion affects economic development negatively. Considering the role that sustainable transport polices can play in addressing these issues, it is puzzling that countries have made very differing levels of progress in this policy area. It is argued that a number of factors contribute to different policy outcomes. Differing pressures from climate change, air quality, congestion, safety, or energy security are likely to influence the time and scale of policy responses, but institutional and political structures determine the consistency and continuity of policy action. The combination of economic and environmental policy objectives makes the transport sector a particularly interesting case for an in-depth analysis of climate change policies. Transport climate change mitigation polices will be used as an example to examine, in more detail, the differences in policy making in different institutional settings.

The political environments can be very different from country to country, which affects the capacity to implement sustainable transport and other climate change mitigation measures. This study aims to explore the relevance of several political science theories to the climate and energy policy context to identify key factors that influence the policy environment in this area. There are a number of studies examining the influence of the concepts of corporatism, coordinated market economy, consensus democracy, epistemic communities, European integration, and centre-left and green party strength on environmental performance [1,2]. Most studies focus on higher-level environmental performance indicators and their relationship to specific institutional settings [1–7]. This paper builds on these studies and aims to explore potential relationships between institutional frameworks and their impact on policy agenda setting and the implementation of policies and specific outcomes in the transport sector, which has often been described as one of the hardest to decarbonise [8–10].

Some of the key institutional indicators are being explored in this paper, which will aim to shed some light on the relationship between institutional arrangements and potential influence on efforts to decarbonise the transport sector. While this will not show a linear relationship between the institutional settings and outcomes, it aims to highlight potential factors that can be considered for a governance framework that can address the complexity of a sector that requires integrated and long-term policy action at all levels of government to meet climate change targets that are in line with a stabilization well below 2 °C above pre-industrial levels [10].

2. Methodology: Factors for Continuity and Change

Social, environmental, energy, and economic drivers to implement policies that increase the efficiency of the transport sector are substantial. However, different policy environments have different effects on the implementation of certain policy measures. While some countries have strong and innovative local sustainable transport policy measures implemented, they lack progress on the national level or vice-versa [11]. There is a large number of local and national policy measures that are ready to be implemented to reduce greenhouse gas emissions and deliver on wider sustainable development benefits [11–13]. The reason why measures are not taken-up at their potential level relates to a number of factors, such as finance, but some are directly related to the policy environment and the institutional structure of a particular country or city. Sustainable mobility polices, such as fuel and vehicle taxation, urban planning and public transport infrastructure, are highly visible and politically sensitive issues, which require strong political support, sufficient capacity at the administrative level, consensus among key actors and stakeholders and a stable policy environment to appear on the policy agenda and to remain in place as they rely on investments that are only cost-effective over the medium to long-term [11,14].

A better understanding of relevant aspects related to the policy environment and institutional structures in which sustainable mobility measures are being considered, can help in the policy design and implementation. An initial analysis of several potential factors of a transport climate change policy framework will be explored in this paper, to build on aspects of policy integration, coalitions, and institutional structures that influence the policy environment.

Several potential factors will be presented in this paper to provide some indications on the policy environment as it is influenced by uncertainty, a shared set of methods and values that is vital for policy agenda setting, usually delivered through epistemic communities. This paper considers these several factors as vital contributors to enable epistemic communities to influence policy agenda setting and for policy continuity. These factors draw on political science theories focusing in particular on political consensus, corporatism, coordinated market economy, consensus democracy, and veto players. These concepts are applied to the climate change and energy policy context. Additional influencing factors are assumed to be the level of integration into the supra-national policy framework of the European Union and the strength of centre-left parties and green parties. This includes an analysis of the level of dependence of climate change mitigation policies iwith support from these parties and if and how policies evolve following changes of government. This analysis is intended to provide an input into the wider climate policy debate by aiming to highlight several governance and institutional issues and their potential to affect the climate and transport policy environment. The strategies needed to get transport onto a 1.5/2 °C stabilisation pathway require an integrated policy approach and a multilevel governance approach [12,15–18].

