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Cost-Benefit Analysis of System Transitions

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Summary / Description

The European Green Deal aims to transform the EU into a modern, resource-efficient and competitive economy, putting the EU on the path towards sustainability. Additional investment needs for sustainability transitions in the EU are substantial, particularly in the energy and transport sectors. The transition towards sustainability will also have implications for society. In this context, economic cost-benefit analysis (CBA) is a key tool that evaluates the broader societal net benefits of these transitions, by summing direct and indirect costs and benefits, and supports decision-making to improve societal welfare.

This study has three objectives. Firstly, it seeks to provide insight into the application of costs-benefits analysis at EU level for sustainability transitions, with a focus on the mobility system. Evidence from quantitative studies is presented to demonstrate the impacts of policies enabling sustainability transitions and conclusions from these studies. Secondly, given the role CBA of supporting decision-making, the study provides a critical review of the methodologies used for assessing sustainability transitions. Lastly, reflecting on the findings of the study, solutions to overcome the methodological challenges of modelling these transitions are proposed.

All reviewed CBAs indicate that the societal benefits of sustainability transitions assessed exceed the costs. However, there is considerable variation in environmental externalities considered across studies, highlighting the need for greater transparency and consistency. Consistent application of CBA guidelines is essential for comparability. Additionally, careful consideration of insufficient risk analysis, the complexity of system transitions, technological progress, and other path dependencies is necessary to avoid overstating costs and understating benefits.

In light of both the strengths and the limitations of cost-benefit analysis in the context of sustainability transitions, it is concluded that CBA should serve as one element within a broader appraisal framework rather than as the primary decision-making criterion.

1 Introduction and Background Information on Costs-Benefit Analysis

Economic cost-benefit analysis is traditionally used for ex ante impact assessments and ex post evaluations of infrastructure projects, to determine whether the economic benefits to society outweigh the costs that are necessary for the implementation. EU-policy making faces the context of high investment costs needed for a sustainability transition, growing awareness for the importance of a just transition, fears of losing economic prosperity in times of crises, and significant potential costs of inaction (i.e., the economics of climate-related risks and impacts). In this context, it is highly relevant to examine how cost-benefit analysis is conducted by institutions (both national and EU-level) and whether these frameworks are fit for purpose in the context of complex system transitions.

Under the framework of the European Green Deal (EGD) and 8th Environmental Action Programme, EU policies are guided by the aim of delivering a sustainability transition, radically reforming core production and consumption systems to reach the goal of 'living well within our planetary boundaries'.[1] There is a strong need for measurable and comparable tools and/or indicators measuring sustainability transitions that can inform policymakers at the EU level. Economic cost-benefit analysis is widely used to support policy decision-making. The application of cost-benefit analysis to sustainability transitions is relatively new and holds the potential to better account for the benefits, not just the costs, of these transitions. In the context of sustainability transitions, the environmental damages incurred by inaction can be viewed as the environmental benefits that could be gained through sustainability transition scenarios (Ekins and Zenghelis, 2021). However, applying cost-benefit analysis (CBA) to these complex and uncertain transition processes presents significant challenges, such as accurately estimating costs based on policy choices within highly complex transition scenarios (Ekins and Zenghelis, 2021).

This study aims to provide insight into the application of costs-benefits analysis at EU level. In addition, the study provides a critical review of the methodologies used for assessing sustainability transitions. While definitions of sustainability transitions may vary, all of them aim to transform how we live and work, particularly in terms how we produce and consume within core economic systems (energy, mobility, food, and buildings) (EEA, 2024). Those transitions aim to increase overall societal wellbeing while acknowledging ecological boundaries and addressing existing social injustices linked to environmental degradation and climate change. While most of the literature reviewed focuses on the costs and benefits of achieving climate neutrality, this study also captures other dimensions of sustainability transitions, such as biodiversity and just transition where possible.

The cost-benefit analysis of system transitions in this study focuses primarily on the mobility system transition. Between 2013 and 2019, 25% of the EU's total GHG emissions came from the transport sector. To achieve the climate target of 55% emission reduction in 2030 compared to 2005, the transport sector must lower emissions by 23% (EEA, 2024b). Following the current path, this means a further decrease of 12 percentage points of GHG emissions between 2022 and 2030 (EEA, 2023b). Beyond those caused by GHG emissions, the transport sector is also responsible for other costs such as accidents and adverse health effects of particulate matter. According to CE Delft et al., (2011) the external costs of transport in 2008 amount to EUR 500 billion in the EU, Norway and Switzerland equivalent to 4 % of GDP (CE Delft et al., 2011). The types of external costs they include are accidents, air pollution, climate change (GHG emissions), noise, up & downstream processes, nature & landscape, biodiversity losses, soil & water pollution and urban effects (ibid).

This study aims to directly inform and support policymakers by outlining the landscape of evidence on the application of cost-benefit analysis to sustainability transitions. It also assesses the methodological challenges of modelling these transitions, highlighting the crucial role that modelling plays in CBA. The

[1] For more detail on the theoretical foundations of sustainability transitions and practical implications, see EEA (2019)

applied method is a systematic literature review. Additionally, the perspective of experts working on transport policy and assessment methodologies at EU-level guided the direction of this analysis. The report is structured as follows:

- **Chapter 1** continues with general background information on cost-benefit analysis.
- **Chapter 2** presents the status quo of selected studies on costs and benefits of ground based passenger transport and other systems transitions (energy and food), focusing on quantified evidence and limitations of the studies.
- **Chapter 3** explores the general advantages and challenges of cost-benefit analysis, as well as the additional methodological considerations that arise from a systemic sustainability transitions perspective.
- **Chapter 4** summarizes key findings from previous chapters and rounds up the analysis by suggesting possible ways to improve the assessment of sustainability transitions.

First, however, the second part of this chapter provides important background information on cost-benefit analysis. **Cost-benefit analysis** involves the monetization and quantification of all (or the most important) relevant costs and benefits associated with the policy alternatives considered within a set system boundary e.g. such as geographical boundaries, time boundaries and sectoral boundaries. A CBA encompasses the perspectives of all affected stakeholders by the policy/ policy scenario, which are usually citizens, consumers, businesses or public administration. While CBA usually aims to predict ex-ante overall social benefits, an ex-post assessment of policies provides valuable information for future decisions. The **Better Regulation Toolbox 2023** by the European Commission refers to a broader methodology of cost-benefit analysis (CBA) that is aligned with the principles of **social cost-benefit analysis (SCBA)** when applied in public policy contexts. Social cost-benefit analysis assesses the net value of a policy or project to society. This toolbox promotes impact assessments that incorporate social, environmental, and economic factors, which are typical of SCBA, by encouraging policymakers to evaluate a wide range of societal impacts beyond just financial costs and benefits. For the sake of brevity, the rest of the study refers simply to cost-benefit analysis.

The Better Regulation Toolbox 2023 describes the term social cost-benefit analysis as follows:

'Social cost/benefit analysis assesses the net value of a policy or project to society. Many non-market benefits (e.g. health, quality of the environment) are often expressed in physical units. Monetisation of non-market benefits is easier when the values can be linked to market prices. E.g. air pollution might reduce crop yields, thus allowing for relatively straightforward monetisation. Other non-monetary benefits, such as improvements in protection of fundamental rights, social cohesion, or international stability, are less straightforward to measure and are assessed by surveys or proxy indicators (e.g. counting LGBTQ laws). However, the full value of many goods (benefits) such as health, environment, or education cannot be easily deducted from the market price. However, these important social impacts cannot be ignored in policymaking (EC, 2023, p. 517f.)'.

The Better Regulation Toolbox 2023 by the European Commission differentiates between **direct costs & benefits and indirect costs & benefits** (EC, 2023). Direct costs and benefits arise directly from the intervention itself, such as the immediate expenses and gains associated with its implementation. Indirect costs and benefits, on the other hand, pertain to the effects on related upstream or downstream markets. For example, an intervention might lead to increased economic activity, which can boost demand in upstream industries that supply materials or impact downstream markets through changes in consumer behaviour. The following graph provides an overview of the direct and indirect types of costs and benefits:

Table 1: Map of Regulatory Costs and Benefits

	Costs	**Benefits**
Direct	Direct Compliance Costs Adjustment Costs Administrative Costs Charges	Improved Welfare Health Safety Environment Direct Economic Benefits
	Enforcement Costs Information and Monitoring Complaint Handling Inspections Adjudication/litigation	Improved Market Efficieny Cost Savings Improved Information Wider Range of Products/Services
	Hassle Costs	
Indirect	Indirect Compliance Costs	Indirect Compliance Benefits
	Other Indirect Costs Substitution Effects Transaction Costs Opportunity Costs Negative Effects on Market Functioning	Wider Economic Benefits
		Other, non-monetary benefits

Source: Better Regulation Toolbox (EC, 2023), own visualization

Direct costs are usually concentrated on specific stakeholders (e.g. enterprises) and some may cancel out at societal level, as a cost to one actor can be a benefit to another actor e.g. the transfer of social benefits from the government to citizens. In contrast, benefits are typically distributed across the society as a whole, extending over longer periods and even across generations. Therefore, it is important to distinguish between net transfers in contrast to the costs and benefits that represent actual net additions or reductions to society's total welfare. The **social effect of a policy (= social costs)** consists of the sum of its economic and the external effects, which will be defined in the next paragraph. (EC, 2023)

A CBA requires quantitative economic valuation - wherever possible - of both private (or internal) and external effects of a policy in monetary terms. The valuation of economic effects, where market prices exist is comparatively straightforward, but it is more challenging for non-monetary benefits (Table 1 bottom right). For external effects, such as environmental or climate costs and benefits, market prices do not exist, so alternative methods must be used to estimate the value that different parts of society place on the effects of a policy.

External effects affect companies, households or governments in ways that are not reflected in market prices. Examples include environmental, social or health costs and co-benefits of a policy, such as the (dis)amenity from ecosystem damage or restoration, climate change impacts, (reduced) road congestion or accidents, (the avoidance of) environmental and noise pollution, along with associated health impacts. External costs and benefits must be measured indirectly by inferring the price that those affected attached to the effects of a policy. Whereas multi-criteria decision analysis (MCA) allows for assessment criteria in various units of measurements, cost-benefit analysis aims to monetize all impacts and puts efficiency as the main policy objective by maximizing society's net benefit.

Box 1: Steps of CBA and Official Guidelines

Practical implementation steps of cost-benefit analysis according to Better Regulation Toolbox (EC, 2023):

1. Identification and monetisation of costs and benefits
2. Selection of the relevant time horizon and social discount rate
3. Choice of a mathematical aggregation rule
4. Presentation of the impacts and the formulation of judgements on the performance of existing public interventions or the comparison of the policy options
5. Checking the robustness of the results
6. Accounting for distributional and cumulative impacts

Central **EU-level guidelines** for the application of cost-benefit analysis:

- Better Regulation Toolbox 2023: chapter on cost-benefit analysis e.g. entails the discount rates to be used (EC, 2023)
- Handbook on external costs of transport: guidance on the monetisation of the external costs of transport, that also includes differentiated monetarization recommendations for EU member countries (CE Delft et al., 2019)
- There are also other guideline documents for cost-benefit analysis by the European Commission that give recommendations on discount rates, the treatment of uncertainty, risks, and other issues (EC, 2014; CE Delft et al., 2019; EC, 2022a, 2022b).

Source(s): EC 2023, CE Delft et al. 2019, EC 2022a, EC 2022b, EC 2014, own representation

2 Evidence and evidence gaps on the economic costs and benefits of system sustainability transitions in the mobility sector

This chapter provides a brief outline of the **assessments of costs and benefits in the mobility system transition**. While the focus lies on the application of cost-benefit analysis as described in the previous chapter, investment needs analysis from specific sources are also considered. The content will explore the practices of cost-benefit analysis applied to the mobility transition in passenger transport and examine how these practices relate to singular cases of costs-benefits analysis in system transitions for food and energy. The ETC report emphasizes mobility, energy and food system transition as these areas because they represent critical sectors with high potential for reducing emissions, improving sustainability, and achieving broader environmental and societal benefits through effective system transitions. Since the analysis focuses on the context of sustainability transitions, only those cost and benefit assessments related to transition scenarios or targets, rather than specific infrastructure projects are taken into account. Rather than offering a detailed methodological comparison between studies, the aim is to develop a typology of the existing evidence of cost-benefit analysis in the respective fields. The **evidence on cost-benefit analysis** is outlined, along with the scope of the mobility transition, the types of externalities considered and other costs & benefits. As basis for assessment of costs and benefits for sustainability transitions, the following sub-chapter 2.1 summarise the investment needs for a sustainability transition, particularly in the context of achieving the EU's climate targets.

2.1 Investment needs for mobility and energy

Policies or strategies that require a fundamental transformation of existing systems often involve high levels of investment. A prominent example is the implementation of the European Green Deal with its ambitious goal of transforming the EU into a fair and thriving society, supported by an economy that promotes resource efficiency innovation and competitiveness, ensuring the EU's just transition to climate neutrality by 2050 (EC, 2019). According to the European Commission (2022a), the **annual investment required to achieve the environmental objectives of the European Green Deal for the period 2021-2030 is around EUR 522 billion (see table A1 in the annex)**. This represents an increase in investment of more than 50% compared to the previous decade (EEA, 2023a).

At EUR 392 billion per year (around 2.7% of EU-27 GDP in 2021), most of the additional investment will need to be directed towards climate and energy policy measures. Around 85% will be attributed to demand-side measures, with the largest share of around EUR 175 billion per year for additional energy-related investments in the transport sector[2]. The remaining 15% will be needed for additional investment on the supply side. These increased investments will contribute to security of energy supply, create new jobs, reduce energy costs for households and industries, and improve health and air quality (EEA, 2023a; EC, 2022a).

Similarly, a study by the I4CE (2024) identifies an annual investment requirement of at least EUR 813 billion between 2024 and 2030, or around 5.1% of EU GDP, in the sectors critical to transforming energy, buildings and transport systems to meet the EU's 2030 goals. This leaves an investment gap of EUR 406 billion compared to the EUR 407 billion in 2022. A doubling of investment is therefore needed to meet the targets.

A study by Klaaßen and Steffen (2023) also highlights the need for increased investment in the energy and transport sectors to meet the EU's net-zero emissions targets. According to the study, annual investments totalling EUR 302 billion will be needed in the period 2021-2025. This represents an increase of around 41%, or EUR 87 billion per year, compared to the level of investment in the 2016-2020 period. A further

[2] Includes transport-related infrastructure like recharging and refueling stations but not investments in rail, road, airports or ports infrastructure.

increase in investment of 14% is required from the period of 2026-2030 to 2031-2035. Despite this, the share of total investment in GDP remains well below 2% in all periods analysed and with different GDP growth forecasts (Klaaßen and Steffen, 2023).

The largest required increase in investment between 2021 and 2025 concerns renewable energy installations (+ EUR 24 billion per year), energy networks and storage (+ EUR 28 billion per year) and low-carbon transport infrastructure (+ EUR 28.5 billion per year). Within low-carbon transport infrastructure, investment in rail infrastructure (+ EUR 24.9 billion per year) is particularly important due to the need for a modal shift, with electric vehicle charging infrastructure (+ EUR 3.2 billion per year) and H2 refuelling infrastructure (+ EUR 0.4 billion per year) making up the remaining investment needs (Klaaßen and Steffen, 2023).

According to Klaaßen and Steffen (2023), the transition to net zero will lead to increased investment needs in almost all sectors, with the exception of conventional energy and oil and gas infrastructure, where annual investment is expected to fall by around EUR 9 billion each. However, this depends in part on how conventional infrastructure is used in the future, for example for hydrogen (EC DG ENERGY et al., 2022). Moreover, reduced investment in fossil fuels contributes to energy independency, especially on Russian gas. This reduction in investment needs can be seen as one of the benefits of the transition, as in addition to meeting emissions targets, it will result in cost savings in conventional energy that can then be used for other purposes.