3. The Relevance of Institutional Political Science Approaches

Consensual political institutions as outlined by Lijphart [19] may lead to higher levels of policy continuity, which in turn would have positive effects for the success of climate change mitigation strategies in the transport sector. This approach also adopts the theoretical concept of "encompassing organisations" [20] and examines the relationships between political and societal actors and their ability or inability to negotiate policies that are based on broad majorities in both politics and society. Crepaz [21] argues that multiparty coalition governments with proportional representation and negotiation are more effective in lowering unemployment and inflation and hence creating a more favourable socio-economic environment. Lijphard and Crepaz [19,22] provide conceptual frameworks and supporting evidence that governments with consensual, inclusive, and accommodative constitutional structures and wider popular cabinet support act more politically responsibly than more majoritarian, exclusionary, and adversarial countries.

In countries with corporatist institutional structures, major policy issues are negotiated in a concerted effort by organised interests. Studies in this domain usually focus on the interaction between unions and employer organisations to negotiate socio-economic policies. Policy coordination among organised interests facilitates favourable policy outcomes, which relates in the case of this study to lower levels of greenhouse gas emissions in the transport sector. According to this, a high level of corporatism may influence the implementation and improvement of policies with a long-term focus. There are a number of elements which may support this, for example: comparatively encompassing interest groups, a consensual social partnership, and a broad acceptance of government regulation due to a history of strong penetration of the state in areas such as the labour market and social policy [4]. Interest groups are integrated into the policy process in a corporatist country and broaden the basis of policies, which creates a high level of continuity that is required for long-term investments. This coalition building locks groups into certain policy directions that further enhance policy progress, which is almost self-reinforcing [23,24]. As a response to economic downturn, high unemployment, and inflation rates triggered by the 1970s oil price shocks, several countries with an open economy used corporatist structures to cope with increasing policy pressures [24–26].

The concept of coordinated market economies is very similar to the general concept of corporatism, as it relies on formal institutions to regulate the market and coordinate the interaction of firms and their relations with suppliers, customers, and employees [27]. Coordinated market economies can be characterised as having long-term relations between key actors in the economy. A particular focus in research has been the relationship between trade unions and employer associations. These long-term, cooperative relations provide coordinated market economies with a comparative advantage that positively affects the policy continuity and policy capability of a country in a similar way as corporatist structures do.

Hall and Soskice [27] argue that the hands-off policy approach and uncoordinated interaction between policy makers, and economic and societal actors, characterises liberal market economies and puts these countries at a relative disadvantage compared to coordinated market economies. The strong interlinks between industry, banks, government, and non-governmental organisations in coordinated market economies are considered to cause inertia, but can also result in continuity and policy stability [27–31]. The analysis of the potential relationship of carbon intensity and continuity and coherence indicators gives some indication of clusters of countries that represent certain institutional arrangements and governance structures and their transport CO_2 emissions per capita. Pluralist and less consensus oriented countries, such as the US, Canada, Australia, and New Zealand, have higher levels of per capita transport CO_2 emissions than nations with a strong focus on consensus building after deliberation, such as Austria, Sweden, Germany, and Switzerland. Countries such as the UK and France have both, leading to low levels of CO_2 emissions. For these countries it is argued that the membership in the European Union acts as a factor of policy stability [32,33]. In addition, cohabitation (France) and the strength of the Labour Party (UK) when it was in power, are considered to have contributed to emission reductions in these two countries in the early 2000s [34]. A follow-up analysis assessing changes after the United Kingdom will have left the EU, may further provide indications of the role of the EU in policy stability, following the UK´s decision to leave the European Union. The divide between various countries becomes even more obvious when comparing the level of consensus in various EU and non-EU member countries regarding increasing or decreasing emissions reductions in the respective transport sectors, which reflects the actual progress in low-carbon transport policy (or the lack thereof). This is becoming particularly obvious when comparing climate policy approaches in the EU and the US, which will be outlined in Section 5 after some of the factors outlined in this section have been analysed in a set of multivariate-variate correlations.