The EU Impact Assessment of the Europe's 2040 climate target and path to climate neutrality by 2050 (EC, 2024a) provides another overview of the investment needs in the transport sector for four different scenarios. The main differences between the first three scenarios are the assumed decarbonisation measures taken and technologies used to reduce greenhouse gas emissions by 2040. The fourth scenario, the LIFE scenario, analyses how circular economy policies, changes in consumer and mobility behaviour, changes in the food system and the resulting more sustainable lifestyles could affect GHG emissions and investment needs. Unlike the three main scenarios, the LIFE scenario does not focus on a specific target, but examines how major societal trends towards more sustainable lifestyles could influence the overall analysis. It shows how demand-side measures can complement the supply-side technological measures examined in the other scenarios.

According to the EU impact assessment, energy system investment needs are more than EUR 660 billion (around 3% of GDP) annually on average over the period of 2031-2050. The average annual investment needs in the transport sector between 2031 and 2050 amount to around EUR 870 billion, or around 4.2% of GDP, and differ only slightly between the three scenarios. About 80% of this investment, i.e., about EUR 700 billion per year, is attributed to road transport, mainly to the purchase of private vehicles. In the LIFE scenario, a shift to more sustainable mobility patterns allows for a significant reduction in investment needs in the transport sector of around EUR 80 billion per year (9%) compared to the other scenarios. This is mainly due to lower investment needs in private cars and air travel. However, investment in public road and rail increases slightly in the LIFE Scenario, by about 4% to EUR 28 billion per year for public road and by 6% to EUR 50 billion per year for rail compared to the other scenarios. This shows that although the demand-side changes presented in the LIFE scenario require somewhat higher investments in public transport and rail transport, the investment needs in private car road transport are significantly lower than in the supply-side scenarios (EC, 2024a).

As part of an impact assessment of the TEN-T Regulation (EC, 2021a), which provides the basis for a multimodal transport network[3] in the EU, the investment required to implement the regulation has been identified. These amount to around EUR 500 billion for the period 2021-2030 for the TEN-T core network, which is an important part of the overall network and covers the main transport flows in Europe. Including the investments for the core network, a total of around EUR 1.5 trillion will be required for the entire network and other transport infrastructure projects up to 2050.

The reviewed studies show that sustainability transitions require high levels of investment, especially in the transport and energy sectors (see overview in table A1 in the annex). Significant shifts and increases in investment are therefore needed to meet the EU's climate targets by 2050. However, the EU Impact Assessment (EC, 2024a) also shows that changes in lifestyle and behaviour can lead to reduced consumption of materials, energy and mobility, and thus lower investment needs in some areas. Sustainability transitions also lead to reductions in investment needs in certain areas, such as conventional energy. These reduced investment needs can be interpreted as benefits and should be emphasised more strongly as such.

It is important to note that these studies do not represent full cost-benefit analyses. Rather, they represent only part of the costs associated with sustainability transitions. With regard to cost-benefit analysis, the investment costs mentioned in the studies can be understood as direct compliance costs (see Table 1), though it is not always entirely transparent what exactly was included under investment costs in the studies. As the studies cover different sectors, time periods and scenarios, it is difficult to compare them, however, they provide a solid foundation for estimating investment costs in a cost-benefit analysis of sustainability transitions.

Across the reviewed studies, the benefits are primarily focused on reduced investment needs and the overall climate goals that the investments are intended to achieve. Other benefits, such as job creation, positive environmental and health effects, or reduced energy dependency on non-EU countries are rarely addressed in investment studies and lack sufficient quantitative support. This narrow focus on the costs of sustainability transitions, without accounting for the many positive effects of these investments, presents a distorted picture. While investment studies do not aim to provide a comprehensive view of all costs and benefits, CBA seeks to include all relevant factors, providing a more balanced and complete overview.

2.2 Costs-Benefit Analysis in Passenger Transport Decarbonisation Scenarios

The following chapter presents various cost-benefit analysis for passenger transport scenarios, both for EU-wide and country level. This is grouped into themes that emerged from the systemic literature review: The usage of cost-benefit analysis in the context of: decarbonisation of urban mobility, deployment of electric and hydrogen-based transport, infrastructure for sustainable mobility, as well as the evaluation of social costs of transport across various modes. Most cost-benefit analyses (CBA) related to the transition context are incomplete in terms of performing a full social cost-benefit analysis. Often, these analyses omit critical components, such as the calculation of welfare impacts. This is a significant gap, as welfare impacts are a key step in the methodology outlined in the Better Regulation Toolbox (EC, 2023), which emphasizes evaluating the broader societal effects, including non-market benefits and distributional impacts. Without accounting for welfare impacts, these analyses provide only a partial view of the true costs and benefits of the transition. Annex 2 gives an overview of which types of costs and benefits are covered in the studies presented in Chapter 2.2.

[3] A multimodal transport network is an integrated system that combines different transport modes - such as road, rail, air and sea - to optimize the efficient and seamless movement of goods and people across different regions (EC, 2021a).

2.2.1 Decarbonisation of Urban Mobility

In the following, a cost-benefit analysis of the urban mobility transition for all EU cities will be presented (Borgato et al., 2021). The analysis by Wolkinger et al. (2018) on the co-benefits from improved air quality and increased physical activity for urban mobility transition in Austria, serves as a complementary source of information.

The **European Institute of Innovation and Technology (EIT)** urban mobility initiative has quantified the costs and benefits of the sustainable urban mobility transition in European cities by 2030 and 2050 (Borgato et al., 2021). To do so, they used **12 representative prototypes for all 779 EU27 cities**. The analysis included three potential scenarios (summarized in Box 2), based on different combinations of policy measures selected from important EU initiatives such as ELTIS and CIVIATIS. The calibration of the respective policies took into consideration the strategic objectives of the EIT Urban Mobility, the EU Green Deal and the EU Smart and Sustainable Strategy.

Box 2: Scenarios for decarbonisation of urban mobility for all 779 EU27 cities, time horizon 2030 and 2050 (compared to 2019)

Urban Mobility Scenarios analysed by the European Institute of Innovation and Technology:

- **Promote and Regulate:** changing behaviour by information and promotion
  e.g. traffic calming measures, electric energy refuelling infrastructure, green public fleet, car-sharing

- **Plan and Build:** investments in technologies and infrastructures
  e.g. metro network facilities and light rail, walking and cycling networks and facilities, demand-responsive transport[4], electric energy refuelling infrastructures, green public fleet

- **Mixed:** combination of most of the policies considered in Promote and Regulate as well as Plan and Build

Source(s): Borgato 2021, EIT Urban Mobility, own representation

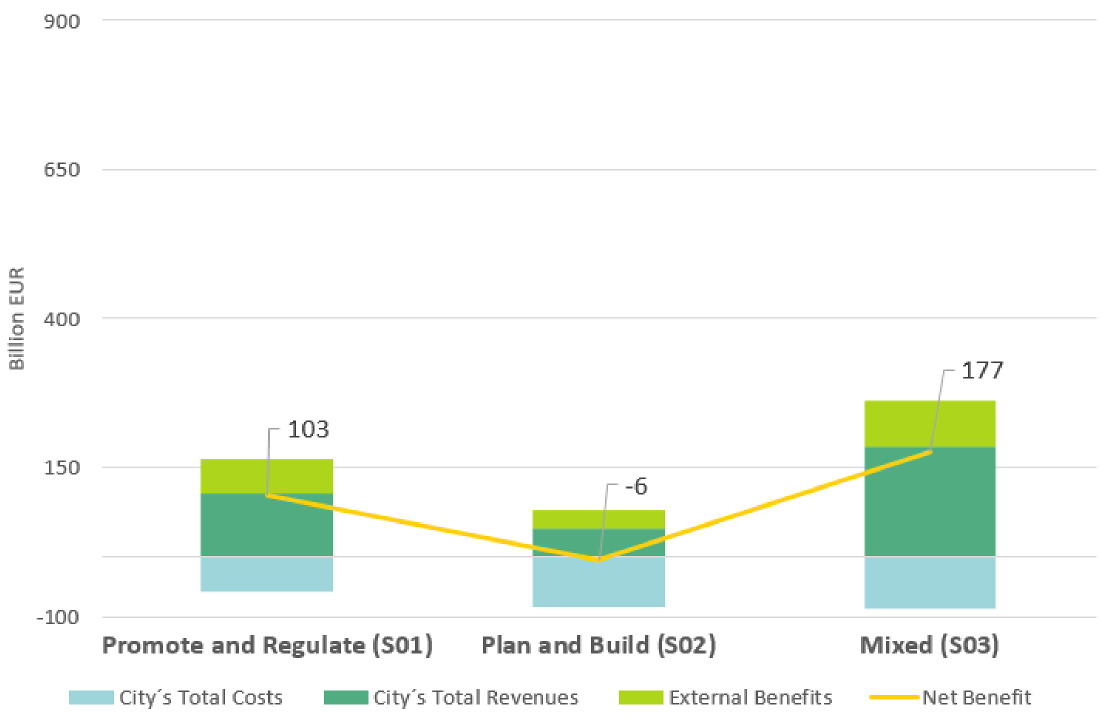
To quantify the costs of moving to sustainable urban mobility, the authors also consider the costs of the following externalities: CO_2-emissions, air pollutant emissions NOx (nitrogen oxides), VOC (volatile organic compounds), CO (carbon monoxide) and PM2.5 (particulate matter 2,5 micrometers), noise as well as deaths and injuries in road traffic accidents. To monetarize these externalities they apply the monetary values by European Commission's 2019 *Handbook on Sustainable Transport Infrastructure Charging and Internalization of Transport Externalities* (CE Delft et al., 2019). The 8 key indicators calculated in the study are modal split, car ownership, CO_2-emissions, fatalities, total city revenues, total city costs, external benefits and net balance (Borgato et al., 2021).

These external costs savings as well as the city's total revenues and costs sum up to the city´s net balance. The city´s total revenues and costs refer to both public administration as well as external providers, who are not directly operated by the public administration (e.g., car sharing, bike sharing, public transport, etc.). As the city´s total costs and revenues are not defined explicitly as net transfers, the results need to

[4] partially replacing the existing bus routes in limited part of urban area

be treated with caution, as e.g. the city's revenues may result mainly from private household expenditure[5]. It is furthermore important to note that the numbers refer to the changes of costs and revenues compared to a business-as-usual scenario. The following figure gives an overview of city´s total costs, city´s total revenues, the external benefits (external cost savings) and the resulting net benefit for 2030. Scenario Mixed (S03) scores the highest net benefit for 2030. For scenario mixed the external benefits almost outweigh the city´s costs and the city´s total revenues are higher than both external benefits and city´s total costs together.

Figure 1: Costs and Benefits of EU urban mobility transition in 2030 (discounted, cumulative from 2019)

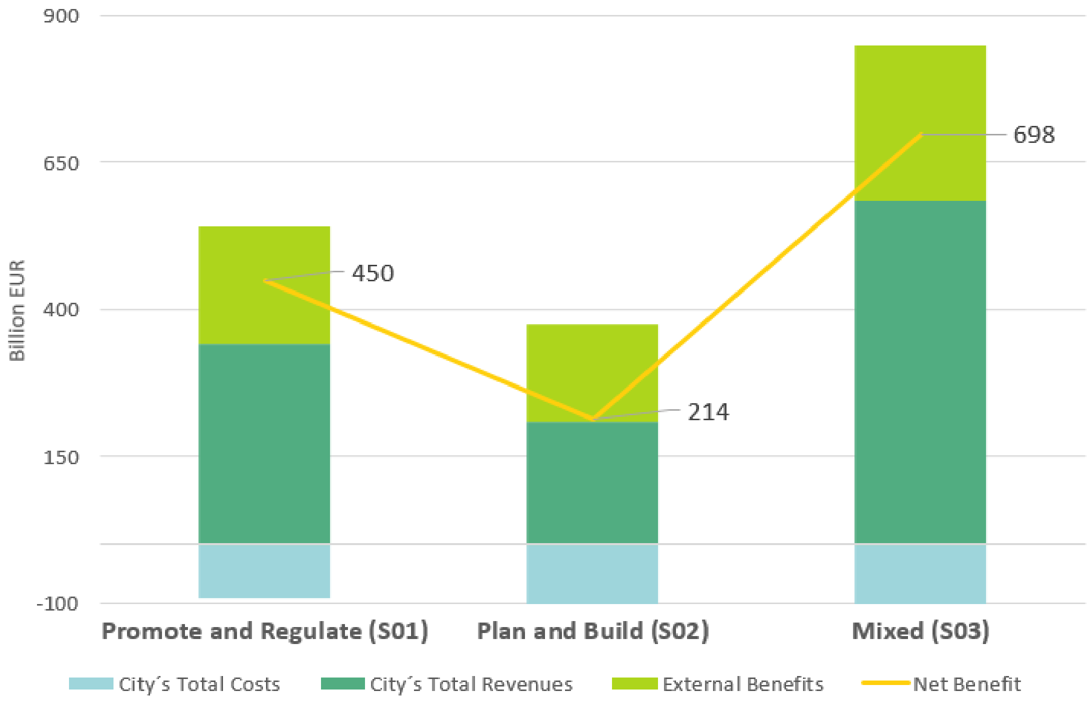


Source(s): Borgato et al. 2021, own representation

Whereas in 2030 for the Scenario Plan and Build (S02) the net balance is slightly negative, because of high average infrastructure investment costs in cities, in 2050 all three scenarios for decarbonising all 779 EU27 cities show a positive cost-benefit results.

[5] Cost-benefit analysis (CBA) does not always calculate with net transfers as a standard rule. It depends on the purpose and scope of the analysis. However, many CBAs do focus on net transfers rather than gross transfers to give a clearer picture of the real economic impact.

Figure 2: Costs and Benefits of EU urban mobility transition in 2050 (discounted, cumulative from 2019)



Source(s): Borgato et al. 2021, own representation

As in 2030, the net benefit for 2050 shows that the scenario mixed (S03) is the most preferable one as it also has the highest total net balance, which is EUR 698 billion for the sum of costs and revenues of all 779 EU27 cities. When comparing the size of the external costs savings and the total net balance, it can be seen that for 2050 for scenario mixed in 2050 (S03) the external cost savings amount to 38 % of the total net balance. For scenario Promote and Regulate (S01), 45 % of the net balance stems from external cost savings and for scenario Plan and Build (S02) the external costs savings are 77 % as high as the resulting net balance. When considering only the city´s costs and benefits excluding external benefits it is also Scenario Mixed (S03) that performs best both in 2030 and 2050. Also, the external costs savings are, both in 2030 and 2050, the highest for the scenario Mixed (S03) followed by the scenario Promote and Regulate (S01).

The EIT analysis considers health effects of urban passenger transport by indicating the main number of fatalities per thousand inhabitants. In all scenarios, the number of urban fatalities is significantly lower in 2030 and 2050 compared to 2019. The lowest numbers of urban transport fatalities are achieved for scenario Mixed (S03), which has also the highest net benefit as addressed before. As indicated above, the EIT analysis also furthermore includes the externalities of air pollution and noise pollution. As they apply the monetary values from the Handbook of External Costs of Transport (CE Delft et al., 2019), where for each of the two externalities they consider direct and indirect health effects via the dose-response-relationship between the exposure of air pollutants and the associated health risks.

In October 2024, an updated version of the discussed EIT analysis was published (Borgato et al., 2024). However, it can only be briefly addressed due to the timing of the respective publications. In the updated study several methodological adjustments were made, including the introduction of new policy measures, a refinement of the study's input data and of the definition of the city prototypes as well as a refinement of intervention levels, policy targets, transition scenario content, and the policy implementation timeline. They find that all three urban mobility scenarios—**S01 Infrastructure and Mobility Services, S02 Regulation and Demand Management, and S03 Zero-Emissions**—achieve the Green Deal target for greenhouse gas emissions by 2050. However, only Scenario 3 meets the CO2 emissions reduction target set for 2030. A cost-benefit analysis reveals that, in both the short term (2022-2030) and the long term (2022-2050), total savings from external costs outweigh the total net costs in Scenarios 2 and 3 (Borgato et al., 2024).

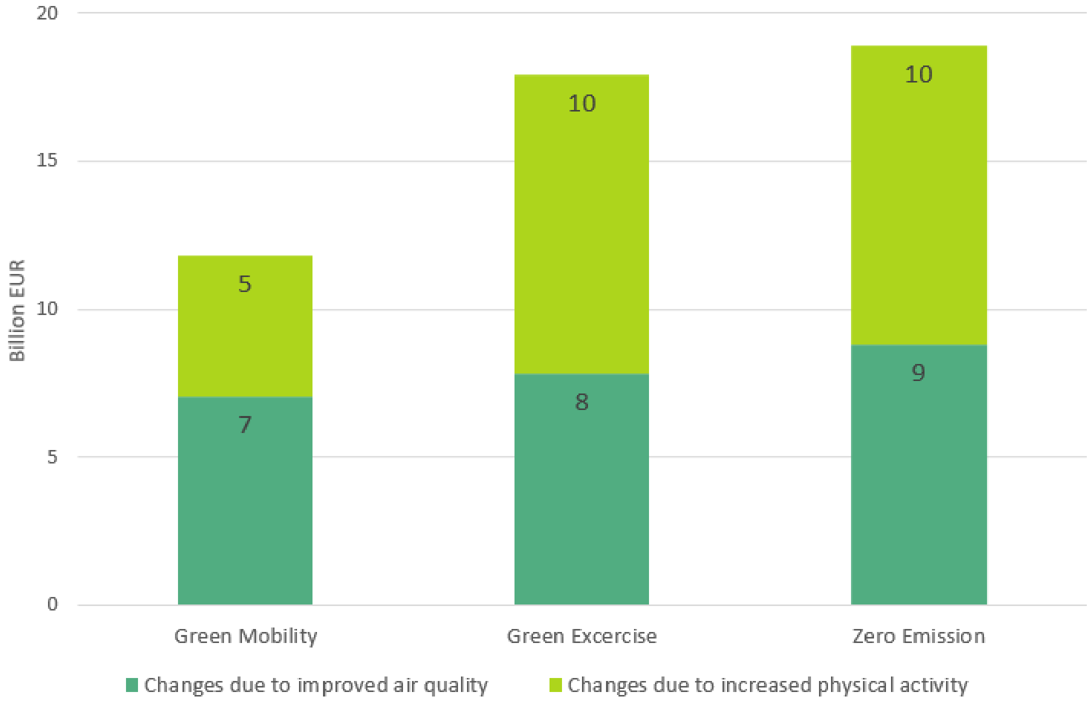
Complementing studies emphasize the health benefits of mobility transition. For instance, Wolkinger et al. (2018) focus on analysing the often overseen health **co-benefits resulting from increased physical activity and improved air quality**, instead of analysing the directly avoided injuries and deaths in road traffic. They investigate the health co-benefits of climate change mitigation in urban mobility in Austria by applying a mixed multi-model approach. To analyze three climate change mitigation scenarios, they combine a transport system model, a transport emission model, an emission dispersion model, a health model and a macroeconomic Computable General Equilibrium (CGE) model. The subject of the study are co-benefits resulting from increased physical activity and improved air quality due to climate mitigation policies for **three urban areas in Austria (Graz, Wien, Linz)** in three **climate change mitigation scenarios**, based on action plans of the respective local government. They use 2010 as baseline, which in this context means they assume the policy intervention has already been achieved in 2010 and compare this hypothetical state to the baseline (Wolkinger et al., 2018):

- **Green Mobility Scenario:** urban parliament´s targets for modal share of trips in 2020/2025 almost achieved
- **Green Exercise Scenario:** change in mobility behavior beyond the politically-accepted urban targets for the modal share
- **Zero Emission:** additional to green exercise scenario measures all motorized trips conducted with electric energy

The analysis shows that mitigation measures for urban transport significantly decrease morbidity and mortality, as they are linked to reduced exposure to pollutants and higher levels of physical exercise. To assess improvements in air quality, they consider both the reduction in healthcare costs for treating acute conditions related to poor air quality (including medication expenses) and the lowered indirect costs associated with illness and premature death. To reflect improvements in air quality, they account for incidences related to air quality of changes in the cost of providing acute in-patient treatment (including medicine) as well as the reduced indirect costs of morbidity and mortality. For increased physical activity, they account for its effect on mortality.

Health benefits are not purely externalities. For instance, the health benefits derived from active mobility are internal benefits from the cyclist's perspective. However, health benefits from acitive mobility also lead to reduced government healthcare spending which is an external benefit. To maintain brevity and because health impacts are predominantly considered as market external costs, health benefits are referred to as external benefits in the rest of the study. In the analysis by Wolkinger (2018) the health benefits in Austria rise with the level of ambition of the respective policy scenario, which means that the highest costs savings can be realized for the scenario Zero Emission.

Figure 3: Direct and Indirect Health Benefits from Urban Mobility Transition in Austria due to improved air quality and increased physical activity



Source(s): Wolkinger 2018, own representation

Next to direct and indirect health benefits, they consider intangible health costs that refer to costs from e.g. pain, anxiety or the hypothetical costs for the value of life lost. Thereby, they apply the Value of a Statistical Life[6], which goes beyond the direct and indirect costs of mortality and assesses the otherwise intangible value of a live. The authors point to the growing recognition that Value of a life year (VOLY) might be a more meaningful indicator, especially for air pollution that shortens everyone´s life year to some extent. Therefore, they also conduct a sensitivity analysis with two different heights of VOLY as measure for the intangible health costs. While these are based on normative assumptions, which may vary across studies, the magnitude of these estimates indicates the importance of considering intangible benefits such as this. As shown in figure 4, for all scenarios the upper bound assumption (VSL EUR 1,650,000) results in intangible costs about 3 times higher than the lower bound assumptions (VOLY EUR 43,000).

[6] The Value of a Statistical Life and the methods used for its determination such as willingness to pay can be critized for their inability to represent true preferences due to income inequality, imperfect information etc.

Figure 4: Direct, indirect and intangible health benefits due to improved air quality and increased physical activity

Source(s): Wolkinger 2018, own representation

Furthermore, the authors find that for all scenarios the expenditures for urban mobility transition (investment costs and operating costs), which is largely public expenditures, are mostly offset by the respective co-benefits, while there is also significant reduction of costs for individual transport. The net balance (sum of health benefits, investment costs, and operating costs) is not presented in the study, which makes it difficult to compare with other cost-benefit assessments. As part of their analysis the authors also provide a macroeconomic assessment (GDP, employment, welfare, relative prices, tax revenues) of the investment and operating costs of all policies and of the corresponding health effects (private and public health costs). The results show positive welfare effects ranging between +0.15% and +0.25%[7]. However, due to a shift of private and public expenditures from relatively labour-intensive goods and services (sale of cars, repair of conventional cars) to capital intensive goods (public transport infrastructure, rolling stock) the unemployment rate increases between 0.05% to 0.1% points, which causes negative impacts on GDP compared to the baseline scenario.

The biggest driver of increased welfare stems from changes in private expenditure. While households spend less on mobility, their utility in mobility consumption stays constant. Overall, the authors conclude that considering economic co-benefits of climate change mitigation policies in urban mobility can be a forceful argument to support climate change mitigation policies.

Beyond urban mobility transitions, there seems to be a lack of cost-benefit analysis that could foster the rural mobility transition. Flipo (2023) argues that the cost-benefit logic of transport provision cuts rural areas out of public transport policy. His study focuses on qualitative research of distributional and procedural justice in the mobility sector. The authors conclude that a mobility transition based on changes by individuals tends to reproduce the high-carbon system´s inequalities of access (Flipo et al., 2023). Though, it should be noted that a shift to increasing awareness for rural mobility transition seems to be already ongoing. Rural Mobility, an ongoing project kicked-off in April 2024 by the EU funded initiative

[7] The range of results is due to a sensitivity analysis for valuations for intangible health costs as in Figure 4.

Interreg Europe, aims to improve rural mobility across Europe through novel transport solutions and innovative policy approaches, which provide cost-effective, convenient public transport in these areas.

Both cost-benefit analysis studies found that all covered urban mobility transition scenarios are beneficial for society. Additionally, the studies provide good coverage of the EU urban mobility transition, while rural areas have so far been inadequately covered. Further discussion is needed on how to fully integrate the health benefits of active mobility, as analyzed by Wolkinger (2018), into cost-benefit analyses for mobility system transitions.

2.2.2 Deployment of Electric and Hydrogen Based Transport

The first study presented in this paragraph is a cost-benefit analysis for different electric vehicle deployment scenarios in Denmark, including and excluding communication of electric vehicles with the electric grid**.** The second study explores the deployment of new vehicle technologies, but differs from the first study in terms of the regional level assessed (EU-level) and the type of vehicle technology (hydrogen mobility) amongst other aspects.

Noel et al. (2018) examines the social costs and benefits of potential configurations of electric vehicle deployment, including and excluding "vehicle-to-grid" (V2G)[8]. To fully explore the benefits and costs of different electric vehicle pathways, **four different scenarios are devised with both today's and 2030 electricity grid in Denmark**. The scenarios differ in terms of the levels of electric vehicle deployment, levels of future renewable energy penetration as well as ability of electric car´s to communicate with external systems, other vehicles and their users. The environmental externalities they consider in the cost-benefit analysis are carbon and health. They find that in a baseline scenario, that assumes no communication ability of electric vehicles, the optimal electric vehicle percentage based on market costs is 57% for 2030 and that the total net present costs[9] for 2015 of transportation and electricity for each are USD 75 billion. When considering the external benefits for carbon and health the value for optimal electric vehicle deployment goes up to 70%. The consideration of external costs also affects the total costs, which in this case rise to USD 83,9 billion.

The authors furthermore find that the vehicle-to-grid increases optimal electric vehicle deployment noticeably to 75% by 2030 under consideration of external costs for carbon and social costs of health. The authors point out that their results are conservative as many more benefits could be included e.g. economic security, energy security, avoided imports of oil, waste etc. They address that future research should look closer at the distribution of the costs and benefits. They explain that potential winners of a vehicle-to-grid transition would be drivers of cars, saving money on fuel[10] for internal combustion engine vehicles, and maintenance costs, along with those at greater risk to the health problems associated with transport related air pollution and GHG emissions. Actors that might lose in the vehicle-to-grid transition could be traditional providers of ancillary grid services, petroleum companies, and incumbent firms offering maintenance and servicing for internal combustion engine vehicles (ICEVs) (Noel et al., 2018).

With regards to studies assessing the potential for hydrogen mobility, Cantuarias-Villessuzanne et al., (2016) analyse **social costs and benefits of hydrogen mobility in Europe**. They integrate the following two externalities of hydrogen transition in Europe: CO_2 (measured using an abatement cost approach) and use

[8] "Vehicle-to-grid" (V2G) refers to a concept and technological shift where electric vehicles (EVs) are not only used for transportation, but also as energy storage units that can interact with the electrical grid.
[9] The total costs don´t include the capital costs of new capacity additions, but capital costs for new natural gas plants, when the additional load due to charging demand is greater than the available hourly capacity.
[10] Because of high upfront costs of electric vehicles, this cost saving may be accessible only for high income groups.

of non-renewable resources to produce fuel cells (measured by possible platinum depletion). Platinum depletion, in contrast to CO_2 -emissions, is a potential barrier to hydrogen mobility transition, as will be elaborated on in the next paragraph. Building on a previous study by Creti et al. (2015), they find that including these external costs in total brings forward the date at which FCV[11]s becomes socio-economically desirable (i.e., provides a net benefit to society) from 2050 to 2040[12]. The results for European hydrogen mobility transition furthermore show, that the external costs of platinum[13] extraction are almost as significant as the external abatement benefits of CO_2 (Cantuarias-Villessuzanne et al., 2016).

As platinum is a scarce and expensive metal, possible depletion might be a barrier for the widespread adoption of hydrogen fuel cells of hydrogen vehicles, where platinum works as a catalyst for the electricity generation amongst others. While the study focuses on integrating possible platinum extraction in cost-benefit analysis, there are also other potential barriers to large-scale deployment of hydrogen mobility such as lack of sufficient infrastructure for hydrogen transport and refuelling of hydrogen vehicles, difficulties in storage etc. Platinum extraction is estimated by the net price methods, which is computed as the market price minus the marginal extraction costs of platinum. They quantify the external costs of platinum extraction in consideration of scarcity and recycling rates of platinum. However, it should be noted that they do not account for social and ecological harm caused by platinum extraction. (Cantuarias-Villessuzanne et al., 2016)

It is generally difficult to find cost-benefit analysis that takes into account social or ecological externalities caused by system transitions in the EU for non-EU countries. Nevertheless, the study provides an example how not also external benefits, but also external costs of sustainability transitions can be considered. The two different studies that have been presented in this paragraph, took different approaches with regard to the unknown variable to be assessed. While the first study calculated the optimal vehicle technology deployment for a specific year, the second study examined the year of social conversion for a vehicle technology.

2.2.3 Cost-Benefit Analysis for Infrastructure for Sustainable Transport

This section provides two examples of how CBA is applied to large ground-based passenger transport decision-making, given the important role of green mobility infrastructure in the mobility transition. Whereas the first study from the Federal Transportation Infrastructure Plan in Germany is an example of how environmental aspects relevant in transport decision-making are considered through a CBA applied as part of a broader assessment, the second study analyses the costs and benefits for the optimized usage of EU-wide railway infrastructure.