4. Institutional Factors and Their Relationship to Policy Outputs and Outcomes

4.1. Epistemic Communities, Societal Consensus, and the Uncertainties of Climate Change Impacts

While the basic physics of anthropogenic climate change are scientifically robust, there remains uncertainty over the scale and timing of climate change impacts, which makes policy making much more complicated than in other areas [12]. The adoption of a precautionary approach is therefore vital and the "lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" [35]. The debate has moved in many countries from climate science to climate action. Since the First Assessment Report was published by the Intergovernmental Panel on Climate Change in 1990, some countries have steadily progressed climate change mitigation policies, while others have experienced substantial political volatility in this area. Uncertainty about the potential impacts of climate change makes decision-making very difficult and complex. A critical factor from the policy makers' perspective is the impact chain, characterised by increasing scientific uncertainty, which is related to the complex nature of the global climate system [8]. While the scientific understanding of the impact pathway has improved, climate change policies are often stalled by uncertainty about risks [36]. Issues such as climate change require particular sorts of information, which are not based on ideology, guesswork, or raw scientific data, but are a human interpretation of social and physical phenomena [37,38]. It is argued that epistemic communities are vital in providing this information to enable policy action and consensus building. The members of an epistemic community share the same values and understanding of causal relationships, which creates the foundation for policy decisions in consensus or compromise [24,39,40]. An epistemic community can produce consensual knowledge, even if the level of scientific evidence is uncertain or inconclusive [38,41].

Epistemic communities are a "network of professionals with recognized expertise and competence in a particular domain and an authoritative claim to policy-relevant knowledge within that domain or issue-area" [38]. Regardless of the professional background, epistemic communities have a shared set of normative and principled beliefs, which provide a value-based rationale for the social action of community members. They share causal beliefs, which serve as the basis for identifying linkages between possible policy actions and desired outcomes [38]. Epistemic communities provide a key input into the policy process, which is particularly effective in certain institutional structures. In corporatist structures, participation in the policy process is limited to a small number of societal actors who collectively form an epistemic community that has a shared set of values. Members of this community are able to influence the policy agenda and they also provide policy stability, which makes shared methods and values an important factor for a common agenda on which climate policies are being developed.

4.2. Consensus Focused Democratic Institutions

A central element of many consensus democracies is a corporatist institutional structure that allows a more coordinated approach to policy making with a small number of large peak organisations [25]. This closed shop approach enables the formation of epistemic communities as it substantially limits the number of players that need to be convinced. The potential comparative advantage of consensus democracies also relates to a number of other elements that characterise these countries, such as the "shadow of state regulation" [5] and a broad acceptance of government regulation due to a history of strong penetration of the state in areas such as the labour market and social policy [26]. The institutional structures of a consensus democracy are the primary drivers behind political stability and continuity that creates better environmental policies over the long term [3,42]. Corporatist institutional arrangements characterised by a strong relationship between large encompassing groups enable decision makers to negotiate policy in a way that is distinctively different from policy making in pluralist, majoritarian democracies [21]. These groups are integrated into the policy process in a country with a corporatist structure and broaden the basis of policies, which creates a high level of continuity that is required for long-term investments [43]. Such coalition building locks groups into certain policy directions that further enhance policy progress, which is almost self-reinforcing [23,24].

The institutions that enable a broader consensus amongst politicians and society are described by a large number of scholars using different approaches and definitions. This study aims to apply these theories in a combined approach which will allow an assessment of institutional relationships that is broader than the isolated approaches used in many previous studies. It aims to relate one particular institutional feature to socio-economic or more specific policy outcomes.

Democratic systems can largely be divided into two major categories: majoritarian and consensus democracies [19,22,44]. Majoritarian system are characterised by the concentration of power in one-party and minimal winning majority cabinets, a two-party system, non-proportional election systems, interest organisation pluralism, centralised forms of government, unicameral parliaments, constitutional flexibility, absence of judicial review, and executive control of the central bank. Consensus democracies on the other hand are characterised by coalition government, balance between executive and legislative power, proportional representation, interest group corporatism, federalism, bicameralism, constitutional rigidity, judicial review, and independence of the central bank [44]. These combinations are not a definitive list of characteristics, but an indication of typical elements of countries that can be described as majoritarian or consensus democracies.