The **Federal Transport Infrastructure Plan 2030** is a federal investment framework program for transport infrastructure planning in Germany. Although this is not a binding implementation plan with a financing guarantee, it is regarded as the most important instrument for the long-term planning of the expansion and new construction, as well as the maintenance and renewal of the highways, railways and waterways under federal responsibility. The FTIP is prepared every ten to 15 years by the Federal Ministry of Transport, Building and Urban Affairs (BMDV) in cooperation with the federal states. To ensure that the construction projects approved in the expansion acts can be implemented, the German Federal Ministry of Transport and Digital Infrastructure prepares non-binding investment framework plans for a period of five years each. These plans define the investment priorities for maintenance, expansion, and new

[11] type of electric vehicle that use hydrogen as a fuel source to generate electricity via a fuel cell
[12] This is the results for scenario “moderate”, which assumes that 60km for daily driven distances.
[13] non-renewable resource used in the manufacture of fuel cells

construction across all modes of transportation (BMDV, 2016). The annual allocation of funds within the federal budget for the infrastructure projects provided for in the FTIP is to be made on the basis of these investment framework plans (Agora Verkehrswende, 2023). A detailed assessment procedure was carried out for the preparation of the FTIP 2030, consisting of four modules:

- **Module A:** Cost-benefit analysis
- **Module B:** Environmental and nature conservation assessment (in the form of a Strategic Environmental Assessment)
- **Module C:** Spatial planning assessment
- **Module D:** Urban development assessment

Modules A and B are particularly relevant to the potential reduction of CO_2-emissions in the transport sector. Thus, the expected investment costs of a project were compared with both the expected economic benefits and the possible additional costs in terms of additional greenhouse gas emissions or environmental damage. The FTIP cost-benefit analysis considered the following components: Investment costs, change in operating costs, travel time, transport time benefits of cargo, reliability, implicit benefits, traffic safety, noise pollution and exhaust emissions, lifecycle emissions of greenhouse gases from infrastructure, change in local separation effects (waiting times and detours for pedestrians), benefits of competing modes of transport, change in operating and maintenance costs of transport routes. (BMDV, 2016)

While this detailed assessment takes a more systemic approach and considers different dimensions relevant for sustainability transitions, it has been argued that it remains inadequate from a climate protection perspective (Agora Verkehrswende, 2023). The German Federation for the Environment and Nature Conservation (BUND) conducted a project titled "Realignment and Ecologization of Long-Distance Road Planning in Germany" that focuses on reforming Germany's long-distance road planning to prioritize environmental concerns based on several detailed expert reports. Bund (2023) argue that the CBA of FTIP 2030 overemphasises travel time and operating cost savings. The authors note that the analysis places a strong focus on factors such as travel time gains and operating cost savings, which account for almost 90% of the identified benefits of road construction projects. As a result, these criteria dominate the outcomes of the cost-benefit analysis (CBA). Yet other benefits such as punctuality, reliability, and the resilience of transport networks are undervalued or neglected (BUND, 2023). The method applied in the Federal Transport Infrastructure Plan 2030 for the evaluation of travel time savings is as follows: Initially, the change in travel time due to the infrastructure project is assessed by comparing travel times before (baseline) and after (planned) the project. The traffic volume between various starting and destination points is considered, focusing on how many people regularly use the route. Each saved travel time is assigned a monetary value in EUR per person-hour. This value varies depending on the purpose of the trip (business or private) and the length of the route. The saved time (in hours) is multiplied by the traffic volume (in trips per year) and the value of time to calculate the overall economic benefit of the time savings (PTV Planung Transport Verkehr AG et al., 2016).

There is a lot of debate on how to value travel time savings, that would exceed the limits of scope of this study. Some transport experts argue that travel time savings have only temporary effects[14] (Knoflacher, 2009). Transport modelling experts engaged with for this study argue that this argument line ignores that the system can then provide services to more transport users than before. They furthermore point out that the role of demand management measures such as congestion pricing can be large and that a good social cost-benefit analysis should also consider alternative ways to solve capacity problems e.g. in the form of congestion pricing.

[14] According to Knoflacher (2009) increases in speed due to faster means of transport or the expansion of roadways or railways, time reduction is only temporarily until a new state of equilibrium is established. This is reached after a few years and the total travel time is again just as long as before the intervention because the structures created by people - apartments, jobs, shopping opportunities - relocate.

The detailed reports for the BUND (2023) project include an analysis by Karlsruhe Institute of Technology (Prof. Dr. Kay Mitusch & Dr. Eckhard Szimba) that provides reform proposals with special emphasis on environmental concerns. The CO_2 prices applied for the monetarization in the CBA of FTIP 2030 are valuations from 2016, that are not consistent with the target of climate neutrality (Mitusch and Szimba, 2024). Mitusch and Szimba (2024) content that other costs and benefits should be considered to provide a more complete assessment, such as particulate matter pollution from tire and break wear, the effect of emissions and noise on fauna (Mitusch and Szimba, 2024). Furthermore, Agora Verkehrswende argues that the increased CO_2 emissions from secondary induced traffic (i.e., additional demand arising from improved infrastructure) should be considered. Such effects can reduce or even cancel out the expected benefits of a measure (e.g. by removing bottlenecks) and represent an important consideration in such assessments (Agora Verkehrswende, 2023). Though, as noted above, this should also consider the benefit from the fact the system can provide service to more transport users as well.

The Environment Agency Austria (EAA, 2024) has considered revisions of the FTIP 2030 to enable the energy and mobility transitions. The recommendations for action, broadly summarized, argue for:

- Consideration of all legally binding targets relating to the environment and required mobility transition in current and future planning and review processes.
- Intermediate assessments of projected and actual investment needs by transport mode, with the results used as a basis for realistic prioritization and planning.

The next study does not focus on overall infrastructure decision making of a specific region, but on the costs and benefits of polices aimed at optimizing the use of the European transport infrastructure. The European Commission requires an impact assessment for major initiatives, which usually includes a cost-benefit analysis of the proposal's financial costs and benefits. The depth of the impact assessment depends on the nature and significance of the proposal and a proportionate approach is required. The calculation of costs and benefits is based on feedback from stakeholders in form of consultation activities, case studies and desk research and follows the Better Regulation Toolbox (EC, 2023).

In 2021, the European Commission published an **Impact Assessment on the use of railway infrastructure capacity in the single European railway area**, amending Directive 2012/34/EU[15] and repealing Regulation (EU) No 913/2010[16] (EC, 2021a). It included a cost-benefit analysis of four policy options on the use of railway infrastructure over the period 2025-2050, relative to a baseline scenario that assumes a high-quality TEN-T rail network as in the revision of the TEN-T Regulation[17] (EC, 2021b). The four investigated scenarios for the use of railway infrastructure capacity are the following:

- **Policy Option 1:** Strengthening the corridor approach by maintaining key elements and tools introduced by the Railway Connection Facility Regulation (RCF) and addressing their shortcomings.
- **Policy Option 2:** Network approach based on common European rules and procedures implemented via cooperation between infrastructure managers
- **Policy Option 3:** Network approach supported by a central entity in charge of defining common rules and monitoring their implications

[15] 2012/34/EU sets up the Union's legal framework for the Single European railway area, by setting rules e.g. for management of railway infrastructure and principles and procedures applicable to railway infrastructure charges.
[16] Regulation (EU) 913/20109, also known as 'Rail Freight Corridors Regulation' provides the governance structure for rail freight corridors, which include lines crossing the territory of at least two Member States and linking two or more terminals.
[17] The TEN-T policy is a key instrument for planning and developing a coherent, efficient, multimodal, and high-quality transport infrastructure across the EU. The network comprises railways, inland waterways, short sea shipping routes and roads linking urban nodes, maritime and inland ports, airports and terminals.

- **Policy Option 4:** Network approach, assigning competences in operational decision-making to the EU network of infrastructure managers, supported by an operational entity

Next to direct administrative and adjustment costs, the Impact Assessments also considers the direct benefits of increase in capacity (additional traffic) and increase in punctuality. Additionally, external environmental benefits (CO_2 -emissions, air pollutant emissions, congestion), other potential external or social benefits such as social impacts in terms of impacts on employment, public health, road safety and fundamental rights are included. As part of the assessment, a macroeconomic assessment of GDP and employment impacts is taken into account. The highest total net benefit occurs for Policy Option 4 with EUR 415,995 million, followed by EUR 11.409 million for Policy Option 3, EUR 6.907 million for Policy Option 2 and EUR 439.3 million for Policy Option 1. This is because Policy Option 4, although it has the highest costs, also has the highest cost benefit ratio (7.9) as it reduces external costs of CO_2 -emissions, air pollution, fatalities and injuries and congestion. Even though Policy Option 4 scores best in efficiency (i.e., has the highest net benefit), the principles of effectiveness, coherence, subsidiarity, and proportionality are also considered in the decision making process.

As a result, the preferred option in the overall assessment was Policy Option 3, as it provided the best balance between the objectives[18]. Whereas the first study in this chapter gave an example of undervaluing environmental costs in transport decision making, this EC example shows a more extensive consideration of environmental externalities in CBA. Beyond, the European Commission uses a more balanced approach of viewing efficiency indicator based on CBA as only one of various decision criteria that also consider factors such as expected acceptance from relevant stakeholders.

Both studies show the importance of not only the types of costs and benefits considered in the analysis, but also the overall decision-making procedure the CBA is embedded in.

2.2.4 Social Costs of Transportation across various modes

The following two studies provide cost-benefit analysis across various transport modes. Rather than resulting with a value for the benefit for the mobility transition, they calculate the social costs per transport modes. Whereas Maier (2023) calculates the social costs per transport mode as costs per capita per year, Gössling et al. (2019) presents the social costs per transport mode as costs per kilometre driven.

Maier et al. (2023) assess the social costs of a decarbonised ground-based passenger transport system in 2040 for Austria based on a Monte Carlo Simulation[19]. Their analysis builds on the concept of Social Costs of Transportation, which is defined as the assets and consumables as well as the labour required to operate a particular transportation mode, as well as travel time costs and external effects of third parties or the general public (Forkenbrock, 1999; Levinson and Gillen, 1998). The social and external cost categories they include in their assessment are accidents, air pollution, climate change impacts, congestion, noise, well-to-tank-emissions, habitat damage, health benefits, barrier effects (i.e., barriers to switch to active modes of transportation) all divided by urban, suburban, rural in EUR 2020/pkm (passenger-kilometer). The underlying baseline scenario assumes that the modal share (i.e. share of travelers using a transport mode) remains the same as in 2020 while mobility demand decreases by about 23%. Against this baseline

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[18] This is partly because depriving the rail structure managers of the important function of strategic capacity management was found to be controversial in the public consultation and also the behavioral response of parties is important for the success of the initiative (EC, 2021a).

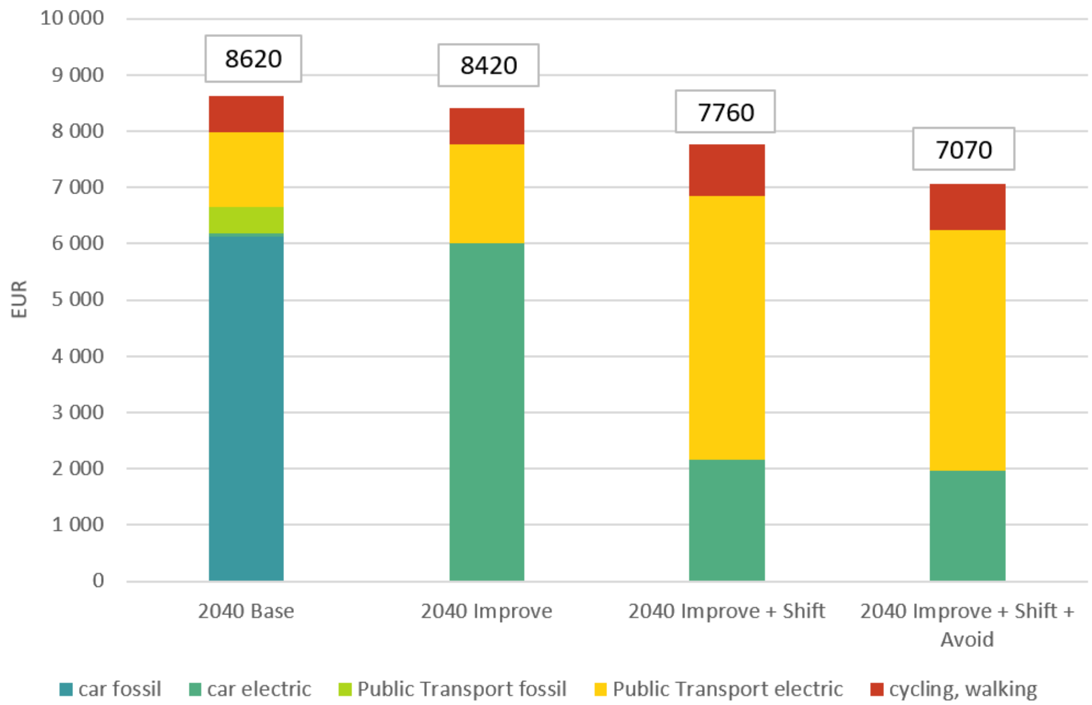
[19] A Monte Carlo simulation is a computational technique used to approximate the probability of certain outcomes by running multiple random trials.

scenario, the analysis considers three **scenarios for a ground-passenger transport system in Austria in 2040 with increasing levels of policy action**:

- **2040 Improve:** modal share remains the same as in 2020 with full electrification of the car and public transport fleet (buses and trains)
- **2040 Improve + Shift:** additionally, modal share shifts towards active transportation and public transport
- **2040 Improve + Shift + Avoid:** additionally, travel demand is reduced by 7%-18% relative to 2020 levels (Maier et al., 2023)

The results show that social costs decline with the introduction of decarbonisation strategies. The resulting social costs for the year 2040 range from an average EUR 7,070 to 8,420 per capita per year, compared to EUR 8,620 per capita per year in the baseline scenario. This is driven by a reduction of vehicle costs and external costs, combined with a rise in social benefits due to positive health effects of active mobility. These outweigh the remaining external costs and possible costs from increased travel time.

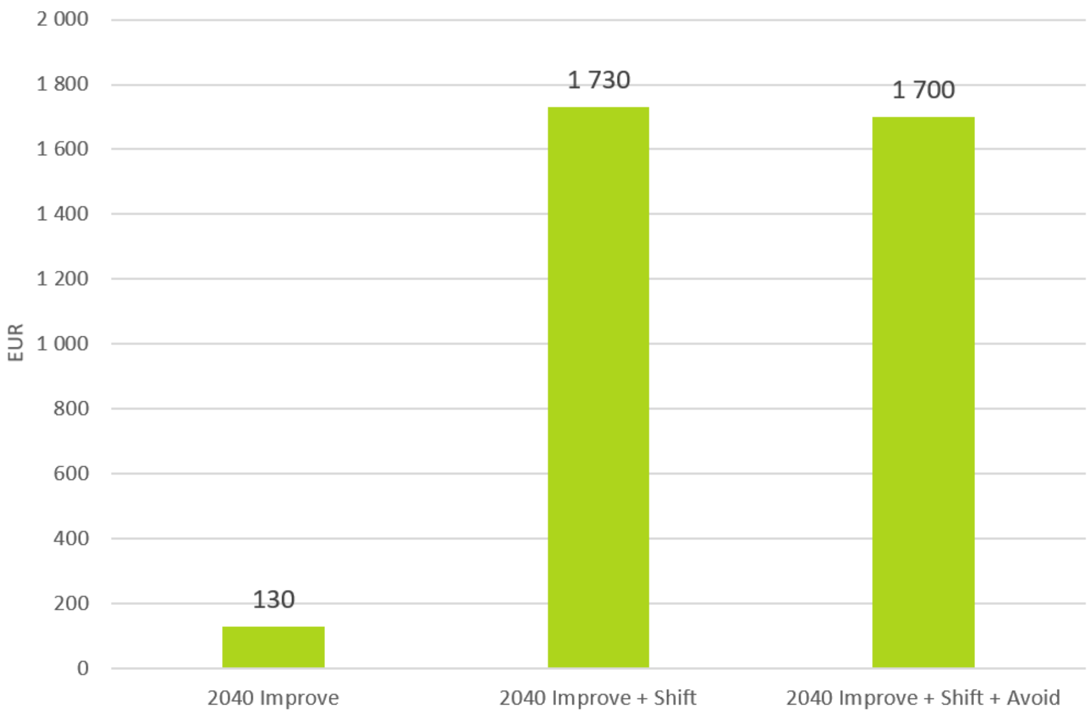
Figure 5: Average Social Costs of a decarbonised ground-based passenger transport system in 2040 for Austria in EUR 2020 (EUR per capita and year)



Source: Maier et al. 2023, own representation based on data provided by the authors

As explained above the consideration of external effects is part of calculating the social costs. For the scenarios *2040 Improve + Shift* and *2040 Improve + Shift + Avoid* the remaining external costs are overcompensated by the health benefits from active mobility. As shown in figure 4 the external benefits compared to Baseline 2040 rise with the ambition of the decarbonisation scenario. Next to the health benefits, the external benefits include costs savings in terms of less accidents, air pollution, noise, congestion, well-to-tank emissions. The variance of magnitude of external benefits compared to Baseline 2040 demonstrates the importance of capturing external impacts to support decision making in the context of the mobility transition.

Figure 6: Average External Benefits of decarbonised ground-based passenger transport system Austria, compared to Baseline 2040 (EUR per capita and year)



Source: Maier et al. 2023, own representation based on data provided by the authors

Furthermore, the authors argue that the shift of cost composition from fixed costs to travel time costs that comes along with the decarbonisation makes the transportation system more societally just. They derive this conclusion from a declining dependence for the purchase of vehicles and fuels, which would release some financial burden from low-income households, whereas the health benefits of active mobility are equally spread across income classes[20].

The authors furthermore point to the lack of research on embodied GHG emissions in vehicles and infrastructure of the mobility system. While only the emissions generated by the operation of the vehicles are taken into account, ideally the emissions generated during the production and recycling phases of both the vehicles and the infrastructure should also be recorded. They also point to infrastructure costs for stationary traffic as a relevant cost factor, which depends on occupancy rate. In their sensitivity analysis for Austria's comparatively low occupancy rate, they find that the increase in public transport infrastructure costs levels off, when occupancy rates increase. Other relevant externalities that they were not able to consider include tire abrasion and embodied emissions of vehicles and infrastructure. In terms of infrastructure, the aspect they considered in their analysis is parking fees for on-street parking, which is just a small aspect of overall infrastructure costs for transport. The authors cite the reasons for not taking other infrastructure costs into account as being that the infrastructure costs per Pkm depend heavily on the conditions in each country and that the data quality on transport infrastructure, especially in the case of local public transport, is insufficient. They conclude that both gaps lead to an underestimation of external cost reductions in decarbonisation scenarios. Maier et al. (2023) further explore the limitations of their own research and address the assumption of unchanging travel time costs per transport mode,

[20] It needs to be noted, that this argument doesn´t consider regional disparities in accessing public transport and that high upfront costs of decarbonised private transport in rural areas could potentially increase inequalities.

while better infrastructure for active mobility and better public transport provision would significantly reduce travel time costs. In addition, they were unable to consider innovations that might shape the future transportation system, such as hyperloops or fully autonomous cars. (Maier et al., 2023). Chapter 3.2 provides more information on the lack of sufficient consideration of innovation dynamics in cost-benefit analysis and other quantitative modelling of system transitions.

Whereas the previously elaborated CBA studies are all in the context of mobility transition scenarios, Gössling et al. (2019) analysed the **social costs of auto-mobility, cycling and walking on an EU-level in the current status quo**. Even though the study does not comply with the focus on system transition, it is highly relevant for this paper as it provides a meta-analysis of EU level for CBA in transport projects. Comparing various CBA frameworks, Gössling et al. (2019) find that typical CBA factors in the transport sector include travel time, vehicle operating costs, accidents, noise and air pollution and climate change. However, this does not cover all the costs and benefits associated with transport and omits important externalities. Gössling et al. (2019) conclude that the range of parameters considered in EU transport CBA is limited. Based on their own meta-analysis, they present a comprehensive list of 14 criteria that should be considered as important parameters in a cost-benefit analysis for the transport sector. External costs include climate change, air and noise pollution, soil and water quality, land use and infrastructure, maintenance of transport infrastructure and resource requirements. Private costs include vehicle operation, travel time, congestion, and perceived safety and discomfort. Additionally, when considering land use for parking, health effects, accidents, quality of life, branding and tourism there are both external and private effects (Gössling et al., 2019).

Building on this framework, Gössling et al. (2019) calculate the external and private costs and benefits of automobility, cycling and walking in the European Union. Results suggest that each kilometer driven by car incurs external costs of EUR 0.11, while cycling and walking provides benefits of EUR 0.18 and EUR 0.37 per kilometer respectively. Also, the private costs are found to be lower for walking (EUR 0.50) and biking (EUR 0.15) than for driving the car (EUR 0.89), as the additional travel time costs are overcompensated by health benefits and congestion costs savings. Extrapolated to the total number of passenger kilometres driven, cycled or walked in the European Union, the external cost of automobility (sum of external costs and benefits) is about EUR 500 billion per year. Due to positive health effects, for cycling, the balance sheet of external costs and benefits results in an overall external benefit worth EUR 24 billion per year and EUR 66 billion per year for walking. Gössling et al. (2019) uses the ExternE project for environmental externalities (pollution, emissions), the UNITE project for a broader range of marginal social costs (congestion, infrastructure, accidents), and CEDelft et al. (2011) for specific studies on transport-related externalities, particularly environmental impacts. These sources are pivotal in calculating and comparing the hidden societal costs of different transport modes, underpinning the study's argument that cycling and walking have significantly lower social costs than automobility in the European context.

Furthermore, Gössling et al. (2019) conclude from the framework comparison, that the representation of different mobility areas/ modes is unequal. Often the focus is on one mode of transport, usually the car, with the result that the substitutability of modes gets overlooked and the contribution to decision making is limited. When comparing different modes of transport, it is also important to take into account spillover externalities, i.e., the ways in which they interact and create costs for each other. For example, motorised traffic has many negative external effects on cyclists and pedestrians (Gössling et al., 2019).

The analysis for ground-based passenger transport transition in Austria showed that the decarbonisation strategies reduce social costs and lead to a strong increase in external benefits. The analysis would benefit from including further cost types like e.g. embodied emissions of vehicle and infrastructure. A meta-analysis at EU level on cost-benefit analysis in the transport sector (without a focus on transformation) shows that a more balanced representation of the different transport modes is needed and that the often missing but important environmental externalities are noise pollution, soil and water quality, land use and infrastructure, maintenance of transport infrastructure and resource requirements.

To build a less context specific understanding of the usage of cost-benefit analysis for sustainability transitions, the next chapter examines examples for the application of cost-benefit analysis in other areas of sustainability transition.

2.3 Cost-Benefit Analysis for other sustainability transition fields (energy and food)

This section provides an overview on the evidence base regarding the cost-benefit analysis of energy system and food system transitions. The aim is to complement the cost-benefit-analysis for mobility system transitions with examples of the application of cost-benefit analysis in other systems relevant for sustainability transition. Similarly to Chapter 2.2., the reviewed studies commonly fall short of performing a full social cost-benefit analysis. First, we revisit the EU Impact Assessment analysing the economy wide GHG reduction target levels for the year 2040. This assessment was introduced in Chapter 2.1. in the role of investment needs, whereas this chapter presents more thoroughly its CBA results. Subsequently, more CBA studies analysing the transitions in energy and food systems are assessed. A summary of the studies is given in Table A3 (Annex).

In February 2024, the European Commission released a Communication about Europe's 2040 climate target and path to climate neutrality by 2050 (EC, 2024b). As the 2040 climate target, the Communication recommends a 90% reduction in the EU's total net GHG emissions compared to 1990 levels, based on an impact assessment looking at three target options for 2040. The options had varying GHG emission reduction targets for 2040 (compared to 1990), ranging from up to 80% (option 1) to a reduction of 90-95% (option 3). All these options require a similar level of investment over the period 2031-2050. Energy system investment needs are almost EUR 660 billion (equivalent to 3.2% of EU's GDP) annually on average over the whole period, which is slightly less than for the mobility system (EUR 870 billion; see also section 2.1. Table 2). For comparison, the annual energy system investments were on average EUR 250 billion between 2011 and 2020 (1.7% of EU's GDP). Energy system costs (including capital costs and energy purchase costs) are expected to increase between 2031 and 2040 to 12.4-12.9% of EU's GDP in 2031-2040, compared to 11.9% of EU's GDP in 2011-2020, before falling to around 11.3% over 2041-2050. A key reason for decreasing energy system costs are declining costs of fossil fuel imports. Energy system investments in agriculture are proposed to be continued at the levels experienced in the recent past (0.1% of EU's GDP).

The **EU Impact Assessment** accompanying the European Commission Communication provides an assessment of four different scenarios of EU's transition to climate neutrality (EC, 2024a). These scenarios are compatible with the target options for 2040, as detailed below. Scenarios (S1, S2, S3, LIFE) all reach climate neutrality by 2050 but with different net GHG levels in 2040.

- **S1:** Continuity of existing decarbonisation trends up to 2040 (compatible with option 1)
- **S2:** Additional wider diffusion of novel technologies by 2040 (carbon capture, e-fuels; compatible with option 2)
- **S3:** Additional faster and wider uptake of novel technologies over 2031-2040 (carbon capture, e-fuels; compatible with option 3)
- **LIFE:** More sustainable lifestyles, circular economy, shared economy > results in lower energy demand (compatible with option 3)

The impact assessment investigates several impacts of the target options. These include GHG emissions, evolution of the energy system and associated raw material needs, environmental and health impacts, and the socio-economic implications of mitigation. The benefits of climate change mitigation are estimated as the avoided costs of climate change, which are estimated in the tens of billions per year, though figures vary across target options. The benefits (as avoided costs) are naturally also highly dependent on the figure of social cost of carbon used. The health impacts accrue from the fact that the system transitions have positive impacts to air quality because of lower energy consumption and a shift to non-emitting renewable energy sources. According to the assessment, the reduction in air pollution and associated benefits are similar across scenarios. The benefit from reduced premature mortality from the most harmful air pollutants is estimated to be in the hundreds of billions of EUR per year. The assessment also tests the sensitivity of results to the value attributed to climate and health impacts using alternative valuation levels (lower valuation and higher valuation).

The assessment includes a cost-benefit analysis for the target options. It includes the overall mitigation costs and monetized environmental benefits regarding climate change and air pollution. The highest results on net benefits differ depending on the level of valuation of externalities. With a lower valuation of external damages (due to GHG emissions and air pollution), Scenario 1 has the highest net benefits. However, with the higher valuation of externalities, Scenario 3 fairs best. These outcomes demonstrate the importance of discussion about the valuation of externalities as the level of valuation of externalities can influence which option achieves the highest net benefit. The assessment makes it apparent that the used monetarization leads to health benefits from reduced air pollution being remarkably larger than the climate benefits. Notably, these two externalities were the only ones monetized directly.

The next subsection presents cost-benefit analyses that are on a lower aggregation level and specifically for energy transition.

2.3.1 Cost-Benefit analysis for energy transition

Energy sector investments and policy proposals are relatively well covered with cost-benefit analysis, but the non-climate environmental aspects receive less attention in cost-benefit analysis in the energy sector compared to transport sector (OECD, 2018). Furthermore, the CBAs of energy system transitions on EU level are scarce. The following two studies bring some elaboration on the subject.

The **European Parliamentary Research Service Report** (Heflich and Saulnier, 2021) looks at the costs of inaction (i.e. benefits of action) at EU level. For the period of 2030 to 2050, the impacts of the policy packages are evaluated using a macroeconomic model. The benefits of action include averted costs of climate change-related damages as well as benefits from various investment types and regulation (estimated by the macroeconomic model as a GDP difference with the baseline). They project **scenarios to look at alternative future pathways**:

- ***Net Zero*** is consistent with achieving a reduction of 62 % (94%) GHG emission below 1990 levels by 2030 (2050);
- ***NO COOP*** refers to a non-cooperative situation at EU and international level;
- ***FRAG*** corresponds to a fragmented and uneven response to climate change in member states.
- The European Commission EU Reference Scenario 2020 (EC et al., 2021) serves as the baseline scenario.

In total, the estimated monetary benefits from ambitious and united EU action (in *Net Zero* scenario) are projected to amount to 5.6% of EU GDP (EUR 1029 billion) in 2050. Comparing averted environmental damages between the scenarios gives the following result: the benefits in *Net Zero* scenario in 2021 (in 2050) are EUR 97 (610) billion per year higher compared to the *NO COOP* -scenario, EUR 41 (305) billion per year higher compared to the *FRAG* -scenario, and EUR 34 (203) billion per year higher compared to the baseline scenario.

Heflich and Saulnier (2021) instead of conducting a full CBA only look at the component of external benefits from energy system transition. In contrast, Sofia et al. (2020) conduct a full CBA that is also on a higher aggregation level (energy, transport and households).

A case study in Italy (Sofia et al., 2020) aims to assess how CBA can be used to quantify the costs and related social benefits of mitigation strategies (in energy, transport and household[21]) towards progressive decarbonization of the energy system. Costs of decarbonisation in the energy sector accrue from investment costs and operating costs. The benefits arise from environmental, morbidity and mortality benefits. The air pollutants assessed were particulate matter (PM_{10}), sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO) and volatile organic compounds (VOC). To calculate the environmental benefit, for each of the pollutants, the corresponding marginal social cost (i.e. the monetary value of damage accruing from one additional unit of emission) is used. Health impacts were based on the morbidity and mortality effects that can be attributed to the external effects of air pollution. They find the health benefits of the various mitigation strategies outweigh the costs involved for all considered sectors (energy, transport, and households). Furthermore, they find that the ratio of benefits to costs is highest for public transport compared to other transition fields. They estimate the total net benefit of the public transport sector transition in 2030 to be over EUR 800 billion. For the energy sector in 2030, they estimate a total net benefit of over EUR 200 billion, which is largely driven by the decrease in air pollutant emissions and their adverse impacts on health and environment.

These two studies, in addition to the EU Impact Assessment presented earlier in the chapter, illustrate different kinds of approaches. Heflich and Saulnier (2021) apply a macroeconomic model, which makes visible the macroeconomic benefits from a variety of policies and investments. This enables them to make a nuanced picture of the costs of inaction. The only externality they consider is the GHG emissions. Sofia et al. (2020) focuses on air pollution and health effects and applies a similar methodology for monetization than the one in EU Impact Assessment. The next subsection changes the context to food system transitions to provide insights on the similarities and differences of CBA approaches applied in assessing different transitions.

2.3.2 Cost-Benefit analysis for food system transition

CBAs of food system transitions on EU level were not found. In this chapter, one global level assessment and one country-level study are presented for the food sector. To take into account the true costs (hidden costs in addition to financial figures) in food systems, there is a framework developed by the United Nations Environment Programme (UNEP)'s The Economics of Ecosystems and Biodiversity for Agriculture and Food initiative[22] (TEEBAgriFood). The framework implementation guidance document discusses whether and how environmental, economic, health and social impacts in a food system assessment should be included, and elaborates on the (limited) possibilities to monetize the impacts. As such, this framework does not give guidance on the details of conducting a CBA in the context of food system transition.

The Food System Economics Commission's Global Policy Report (Ruggeri Laderchi et al., 2024) studied the economics of transforming the global food system. They utilized two tools to estimate the several impacts of the alternative food systems and convert them to economic variables. First, they used a bottom-up hidden cost approach to assess the hidden costs related to, for example, poverty, environment, and health. Secondly, they applied a top-down social welfare function approach[23] to assess all the positive and

[21] energy redevelopment of buildings and the use of heat pumps for electric heating
[22] See https://teebweb.org/our-work/agrifood/understanding-teebagrifood/ for more details.
[23] Social welfare function approach does not produce a figure for gross benefits, it only gives a figure for net benefits. On the other hand, net benefits are tricky to calculate from the hidden cost approach. All in all, it is not easy to produce directly comparable figures from these two approaches.

negative welfare effects from the food systems. Both approaches estimate the net benefits from transferring to a particular food system pathway compared to BAU.

Hidden health costs are calculated by estimating the degree of labour productivity losses due to poor diets. These costs are largely driven by obesity and chronic health conditions like diabetes, hypertension, and cancer. Hidden environmental costs stem from the negative effects of the food system on ecosystems and climate. The costs also include the costs of loss of biodiversity and environmental damage caused by pollution of water bodies and air with excessive nitrogen. Poverty costs are estimated as the income gap from the poverty line. This gap means the amount of money needed to raise all poor people above the USD 3.20 poverty line. Food systems contribute to this gap through the cost of food.