Due to its characteristics it could be argued that a majoritarian democracy is decisive and able to implement climate change mitigation measures faster than a consensus focused counterpart. This argument may have some merit when looking at the amendments to the vehicle fuel efficiency standards introduced by Australia, Canada, and the US in recent years. All three countries are typical majoritarian democracies and changes in the standards have been introduced in the US and Australia by Democratic and Labour-led governments, respectively. Canada´s regulation is aligned with the US standards. This shows that change is possible and can be implemented fairly swiftly in majoritarian systems, but this relies on support of the minimal majority, which may change and with that, possibly support for the policy. This paper argues that the decisive factor of success for climate change mitigation policies is the reliability of the policy environment over the long term. It challenges the theory that majoritarian democracies are more effective and argues that consensus orientated democracies are more likely to be successful in moving towards sustainable development over the long term. This has become particularly obvious when looking at the high level of political volatility of the position of the United States in the United Nations Framework Convention on Climate Change (UNFCCC), adopted in 1992 by George H.W. Bush although with watered down targets, followed in 1997 with the Kyoto Protocol as major milestone, first signed and actively supported by Al Gore on behalf of the US administration and then abandoned by the George W. Bush administration. With insufficient parliamentary support, the Obama administration struggled to pass major climate change legislation, but helped championing the Paris Agreement in 2015, from which the Trump administration withdrew in 2017, making it the only country in the world except for Syria and Nicaragua not being part of this global climate change agreement. While sometimes being slow in the adoption of climate policy measures [45,46], the EU has maintained a steady and gradually improving approach to climate change mitigation policy that has endured many elections at the member states and EU level. This shows a link between institutional and climate change indicators and provides an indication that consensus democracies can outperform majoritarian democracies by creating a more stable policy environment through more efficient institutional relationships [19]. It is argued that consensus democracies are even more responsive and decisive than majoritarian systems, at least over the longer term, because of the more coordinated interaction with societal actors [21]. This positive impact on the stability of the policy environment depends on a number of elements that are characteristic for a country with a corporatist structure, for example: comparatively encompassing interest groups, the 'shadow of state regulation', and a broad acceptance of government regulation due to a history of strong penetration of the state in areas such as the labour market and social policy [4].

Corporatist institutional arrangements are characterised by a strong relationship between large encompassing interest organisations that enable decision makers to negotiate policy in a way that is distinctively different from policy making in pluralist, majoritarian democracies. The difference between corporatist and pluralist institutional arrangements has been studied for many years. However, there is still debate about corporatism creating more positive impacts, in particular on socio-economic performance [29,47] as opposed to negative effects [48,49]. Corporatist intuitional interaction is considered to have less collective protests and strikes [50], which gives an indication of political stability. It can be claimed that corporatism is beneficial for climate change policy development if the encompassing groups have vital interests that foster environmentally sustainable policies. These groups are integrated into the policy process in a corporatist country and broaden the basis of policies, which creates a high level of continuity that is required for long-term investments. This coalition building locks groups into certain policy directions that further enhance policy progress, which is almost self-reinforcing [23,24]. Based on this analysis consensus oriented democratic institutions and encompassing corporatist structures are considered to be highly relevant factors for the framework presented in this paper.

4.3. European Integration

The interrelations between European and domestic politics and policies create a new dimension for societal and political actors [51–53]. The European level opens new opportunities, but potentially also constrains the pursuit of specific political interests. This provides societal actors with an opportunity to advocate for policy measures, for example, climate change mitigation policy measures even if the particular issue has no or little priority on the domestic political agenda [32]. Even more important are the formal institutions of the European Union, which provide the opportunity for new policy initiatives. They also create a policy environment that is less dependent on national elections and hence less likely to become subject to radical change after an election [54]. The "logic of appropriateness" [53] and processes of persuasion in the European Union are mediated by the influence of change agents who persuade others to adjust national interests to the overarching European framework and a European political culture which aims for political consensus and cost-sharing [32]. The European Union influences climate and energy polices of its member states both directly and indirectly [30,51,52]. Due to its supra-national character, the European Union is a significant policy driver. How much influence this driver has in comparison with, for example, the United Kingdom and Germany. Both are members of the European Union, differ significantly in their level of corporatism, but have similar developments in energy intensity in the transport sector. Hence it could be assumed that membership in the European Union is a contributing factor to more political continuity. Considering the role of the European Union for example in the area of EU-wide fuel efficiency regulations, it is fair to say that European institutions are not only a contributing, but a driving factor to more political continuity in this policy area.