The total reduction in hidden costs in the period 2020-2050 was estimated to be USD104 trillion globally, equivalent to USD5 trillion a year (annuitized). Reducing health-related hidden costs account for 55% of this total sum. Reducing hidden environmental costs accounts for 45% of the total reduction. The hidden costs of poverty remain virtually unchanged, but the relative importance of the hidden cost categories changes remarkably over the time period. The reductions in hidden environmental costs account for the majority of the total reduction at the beginning of the period, while the reduction in hidden health costs becomes much more pronounced later. The costs of transforming food systems accrue from specific measures required to make the transformation and the pricing of those actions. The estimated costs are between USD 200 billion and USD 500 billion a year globally until 2050.

Additionally, the net benefits of the food system transitions were assessed by a top-down approach applying a social welfare function. This approach encompasses the impact on welfare caused by improvements in health and environment as well as real income growth. The net economic benefits of food system transitions estimated by this approach are USD 10 trillion a year until 2050, roughly equivalent to 8% of global GDP in 2020. Accumulated net welfare gains were estimated to amount to USD270 trillion globally by 2050. The estimated benefits were much higher with this approach compared to the bottom-up hidden cost approach. One reason for this is that the social welfare analysis takes a broader approach to valuing the income component of the transformation by valuing the income changes of the whole population rather than among the poor only.

To complement the insights from the global study of Ruggeri Laderchi et al., (2024), a look at a smaller regional level is warranted. **A case study in Netherlands** conducted a social CBA of a policy including meat taxation and a fruit and vegetables subsidy in the Netherlands over a 30-year period (Broeks et al., 2020). The assumed meat price increases at consumer level were 15% and 30% respectively, and the assumed fruit and vegetable price decrease was 10%. They modelled future food consumption and health effects and used Life Cycle Analysis to estimate environmental impacts. They considered health effects of five diet-related diseases and assessed changes in the Quality Adjusted Life Years (QALYs) values. Environmental effects included were GHG emissions, acidification, eutrophication, and land use, and were monetized using literature values. The policy was found to remarkably decrease the healthcare costs, increase quality of life and productivity levels. The benefits to the environment of a meat tax were estimated to be EUR 3.4 billion with 15% price increase and EUR 6.3 billion with 30% price increase. However, the increased fruit and vegetable consumption would increase the costs to environment by EUR 0.1 billion. The consumer surplus[24] from the subsidy amounts to EUR 10 billion, but consumers experience costs from the taxes equivalent to EUR 21-41 billion (depending on the tax level chosen). The positive effects of meat taxes on consumer health are outweighed by the subsequent loss in consumer surplus, resulting in a net loss of welfare. The net benefit to society over 30 years from the tax on meat was EUR

[24] Consumer surplus is defined as the monetary gain consumers obtain from consuming a number of a given product at the given price. The surplus is obtained if the consumers are able to purchase a product at a lower price than the maximum price they would be ready to pay.

3.1-7.4 billion for a price increase of 15% and EUR 4.1-12.3 billion for price increase of 30%, respectively. The net benefit from the food and vegetable price decrease was estimated to amount to EUR 1.8-3.3 billion.

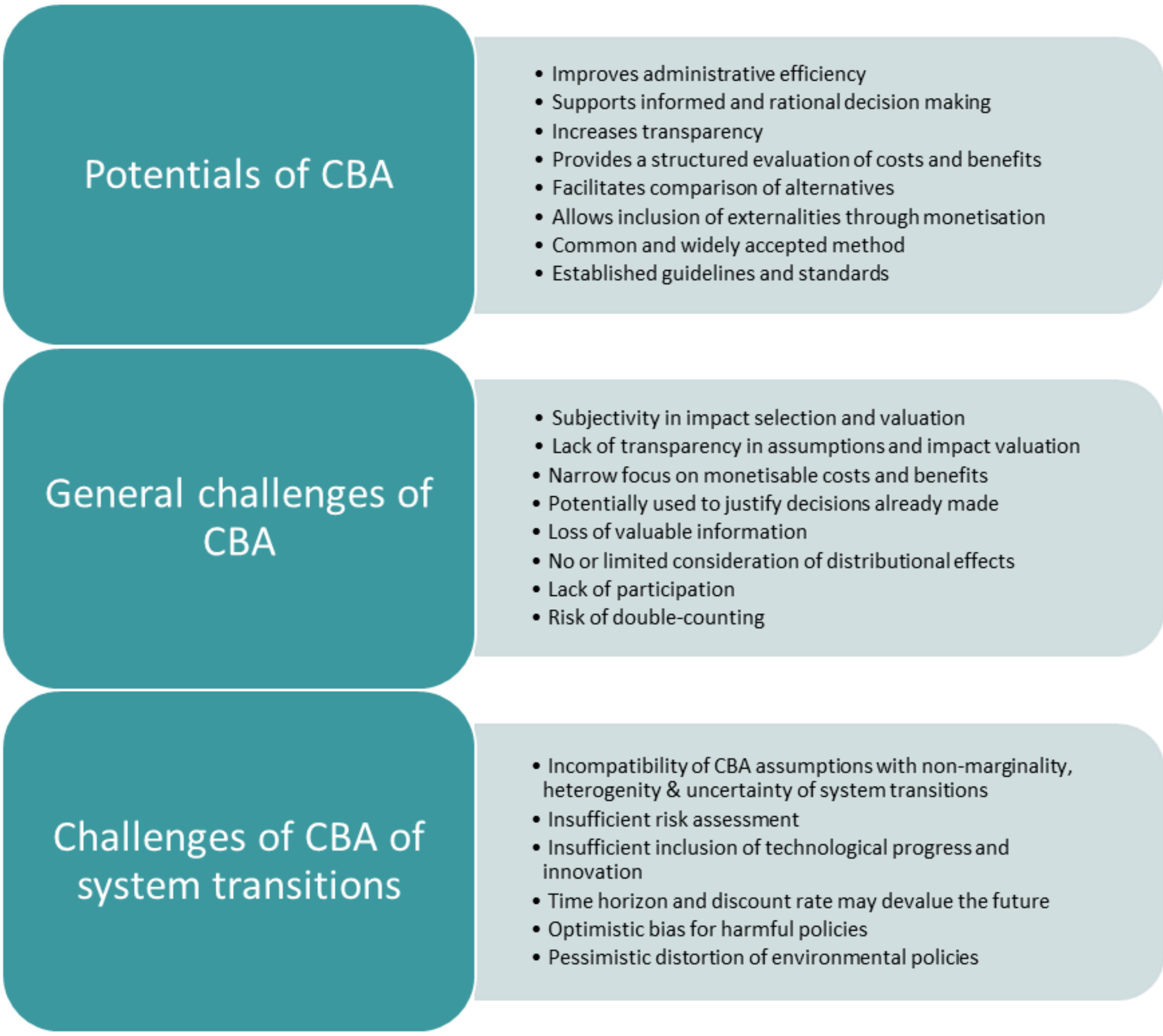
These two studies differed in their geographical scope and partly in their methods, but they both showed remarkable health benefits from food transition. Furthermore, both recall the importance of taking into account the impact of the transition on customers, and (Ruggeri Laderchi et al., 2024) emphasize the customers with lower income.

3 Methodological Strengths, Challenges and Limitations of Cost-Benefit-Analysis in the context of Systemic Sustainability Transitions

This chapter discusses CBA and quantitative modelling as methods for impact assessment and decision support. It first outlines the general advantages and disadvantages of CBA as a methodology and explains how, despite criticism, it has become an important tool. The chapter then examines the suitability of quantitative modelling approaches and CBA for analysing sustainability transitions.
With regard to quantitative modelling, not all challenges are discussed, but only those relevant to the analysis of sustainability transitions.

Figure 7 shows the identified advantages and challenges of CBA in general and for the analysis of system transitions.

Figure 7: Overview Potentials and Challenges of CBA



Source: own visualisation based on all sources mentioned in Chapter 3

3.1 General potentials and challenges of CBA

CBA originated in welfare economics with the aim of improving administrative efficiency and ensuring the effective use of public funds. With the transition to market-oriented administrative systems at the end of the 1980s, CBA became the central method for evaluating the use of public funds and the design of public policies. Eventually, in the 21st century, CBA became an important tool for introducing economic efficiency and rational decision-making processes into public policy, and for ensuring transparency and accountability to government and the public (Dennig, 2018; Wright, 2020; Sharpe et al., 2020).

CBA is a valuable decision-aiding method as it allows comparison of the costs and benefits of projects or measures, providing a comprehensive overview of their impacts. It can be used to assess their efficiency and allows different alternatives to be compared. By identifying advantages and disadvantages of projects and policies, better alternatives can then be developed (Marleau Donais et al., 2019). In the EU, it is used to assess the net economic impact of project proposals. According to the European Commission's Better Regulation Toolbox (2023), such an impact assessment is required when a policy proposal is likely to have significant economic, environmental or social impacts or involves significant expenditure.

The possibility to include externalities through monetisation also allows hidden costs to be captured and projects and policies with negative environmental and social impacts to be identified and avoided (Gössling et al., 2019; Marleau Donais et al., 2019). Properly applied, CBA can thus provide a comprehensive analytical methodology for examining the potential impacts of projects and policies on a wide range of factors.

Moreover, CBA is one of the most widely used and recognised methodologies, particularly in the transport sector (Gössling et al., 2019; Damart and Roy, 2009). It is based on well-established assumptions and theories, such as social welfare theory, which have been extensively reviewed and formalised in various guidelines and frameworks. This standardisation leads to a common language and methodology (see Box 1), which simplifies the communication of results and allows a degree of comparability between different CBAs, even when different costs and benefits are taken into account (Marleau Donais et al., 2019). CBA is still one of the best tools available for helping governments to appraise and prioritize potential investments (Atkins et al., 2017).

Nevertheless, the potential of CBA is not always fully realised. The results of CBA can be misused, inconsistent and poorly communicated (Atkins et al., 2017). In particular, mandatory CBAs are often used only to confirm decisions that have already been made, thereby undermining the purpose of CBA, which is to provide an objective and comprehensive basis for informed decision-making and impact analysis (Marleau Donais et al., 2019).

There are several challenges when using CBA as a tool to inform political decision-making. In general, CBA represents a highly reduced perspective, as it only considers costs and benefits in monetary terms. Beyond the ethical dilemma of whether all impacts, such as human lives or habitat destruction, should or can be monetised, it is crucial to question which externalities are included and how they are monetised (Aldy et al., 2021). This concern is particularly pressing as there is far more research on monetising certain impacts, such as travel time or safety, than on others, such as biodiversity (EEIST, 2021b; Marleau Donais et al., 2019). Since these aspects vary widely from study to study, they underscore the subjectivity underlying CBA, which has significant impact on the results and leads to reduced transparency. Furthermore, the costs and time of projects are almost always underestimated (Atkins et al., 2017). In addition, models to estimate dynamic effects (such as job creation and GDP increase) are expensive and underdeveloped, so claims about dynamic effects should be carefully examined (Atkins et al., 2017).

When selecting the impacts to be analysed, care must be taken to ensure that they are not recorded more than once. Doublecounting of costs or benefits, such as considering an effect as a cost to one group and a benefit to another, can distort the results of the analysis and lead to an inaccurate representation of the true impact (EC, 2023; Mishan and Quah, 2021).

CBA is often perceived by some stakeholders as a 'black box', primarily because the process of selecting impacts and convert them into monetary values might seem unclear and difficult to understand (Marleau Donais et al., 2019). By further reducing the results to a single value, the net benefit, even more valuable information is lost. This increases the lack of transparency and makes it harder to understand decisions that are often already perceived as subjective. In addition, benefits that are hard to monetize, such as those related to health and the environment, are often measured inconsistently across projects (Atkins et al., 2017). The resulting uncertainty can undermine confidence in the results of a CBA and significantly limit the acceptance of its use as a basis for decision-making.

Another frequently criticised aspect of CBA is its failure to consider the distribution of costs and benefits, although the Better Regulation Toolbox suggests that distributional effects should be taken into account (see Box 1). Traditional CBA aggregates total benefits and costs, thereby discarding important information about the specific winners and losers of a policy (Dennig, 2018; Gössling et al., 2019; Marleau Donais et al., 2019). However, this information is crucial for assessing the effectiveness and fairness of a policy. Without considering distributional effects, a CBA cannot fully capture the social and economic impacts of a policy, which significantly reduces its relevance and significance.

The choice of time horizon and discount rate is another challenge in CBA. Discounting, which converts future costs and benefits into present values, is a key aspect that can significantly influence the results, especially when costs and benefits occur at different times (Aldy et al., 2021). In particular, it affect intergenerational equity as long-term effects are often ignored and future values are discounted more heavily than present values. This means that potentially significant long-term effects may not be adequately considered and future generations may be disadvantaged, further calling into question the fairness and ethical acceptability of the method (Dennig, 2018; Gössling et al., 2019).

Carolus et al. (2018) propose a bottom-up approach to CBA, which begins with the underlying environmental problem (instead of starting out with a predefined policy option) and assesses the costs and benefits of candidate solutions. The information for this assessment is collected from local and directly affected stakeholders. The approach utilizes local knowledge, assesses plans which are not only developed for local conditions but are also likely to be more accepted by local societies, and also capture possible distributional effects. Bottom-up CBA supports participatory environmental planning and embeds stakeholder participation.

After outlining the general advantages, potentials and challenges of CBA, the next chapter examines in more detail the specific challenges and limitations of applying quantitative economic modelling and CBA to system transitions.

3.2 Challenges and limitations of quantitative economic modelling including CBA of system transitions

Quantitative economic modelling approaches study economic behaviour and decision-making using empirical data. They can be used to evaluate the economic impacts of political decision-making, usually measured in monetary terms. As such, they illuminate possible future pathways. While quantitative economic models can and should inform about possible economic effects of policy decisions, there are some major limitations when using them for modelling sustainability system transitions. The challenges and limitations of general quantitative economic modelling also apply to CBA when analysing system transitions, with additional specific limitations further discussed in this chapter. CBA has been an integral part of policymaking since the 1990s. Initially used in relatively small and less complex areas, its use has expanded over time. In particular, its integration into climate policy has been an important step, as it is confronted with a broader and more complex range of issues (Dennig, 2018). Conducting CBA has some general advantages and disadvantages, as highlighted in the previous chapter. However, this the integration in climate policies also brought about new challenges. The application of CBA to sustainability system transitions raises many questions, because the value of nature is limitless and hard to capture within traditional economic models. This chapter therefore discusses the challenges and limitations of quantitative economic modelling in general and CBA specifically, both in the context of system transitions.

3.2.1 Insufficient risk assessment and uncertainty

One of the main critiques of using quantitative economic modelling to assess sustainability system transitions is the gross underestimation or omission of potential future risks of climate change and biodiversity loss (DeFries et al., 2019). Climate change is marked by deep uncertainty regarding factors such as climate outcomes, the pace of change, policy effects, and potential economic impacts. Simultaneously, it presents extreme risks, with a small but significant probability of catastrophic events, such as tipping cascades or societal collapse (Stern et al., 2021). There is also a gap between the potential physical impacts of climate change and the potential economic impacts in the IPCC assessments. The underestimation of the economic risks of climate change arises from several contributing factors, which are analysed in the following.

DeFries at al. (2019) argue that economic assessments do not account for large concurrent impacts around the world that would cause displacement, mass migration, conflict and enormous loss of life. Economic models of climate change rarely incorporate the scale and magnitude of those repercussions for lives and livelihoods. Due to model limitations, quantitative economic assessments of climate change often overlook the most significant potential risks , such as the destabilization of the Greenland ice sheet or the possibility crossing of multiple simultaneous and potentially irreversible thresholds within the climate system (DeFries et al., 2019). Especially environmental tipping points received too little attention in quantitative modelling of sustainability transitions (Ekins and Zenghelis, 2021).

Köberle et al. (2021) stresses problems of probabilistic methods. They argue that economic assessments of the gross costs of climate mitigation generally do not fully include impacts of climate change (like loss of agricultural and labour productivity, heat induced mortality and morbidity, infrastructure losses, biodiversity losses, etc.). Environmental impacts are difficult to include in models because of the high uncertainties surrounding these events. Economic assessments hence usually assign a probability of zero and thereby exclude those large impacts. The focus of most economic assessments is on smaller risks that are easier to quantify. The issue here is that the impacts of climate change are characterized by fat-tailed uncertainty (Weitzman, 2011). Meaning that the probability of extreme events is higher than in normal distributions. Wagner and Weitzman (2016) find that the probability of global temperature exceeding 6°C at an atmospheric GHG concentration of 700 ppm (in line with IEAs projections for 2100 with current policies) is 11%. The authors state that a global temperature exceeding 6°C would be an indisputable global catastrophe. Ignoring the potentially catastrophic effects in economic assessments can lead to misinformed policy decisions when addressing system transitions.

Since many risks of climate change and biodiversity loss are still unknown to scientists, they cannot be part of economic modelling of system transitions (DeFries et al., 2019; Ekins and Zenghelis, 2021). The current pace of climate change is unprecedented in human history and possible future risks exist that scientists are still working to understand and explore.

This issue is also reflected in conventional CBA of system transitions, which tends to underestimate or even ignore the potential future risks of climate change and therefore underestimate the benefits of introducing a system transition, CBA requires that the parameters and potential impacts analysed are sufficiently well known and that their probability can be estimated. However, this is not always possible when applying quantitative economic approaches, because predicting all possible future developments and their respective probability is impossible. These uncertainties cannot be adequately taken into account by conventional CBA, which is based on quantifiable costs and benefits, and this possibly leads to distorted results (Sharpe et al., 2020). Another challenge of CBA highlighted in the context of climate uncertainty is the comparability of criteria. CBA aims to monetarise different criteria to make them comparable. As such irreversible climate damages might be offset with potential savings in travel time costs, leading to a distorted evaluation (e.g. BUND, 2023).

Another limitation of quantitative modelling of sustainability system transitions is that many economic models are based on data of past human experiences, but current and future changes in the climate system are unprecedented and not captured in such data (DeFries et al., 2019). The focus on past data imposes a **status quo bias** and represents the economy as statistically predictable (EEIST, 2021a), downplaying crucial system dynamics that drive transformative changes. Stern et al. (2021) argue that in the case of high uncertainty, it is problematic to extrapolate the future based on current or past data, as e.g. non-linearities in climate outcomes such as tipping points cannot currently be predicted. Hence current estimates of economic effects regarding climate action and system transitions are likely to be misleading.

3.2.2 Insufficient inclusion of innovation and technological progress

In addition to the uncertainty surrounding the effects of climate change, there is considerable uncertainty regarding the technologies and innovation processes needed, which play a critical role in shaping policy and investment decisions. Economic resources and structures are constantly changing due to innovation, technological change, the complexity and interdependence of systems, the behaviour of different economic agents and other unforeseen events. A sustainability system transition heavily depends on new technologies widely available that enable emission reductions. EEIST (2021a) argue that technology evolution is characterized by complex dynamics and large uncertainties and a flexibility of policy frameworks should be incorporated that responds to the evolution of technology. Accurately modelling a system transition requires an understanding of the processes involved in technological development, roll-out and innovation. When analysing climate change, economic models often do not take the innovation process into account. Aghion et al. (2019) argue that innovation is a path dependent process in which history and expectations matter greatly when determining possible outcomes. Phenomena, which lead to path dependence include knowledge spillovers, network effects, switching costs, feedbacks and complementarities. Innovation has often been overlooked in economic models of climate change, yet it is a critical factor that should play a key role in shaping policy decisions. For example, the neoclassical integrated assessment model (IAM) DICE by Nordhaus (Nordhaus, 1992) allows for technological progress by including a technological parameter that grows exogenously over time, while the empirically observed drivers of innovation are ignored (Aghion et al., 2019).

The policy conclusion of such a model generally is to introduce a carbon tax. The assumption is that the right price will lead to sufficient emission reduction to avoid climate change. Ekins and Zhengelis (2021) find that some climate economic models do incorporate innovation, but often ignore important firm-level, sector-specific effects, possible spillovers and interactions as well as the role of mission-oriented, targeted R&D efforts. Once these knowledge spillovers and complementarities are accurately addressed in models, new policy recommendations targeting the innovation process based on the results of those models emerge (Aghion et al., 2019).

In CBA of system transitions, inaccuracies in accounting for technological progress and the underestimation of positive feedback effects and path dependencies associated with innovation and new technologies can lead to an overestimation of the necessary costs of system change. In addition, the importance of social tipping points, which can be crucial for faster and wider adoption of sustainable practices, is often neglected. These shortcomings may lead to a distorted picture of the real benefits and feasibility of sustainable measures, potentially hindering the implementation of sustainability initiatives (Ekins and Zenghelis, 2021).

3.2.3 Optimization based methods and the complexity of system transitions

Another limiting factor is the complexity of system transitions. Interactions between climate change, natural climate variability, demographic shifts, political processes, economic insecurity and land-use practices are generally difficult to model (DeFries et al., 2019). In contrast, many commonly used economic models are equilibrium and optimization based, and thus fall short in capturing the complexity of system transitions in the following five ways, as outlined by Mercure et al. (2016). Equilibrium and optimization-based approaches implicitly assume that there exists a unique stable equilibrium, to which the economy returns after external disturbances (externalities). They argue that such an approach is rather normative, since it tries to identify optimal strategies rather than describing actual system behaviour. Traditional CBA is generally applied in a market failure framework that is based on the theoretical foundations of welfare economics. Market failure can be a consequence of unintended external effects (externalities) of production or consumption, like damages to human health or the environment. Policy measures aimed at addressing market failures seek to correct these issues, often by internalizing unintended externalities and restoring market equilibrium. This approach assumes that policy interventions only lead to marginal changes. This means that there will not be major structural changes as a result of a policy measure, but only small, gradual and predictable changes. Sustainability transitions, on the other hand, aim at profound decarbonisation and structural changes to existing systems (Sharpe et al., 2020; EEIST, 2021b; Ekins and Zenghelis, 2021).

Furthermore, full rationality of agents is generally assumed in equilibrium and optimization-based approaches. This does not allow non-rational behaviour of agents. Assuming full rationality of agents proves to be useful, because it allows for the use of models simply with mathematical solutions. It does however not represent reality as many psychological studies have found (Camerer, 1999). The field of behavioural economics combines psychological findings and economics, which offers a more realistic and thoughtful basis for political decision-making.

A third deficiency lies in the inability to account for mutual influences between agents (multi-agent interactions) and capture related self-reinforcing (positive feedback) processes. Optimization and equilibrium-based approaches often do not allow for increasing returns. This neglects the process of technological advancements and innovation that heavily relies on multi-agent interaction and positive feedback mechanisms leading to possible increasing returns (Aghion et al., 2019).

Additionally, such approaches are often unable to present multiple solutions and path-dependencies. Path dependency is a key aspect in the process of technological change and is rarely incorporated in many economic models and integrated assessment models (IAMs) analysing the effects of climate change. A multiplicity of equilibria arises when path dependent phenomena, such as switching costs, inertia, knowledge spillovers, network effects, feedbacks and complementarities are included in the assessments (Ekins and Zenghelis, 2021). Such a multiplicity leads to difficulties in predicting costs and benefits of transitions, since there is no single optimum.

Lastly, such approaches seldomly incorporate diversity of agents (agent heterogeneity). Homogeneity of agents among the actors involved is also a key assumption of CBA. Therefore, CBA is only effective when the diversity among affected groups is either minimal or irrelevant to the choice of policy measures. However, when considering system transitions, this requirement is not met. Structural changes have various effects on different groups, so it is crucial to consider who is affected by policy measures and how. The criticism regarding the neglect of the distribution of costs and benefits, as discussed in section 3.1, becomes even more relevant in the context of system transitions. Given the diversity of groups affected by such transitions and their varying levels importance, conventional CBA is insufficient to adequately analyse these changes.

As discussed in Chapter 3.1., CBA is a useful tool for policy advice if certain standards are met such as methodological transparency. The assumptions of marginality, homogeneity and certainty play a key role in the appropriate application of CBA and pose a particular problem when analysing system transitions. The non-marginal nature of transitions, combined with a high degree of uncertainty and dynamic variables, as well as a large diversity of affected actors, challenge the assumptions of traditional CBA. An appropriate tool for analysing policy measures is, however, necessary for the implementation of a Just Transition (Sharpe et al., 2020; Renda et al., 2013).

Mercure et al. (2016) hence propose a fundamental change in methodology to account for complexity in sustainability transitions by adding complexity dynamics and agent heterogeneity.

3.2.4 Focus on monetary variables

Economic assessments of climate risks often focus on climate impacts in monetary variables, such as GDP or economic output (DeFries et al., 2019). These measures do not correctly represent the possible damages to lives and livelihoods and their scale. The cost of climate change is often represented by the market price of CO_2. This measure mostly reflects companies' willingness to pay for future climate policies rather than true external costs. In the case of extreme risks, individuals generally exhibit a greater willingness to pay to reduce climate change than predicted by the standard economic model of expected utility maximization (Stern et al., 2021). A better measure for the cost of climate change would be the costs consistent with stabilizing the GHG concentrations on levels in accordance to achieving the 2°C target (Stern, 2008; Gössling et al., 2019). The method of evaluating CO_2 -emissions is called abatement-cost-approach, where the necessary costs to achieve a given CO_2 reduction target (e.g. 2°C target) are measured (cost of exchanging heating systems, power plants, fossil cars, etc.). For informed policy decisions, decision makers need to understand the scale of these missing risks and their potentially drastic consequences.

3.2.5 Discount rates and time horizon

Determining appropriate time horizons that adequately take into account the long-term nature of system changes is a key challenge for economic assessments of system transitions, especially for CBA. Traditional cost-benefit analysis often reaches its limits when dealing with long-term policies. In particular, the debate on appropriate discount rates for long-term problems such as climate change illustrates the complexity and uncertainty of applying CBA to issues with long time horizons (EEIST, 2021b; Gössling et al., 2019).

It is often observed that quantitative economic models utilise inappropriate discount rates that fail to adequately reflect the impact of potential future losses (Stern, 2008; DeFries et al., 2019). For example, the application of a high discount rate in the assessment of future risks tends to downplay the potential future impact, even if the risks have been correctly incorporated into the economic models. A discount rate of 3% per year, for example, would mean that the costs or losses incurred in 100 years would be devalued by approximately 95% today. Consequently, the interests of future generations would be undervalued, and the long-term consequences of policy decisions overlooked (Dennig, 2018).

The challenges of assessing sustainability transitions are exacerbated by the difficulty of defining an appropriate time horizon. CBA typically considers shorter time horizons, where impacts are easier to assess. However, sustainability transitions extend over long periods of time and the assumption of the marginality of changes becomes even more unrealistic. A focus on short time horizons therefore means that environmental policies with long-term effects, such as reducing greenhouse gas emissions or adapting to climate change, are not adequately assessed (Gössling et al., 2019). This one-sided perspective leads to a pessimistic distortion of environmental policies, as their long-term benefits are not sufficiently taken into account. At the same time, it creates an optimistic bias in the case of environmentally harmful policies, as their long-term costs are neglected (O'Mahony, 2019). Traditional CBA is therefore unable to adequately take into account the time dimension of these far-reaching changes.

In light of these challenges, the following chapter presents suggestions and recommendations on how CBA can be improved to make it a more effective tool for assessing system transitions.

4 Conclusions: Opportunities to improve economic assessments of sustainability transitions

Once the available evidence on the use of cost-benefit analysis[25] for sustainability transitions and its methodological limitations have been identified, the challenge is how to address the identified issues to better support policymaking and enable the assessment of a sustainability transition of key production and consumption systems. Based on the key findings of Chapter 2, conclusions are drawn on the status quo of the application of cost-benefit analysis for mobility transition as well as other sustainability transitions. Building on the methodological analysis in Chapter 3, further recommendations are added on how to adequately adapt cost-benefit analysis and its practise to be fit for purpose in the context of sustainability transitions. Additionally, the discussion of the results was shaped by feedback from experts working on transport policy and assessment methodologies at the EU level, as well as input from the Eionet Mobility group. All of these aspects are part of the overall goal of this analysis to identify solutions or opportunities to improve economic assessments supporting policy decisions in the context of sustainability transitions.

As described in previous chapters, the **lack of transparency and comparability** of CBAs is a major challenge. For many stakeholders, CBAs are often perceived as black boxes, as the underlying assumptions - in particular the selection and monetisation of impacts - are often not transparent. Although official guidelines for CBAs exist, as described in Chapter 1, there are major differences in the frameworks used in practice, particularly in the area of mobility and sustainability transitions, making comparability difficult. It is important to emphasise that many of the challenges discussed below, such as monetising externalities and assessing distributional impacts, are more related to the practical implementation of Cost-Benefit Analysis than inherent flaws of the method itself. Therefore, ensuring the proper application of the official guidelines outlined in Chapter 1 is important to help mitigate these issues, ensuring greater transparency and comparability.

Several relevant external benefits tend to be lacking in the reviewed CBAs. The externalities considered typically focus on CO_2 emissions and health issues. This is in line with other findings that climate typically receives more attention than other environmental issues, while aspects such as biodiversity and water quality are often overlooked (OECD, 2018). Apart from health and carbon, CBA for mobility transitions typically includes travel time, vehicle operating costs, accidents, noise and air pollution (Gössling et al., 2019). However, additional benefits of shifting to more sustainable modes of transport should also be taken into account, such as noise reduction, improved air, water and soil quality, more sustainable land use, impacts on infrastructure maintenance and changes in resource requirements (Gössling et al., 2019).

The recommendations from Gössling et al. (2019) on the externalities to include for mobility CBA are similar to the respective recommendations in the Handbook of External Costs of Transport (CE Delft et al., 2019). A more widespread application of the Handbook of External Costs of Transport to CBAs conducted on different regional levels would improve the validity of CBA results for mobility system transitions. As the externalities considered strongly influence the result, comparisons of the net benefits reported in different CBA studies should be treated with a lot of caution (see Annex 2 & 3 – comparison of considered costs & benefits).

Experts consulted for this analysis, who specialize in transport policy and assessment methodologies at the EU level, contend that the categories proposed by Gössling et al. (2019) are considered standard practice for cost-benefit analysis (CBA) in the mobility sector. However, some impacts such as biodiversity, water quality or the ecological costs of infrastructure, waste etc. are still less well known, making their inclusion in CBA still difficult. For these impacts not only the economic valuation but also the physical

[25] In this study, Cost-Benefit Analysis specifically refers to Social Cost-Benefit Analysis, as detailed in Chapter 1.

effects still need to be explored further. Noel et al. (2018) also suggest that CBA could take into account wider impacts such as economic security, avoided imports of oil or waste.