Integration into the European Union as a factor of political continuity touches on various concepts, in particular rational choice institutionalism and constructivist institutionalism (see for example: [32,51,52]. In contrast, participation in international forums and international governance structures, most notably the United Nations Framework Convention on Climate Change (UNFCCC) influences national climate policy strategies, but to a much smaller degree as the withdrawal of the US from the Paris Agreement and the Kyoto Protocol before showed. Pressures on countries for acting on climate change in international negotiations may vary depending on the country's role in the international community and its track record on climate change policies. This may influence a country's motivation to implement policies that curb emissions. International agreements are relatively weak compared to the supranational structure of the EU. Hence, it is assumed that the integration into international agreements only has little influence on the ability of countries to deliver on long-term climate change policy goals, while the integration into supranational structures (as of now only the EU is a supranational body) does play a significant role for the governance framework presented in this paper.

4.4. Influence of Centre-Left Parties and Green Parties

Several authors suggest that the strength of centre-left and green parties has a significant impact on the effectiveness of environmental policies [53–56]. Green parties' central, if not defining, political objective is environmental protection. Hence, their political representation and influence in Parliament and government is likely to impact positively on climate change policies. Centre-left parties are the more likely coalition partners for Green parties and also tend to be more interventionist in their policy making [56–58]. Several papers indicate that the dependence on centre-left and Green party-strength is less relevant for policy outcomes than the higher level of continuity in corporatist countries and consensus democracies. This could be linked to the integration of climate change mitigation and energy security as important policy objectives by the societal actors. With regard to the framework to be developed in this paper, a reliance on Centre-Left Parties and Green Parties to adopt and implement climate change policies would indicate a potential for swifter action, but would bear the risk of political volatility if policies are not based on a broader societal and political consensus.

5. Example: Vehicle Fuel Efficiency Regulation in the EU and US

To illustrate the role of institutional factors, this section provides an example from one of the key policy interventions to improve the efficiency of the light-duty vehicle fleet—fuel efficiency standards. This type of regulation aims to ensure a supply of efficient vehicles and, even more importantly, aim to limit the level of fuel consumption throughout the vehicle fleet.

The USA was the first country to introduce vehicle fuel economy standards, in as early as 1975, just two years after the first oil crisis, in the form of the US Corporate Average Fuel Economy (CAFE) standard, which requires car manufacturers to meet sales-weighted average fuel economy standards for light vehicles sold domestically. This mandatory standard was effective in improving vehicle fuel efficiency for around a decade, with the fleet-average fuel economy of passenger cars rising from approximately 15 miles per gallon (15.68 L/100 km) in 1975 to approximately 28 mpg by 1989 (8.4 L/100 km). After oil prices recovered in the 1980s and policy-makers' attention in this area decreased, so did the effectiveness of the CAFE standards. A number of factors contributed to this, most notably that CAFE standards remained unchanged for more than two decades and failed to include light trucks (SUVs). In 2009, when the political environment was more favourable to policy action in this area, the Obama administration adopted a uniform federal standard that required an average fuel economy standard of 35.5 miles per US gallon (6.63 L/100 km; 42.6 mpg-$_{imp}$) by 2016 with an extended target being adopted by the US Environmental Protection Agency (EPA) of an average of 36 miles per gallon by 2025 for cars and light trucks, which was adopted just days before the new administration took office. However, one of the very early steps in the Trump administration's term was a review of EPA standards and regulations and the Clean Power Plan, which may well lead to a "review, and if necessary, revise or rescind" regulations that may place "unnecessary, costly burdens on coal-fired electric utilities, coal miners, and oil and gas producers" [58].

The EU moved from voluntary arrangements with the automobile industry to regulation later than the US. The Regulation EC 443/2009 was based on a target of 120 g CO_2/km for the European car industry by 2015 and an extended target was adopted of 95 g/km of CO_2 by 2021 [59]. While the regulations have several shortfalls, and are in some respects (e.g., vehicle testing) weaker than their US counterparts, there is a constant process to improve and upgrade these regulations and supporting measures [59]. Considering that the responsibility for these regulations lies at the European Union level, partisan considerations are less of a relevant factor as members of the European Commission and the European Council are from various political parties. The approach to integrate European peak organisations early in the policy process leads to several concessions, but also to a broader coalition on which decisions are being based. Energy efficiency regulations need to be based on a durable and stable policy and political environment as they require large, long-term investments into research and innovation. A structured non-partisan approach that incorporates the perspectives of peak organisations representing relevant societal and economic actors is more likely to create this stable policy environment [34]. In the specific case of vehicle fuel efficiency, the lower levels of the historic emissions and standards in the EU may be one indication of continued and sustained policy progress. These targets are enshrined in EU legislation that went through an extensive consultation process and was adopted by the broad majority in the European Parliament and among the EU member states in European Council. The relatively strong targets adopted in the US adopted through executive action have no legislative backing and may be revised or repealed as part of the broader move of the Trump administration to roll back environmental and climate change policy.

6. Example: Urban Mobility Solutions in India and Brazil

Political volatility can affect national and local level policy environments. While there has been extensive work carried out on the relationship between institutional structures and socio-economic outcomes in many industrialized countries, similar analyses for emerging economies are still rare. The urban mobility SOLUTIONS network has worked with several key emerging economies, including India and Brazil. The two countries are dynamic democracies that face substantial challenges from rapid urbanization and economic development.

Brazil is the largest economy in Latin America and has put forward a relatively ambitious Nationally Determined Contribution (NDC) as part of the UNFCCC process, i.e., reducing CO_2 emissions by 37% reduction below 2005 levels by 2025 [60]. On the federal level, however, there are a number of inconsistencies in the policy approach, such as the halving of the budget of the Ministry for the Environment [61]. On the local level, there are a number of cities that have been working very proactively on sustainable mobility solutions for many years, such as the city of Curitiba that established the world's first Bus Rapid Transit system. As part of the SOLUTIONS project, the city of Belo Horizonte (Minas Gerais, Brazil) worked with partners on the implementation of several sustainable urban mobility measures, such as traffic calming, low/speed zones, and promoting cycling in the city. While Belo Horizonte (population: 2.4 million, with 5.7 million in the official metropolitan area) has seen a seismic political shift in 2016, there is some stability in the city's policy environment, which is building on a coalition between staff within the local government administration who remained largely in their positions and an active civil society that coordinates well among the various interest groups working on different policy objectives (air quality, safety, access, etc.).

India, the largest democracy in the world, has also seen rapid economic development and urbanization with some of the challenges deriving from such air pollution and road congestion being particularly prominent. The Government of India has set out a number of programs at the federal level in the areas of renewable energies, transport, and urban development. At the local level, city authorities often lack the intuitional capacity or even the mandate to shape the mobility system of the city. The city of Kochi (Kerala, India, population: 2.1 million in the metropolitan area) has also been part of the SOLUTIONS network and has worked on measures to increase the walkability in the city and identify last-mile connectivity solutions linked to the Metro and waterway systems that are being built or upgraded [62]. While all three levels of government (union, state, and city) have seen political change over the duration of the project, there has been a relative level of stability, which was built again on staff within the administration that remained in their positions, an active civil society, but also the Kochi Metro Rail Ltd. Kochi, India, a legal entity (special-purpose vehicle) tasked to deliver on the Metro Rail project, which effectively acts as a Unified Metropolitan Transport Authority for the city.

7. Analysis

Consensual political institutions may lead to higher levels of policy continuity, which in turn would have positive effects for the success of climate change mitigation strategies in the transport sector. This approach also adopts the theoretical concept of "encompassing organisations" [20] and examines the relationships between political and societal actors and their ability or inability to negotiate policies that are based on broad majorities in both politics and society. Multiparty coalition governments with proportional representation and negotiation can be more effective in lowering unemployment and inflation and can create a more favourable socio-economic environment [21]. Lijphard and Crepaz provide conceptual frameworks and supporting evidence that governments with consensual, inclusive, and accommodative constitutional structures and wider popular cabinet support act more politically responsibly than more majoritarian, exclusionary, and adversarial countries [20,21]. Based on the analysis presented in this paper a transport climate change policy framework can be summarized as shown in Figure 1, building on aspects of policy integration, coalitions, and institutional structures that influence the policy environment.

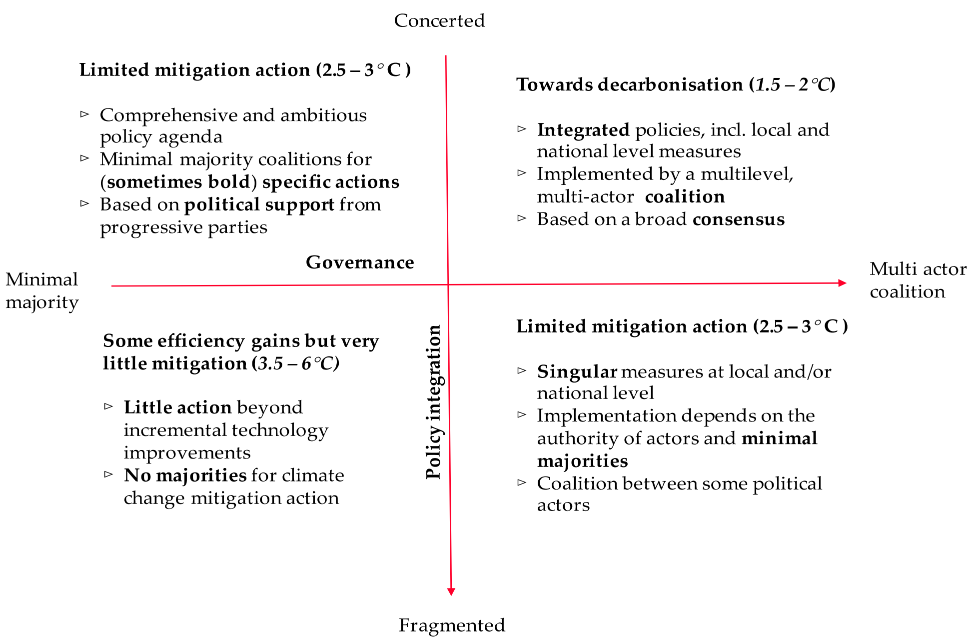

Figure 1. Climate policy governance and integration framework.

The objective of this framework is to show the linkages between policy approaches and governance aspects, stressing the point that an integrated policy approach that addresses the objectives of key actors and stakeholders can help reach a broader consensus on sustainable, low-carbon transport policy. It also aims to highlight that such a consensus and integrated approach is vital to reach global climate change goals.

The indicative pathways of the various governance approaches are in line with the assessment that climate change mitigation in the transport sector will only be able to move towards a 1.5 °C or 2 °C scenario if all available measures at the local and national level are being implemented in an integrated way [12,15]. If short-term technology shifts would be sufficient to reach the required greenhouse gas emission reductions, minimal majority coalitions could deliver bold and swift political action if political parties in favour of climate change policies can muster a majority. However, a combined, long-term structural, technological and behavioural transition is needed for the transport sector to actively contribute to global climate change targets and deliver on wider sustainable development benefits. Hence, an integrated policy and governance approach is needed that builds on coalitions and can endure political change to address the complex nature of the transport sector.

8. Conclusions

Sustainable transport policies need an agreement on the necessity for policy intervention and a strategic, coherent, and stable policy environment. Policy interventions within the transport sector, like fuel and vehicle taxation, can be extremely politically sensitive, even more so when they are associated with only one policy issue, such as climate change that may only be relevant for some political actors. They need a powerful political commitment to appear for the transport policy agenda and to remain there ensuring that investments in cost-efficient sustainable mobility measures can endure over the medium to long-term. Maintaining such a stable policy environment is very challenging and highly dependent on political and institutional structures. Among industrialised countries, only the EU and (most of) its member states, Switzerland, and Norway have shown relatively high levels of stability in the area of sustainable and efficient transport policies. Countries such as the US, UK, Canada, New Zealand, and Australia have experienced remarkable shifts in policy priorities and approaches, in particular when related to climate change mitigation. These political and institutional patterns do not re-appear in the same form in many developing and emerging economies. While political tensions and ideologies within the political spectrum, for example in India, Mexico, and Brazil are similar in some policy areas, the close interlink of low-carbon transport policies with other key policy objectives such as air quality, congestion, road safety, and access creates political pressure that allows for a certain level of continuous progress towards sustainable mobility solutions in particular at the local level. This could be a vital contribution to a broader mix of local, national, and (where applicable) supra-national measures that help mitigate political volatility to some extent at the different levels of government and foster policy coherence. Similarly, the cases of India and Brazil show how coalitions can be formed at the local level to provide a certain level of stability in the policy environment.

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