In the context of cost-benefit analysis for sustainability transitions, **overly simplistic assumptions and biases** are prevalent issues that lead to a distorted view of the transition processes. For example, certain types of behavioural shifts, such as changes in car occupancy rates, are often neglected. Certain aspects of sustainability transitions that can have big impacts, like certain long-term innovations (e.g. fully autonomous vehicles), or the impact of changing travel time costs associated with infrastructure improvements, are seldom included in transition scenarios. To address these issues, it is crucial to ensure transparency in the assumptions underlying the scenarios. Another important bias is the decisions being made about which areas of the sustainability transition are covered with cost-benefit analysis. For mobility transition there is a lack of systematic coverage of rural mobility transitions and the spillover externalities across different travel modes, which are essential for a holistic understanding of sustainability transitions. There needs to be a more balanced representation of different transport modes. Only CBA across different travel modes can also account for the spillover externalities that play a crucial role in sustainability transitions.

The reviewed CBA studies differ not only in terms of what externalities are covered, but also in terms of how those externalities were monetised. The **monetisation of externalities in CBA often places a strong emphasis on health benefits**. For instance, in the context of the energy transition, the health benefits from reduced air pollution are often considered more valuable than the climate-related advantages. Similarly, in CBAs for food transitions, health benefits tend to overshadow environmental benefits, particularly in the long term. As shown in Figure 4 (Chapter 2.2.1.), the intangible health benefits from mobility transition (refers to cost savings from e.g. pain, anxiety or the hypothetical costs for the value of life lost) show a large range depending on the valuation approach. In all urban mobility transition scenarios assessed by Wolkinger (2018), the intangible health costs surpass the sum of direct and indirect health effects from sustainability transitions by far. In the Handbook of External Costs of Transport, which is applied e.g. in Borgato (2021), the health costs are measured as numbers of fatalities as well as the direct and indirect health effects of air pollution and noise pollution. The Handbook also gives recommendations on which values to use for the intangible health costs measured as value of statistical life (VSL) or value of a life year (VOLY) (CE Delft et al., 2019). Beyond focusing solely on the external costs of transport, further analysis is required to examine the health benefits of active mobility, as explored by Wolkinger (2018) in the context of decarbonizing urban mobility in Austria. A comprehensive inclusion of the health benefits of active mobility in cost-benefit analyses for mobility system transitions is considered essential.

Furthermore, there are **different approaches for evaluation of CO_2** benefits from sustainability transitions. Some CBAs refer to old CO_2 prices, which are not consistent with the target of climate neutrality, e.g. Germany´s Federal Transport Infrastructure Plan 2030 (Mitusch and Szimba, 2024). Most reviewed studies use abatement costs approach for determining CO_2 prices, which evaluates the CO_2 price needed to reach a certain emission target. This approach still has the issue of choosing the right target. The Handbook of External Costs of Transport suggests to use the abatement cost approach and the target of the Paris Agreement to limit temperature rise to 1.5-2 degrees Celsius (CE Delft et al., 2019). Evaluations of system transitions frequently overlook the embodied emissions of vehicles and infrastructure, as well as the varying costs of mobility infrastructure across different countries. However, there are a few exceptions, such as Broeks et al. (2020), who, in their CBA on meat taxes and subsidies for fruits and vegetables in the Netherlands, incorporated the environmental impacts of food products using Life Cycle Analysis (LCA). A comprehensive inclusion of embodied emissions in EU assessments would likely put demand-side policies in a more positive light and lead to fairer outcomes. Beyond that, there are potential impacts of sustainability transitions that are generally very hard to quantify, e.g. due to lack of information as stated in the Better Regulation Toolbox 2023 (EC, 2023). If there is no monetary valuation for certain impacts, it should be considered whether it would be beneficial to commission a study to quantify these impacts in monetary terms. This decision should take into account whether it is feasible within available resources, whether it would produce reliable results, and whether the results would be valuable for future decision-making. **Impacts that cannot be meaningfully monetized should be described in non-monetary units or qualitative terms**, which can then be incorporated into alternative methods such as multi-criteria analysis (EC, 2023). This ensures that also costs and benefits that are hard to quantify are considered in the overall analysis.

It remains challenging that monetization approaches often prioritize health and time-saving benefits over environmental concerns. This issue is compounded by ongoing debates on how to properly evaluate time benefits, as these depend heavily on regional mobility infrastructure. Lastly, it is important to acknowledge the ongoing **challenge of capturing the full scope of averted costs from inaction**, beyond the direct environmental benefits. Experts consulted for this project emphasize the need for EU guidance to provide a comprehensive assessment of these costs and incorporate them into policy scenarios.

A full and accurate assessment of external costs and benefits is challenging, given the uncertainty, reliance on normative assumptions and need to ensure any assessment is proportionate given limited resources. **Sensitivity analysis should be conducted** in these cases to explore the sensitivity of expected outcomes to variations in key input variables. For instance, in the EU Impact Assessment accompanying the European Commission Communication, scenarios with lower valuations of external damages (climate change effects due to GHG emissions and health effects due to air pollution) show the best outcomes when sticking to existing decarbonisation trends, whereas higher valuations of externalities favour the most ambitious target scenarios, resulting in the highest net benefit (EC, 2024a). Alternatively, switching values can be estimated, which show the value an input variable would need to change to in order to make an option no longer viable.

In policy discussions, the focus is often on investment needs that reflect the cost of the transition and challenge in unlocking sufficient finance to meet climate targets. While studies assessing investment needs and investment gaps are an important tool to support policy-making, this focuses on investments as an economic cost. Yet investments are fundamentally about laying the foundations for future economic prosperity and well-being (OECD, 2022). **Focusing on investment needs as a cost without discussing the benefits therefore presents a distorted picture and one-sided policy discussion**. This underlines the importance of tools such as CBA that consider both costs and benefits equally to broaden the discussion and consider the benefits or cost-effectiveness of climate policies. Furthermore, it is not always clear what exactly has been included in the investment costs, as the approaches and assumptions differ between studies. Greater transparency on the costs included and the assumptions or methodologies used to assess investment needs would improve the comparability and reliability of these investment studies. When using investment studies as a source of information for cost-benefit analysis, different investment studies should be compared to account for potential outliers.

CBA is frequently the subject of criticism due to the failure to consider the **distribution of costs and benefits**. A CBA typically only assesses the socioeconomic welfare as a whole and does not account for distributional impacts (ESABCC, 2023; OECD, 2018). Whereas internalising environmental externalities on an individual level (e.g. CO_2 tax) can have potentially regressive impacts on consumers, internalising environmental externalities on a societal level in a CBA can have progressive impacts. This is because whereas the costs usually occur for specific stakeholders, health and environmental benefits are usually more evenly spread across society (e.g. Maier et al., 2023).

Furthermore, the European Scientific Advisory Board on Climate Change (ESABCC, 2023) and OECD (2018) note that there are reasons why identifying the winners and losers of the studied proposal would be valuable. In a lot of the reviewed CBA studies the **distributional aspects of sustainability transitions are addressed as a need for future research**, e.g. (Noel et al., 2018). There are also several social justice aspects concerning specifically sustainability transitions that need to be considered in the conduction of a cost-benefit analysis. The risks concerning the undesirable effects of the transitions can also be addressed directly with transfer programs. Ruggeri Laderchi et al. (2024) include in their CBA of global food transformation the specific costs covering the safety net support needed to keep food affordable for the poorest, because in their projected transformation pathway the price consumers pay for food may increase significantly.

In this context, the guideline for *Better assessing the distributional impact of Member States´ policies* published by the European Commission in 2022 provides a general framework for assessing socioeconomic effects of policies on vulnerable groups. During the expert consultations for this project, it was highlighted that the distributional effects of the sustainability transition on smaller companies require more attention, as they are more vulnerable to such changes. The consideration of distributional effects on smaller companies is also addressed on a general level in the Better Regulation Toolbox (EC, 2023). From an international justice standpoint, consideration of the impacts outside of Europe also merits further discussion.

In practise, the aim of having complete coverage of all possible external benefits of a transition including sensitivity analysis needs to be balanced against the need for proportionality, as the resources for conducting a cost-benefit analysis are limited. The **level of aggregation varies a lot between different CBAs** for sustainability transitions. The focus in the reviewed studies varied from the impacts of a specific policy connected to mobility transition and assessing the total social costs of ground based passenger transport for a country, to the EU impact assessment, where the CBA was conducted across different sustainability transition scenarios. There can be a dilemma between going into more detail and focusing or assessing a wider scope instead. Assuming the resources for conducting a CBA in transition context are set, a decision for a wider level of aggregation will go counter the feasible detail level in the assessment of related costs and benefits. The decision about the proportional aggregation level of the CBA should of course also consider societal goals and the regional level of actual decision making in the specific policy context.

In general, CBA is a valuable tool for supporting decision-making. It has the potential for more balanced consideration of not only costs but also benefits of sustainability transitions as it provides a comprehensive overview of the different impacts of a policy and its efficiency. This facilitates the comparison of alternatives and enhances transparency in the decision-making process. However, in order to exploit this potential, it is necessary to clearly communicate and justify the assumptions on which the CBA is based. Despite its clear comprehensibility, it should be noted that CBA cannot provide a complete picture of all costs and benefits and their values. Moreover, CBA is usually aimed at evaluating a single policy. Analysing a complex system transition involving several policies is therefore beyond the usual scope of CBA.

CBA is a tool to aid decision-making, and its results are dependent on the assumptions made, emphasizing the need for robustness in the results. **Traditional CBA assumes and works best where policy impact is marginal** (Barbrook-Johnson et al., 2024). It faces significant challenges in assessing sustainability transitions due to its assumptions of marginality, homogeneity, and certainty. The scenarios typically assume a smooth transition and market equilibrium, ignoring potential challenges and disruptions that could arise during a comprehensive transformation. These assumptions do not fully capture the complex, dynamic, and long-term nature of sustainability transitions. The application of CBA in the context of the climate transition often overestimates the costs while underestimating the benefits (Sharpe et al., 2020). Policymakers need to be aware of the limitations of CBA and how to ensure good practise of CBA when making decisions about sustainability system transitions. It is advised not to attempt to cover entire system transitions using CBA, as it cannot be made fit for purpose for such comprehensive analyses. However, it can be applied for aspects of sustainability transitions under adequate consideration of the complexities and risks of sustainability transitions. The use of CBA can still be valuable in understanding the impacts a policy may have including the distributional impacts, if those are comprehensively included in the analysis. Nevertheless, given its methodological limitations, it should not be used as a major decision criterion for sustainability transitions, but instead as one assessment within a wider appraisal framework.

The challenges and limitations for the application of CBA to sustainability transitions are also closely related to the general challenges of quantitative economic modelling of sustainability transitions. Quantitative economic models can be useful for evaluating the potential economic effects of policy decisions. However, they face significant limitations when applied to sustainability system transitions. These limitations include the underestimation or omission of potential future risks of climate change and inaccuracies in incorporating innovation and technological progress, leading to an underestimation of positive feedbacks and path dependencies associated with innovation and new technologies. There is also a **status quo bias**, as model inputs are usually based on data from past human experiences. Additionally, these models struggle with depicting the complexity of system transitions and tend to use monetary measures to evaluate climate impacts, which may not accurately reflect the potential damages to lives and livelihoods. Transition scenarios often presume that agents behave rationally, overlooking the complexity of real-world behaviour changes. Additionally, the dynamics involved in the innovation process (like path dependencies, feedbacks and knowledge spillovers) are often inaccurately represented in these analyses.

To address these limitations, several adjustments to modelling approaches can be made. These include incorporating fat tail events to account for large, concurrent climate impacts, and **better understanding and incorporating innovation and technological progress** by considering knowledge spill overs, network effects, switching costs, feedbacks, and complementarities. This can be informed by examining past technological developments, such as the spread of mobile telephone and the associated dynamics. In addition, uncertainty about future developments of technology prices should be factored into the analysis. Furthermore, **accounting for the complexity of system transitions** by adding complexity dynamics and agent heterogeneity is crucial. A variety of sustainability goals should be considered together with other criteria. Moving towards a wider set of considerations (and away from CBA) by **incorporating uncertainty and assessing risks and opportunities** is also necessary, when analysing complex sustainability system transitions. Alternative approaches like risk-opportunity analysis (Sharpe et al., 2020) or multi-criteria analysis (Marleau Donais et al., 2019) address some of the shortcomings of CBA and can be used alongside CBA to paint a more balanced picture of sustainability transitions.

Policy makers need to keep these limitations of quantitative economic modelling in mind when making decisions based on cost-benefit analysis for sustainability system transitions. The question on suitability of CBA for sustainability transitions also needs to take into account the overall **decision-making procedures** the CBA analysis is embedded in. Unbalanced decision procedures between CBA and other tools can be problematic, where higher emphasis is given to the CBA result. It is not enough to take other decision-making tools next to CBA into account. A balanced valuation between various decision criteria and different evaluation tools for decision-making must be ensured. **When deciding for the best policy option, the net-benefit, being the result of a CBA, only represents the aspect of efficiency.** Other methods should be used in decision-making, either in tandem with or instead of CBA. An example for an alternative method is for instance, multi-criteria evaluation, a non-monetary approach to ex-ante assessments (Munda, 2019). It aims to achieve a comparability of incommensurable metrics and thus allowing a plurality of criteria and perspectives besides efficiency to be considered. Another approach for analysing system transitions can be a risk-opportunity analysis, which moves away from quantifying every possible outcome and focuses on assessing all significant opportunities or risks, whether quantifiable or not (Sharpe et al., 2020). Future research could focus on analysing the application of multi-criteria evaluation and risk-opportunity analysis for mobility or other system transitions.

Considering the aspects of effectiveness, coherence, proportionality and subsidiarity might lead to a different choice in policy. A positive example of a balanced decision-making process is the European

Commission's Impact Assessment on the use of railway infrastructure capacity in the single European railway area (EC, 2021b). In this case, the option chosen was not the most efficient according to the CBA, but the one that offered **the best balance between effectiveness, coherence, proportionality, and subsidiarity**. The Federal Transportation Infrastructure Plan 2030 (FTIP 2030) in Germany demonstrates how CBA is used within a broader multi-criteria decision-making approach. However, critics argue that the framework of FTIP 2030 ultimately hampers an ambitious mobility transition, as environmental factors are underrepresented in the CBA, and more weight was given to the CBA than to the strategic environmental assessment (Mitusch and Szimba, 2024; Agora Verkehrswende, 2023). In summary, the decision-making framework CBA sits within can be just as important as the CBA framework itself.

Some of the challenges in implementing CBA in the context of mobility transitions may mean the costs are overestimated while benefits are underestimated. Still, it is interesting to note that all reviewed CBAs for ground-based passenger transport, food and energy **decarbonisation had a positive net benefit, increasing with the level of ambition**, at least in the long run and without claim to completeness of all existing CBAs for sustainability transitions. The net benefit usually rises with ambition level of sustainability scenarios because of the significant benefit of environmental costs savings. Additionally, for mobility transition, the combination of demand and supply-side policies led to best outcomes. Furthermore, the assessments of the spillover effects can have large benefits in other sectors (e.g. V2G). This suggests that while some of the challenges in implementing CBA may skew results, CBA would still support policy decisions for sustainability system transitions.

Given the limitations of CBA in the context of sustainability transition, depending on the scale of the policy scenario and change it seeks to deliver **CBA should be used as one assessment within a wider appraisal framework instead of a major decision criterion**. When applying cost-benefit analysis to sustainability transitions, special attention should be given to enhancing transparency and comparability, addressing distributional impacts, refining decision-making frameworks, and accounting for the methodological challenges inherent in using cost-benefit analysis to assess systemic transitions. For a summary of recommendations, refer to Box 3 on the following page.

Box 3: Overview Recommendations for CBA of Sustainability Transitions

- **Improving transparency and comparability:**
  - When conducting CBA, ensure transparency on covered types of costs and benefits. Also address the cost and benefits that cannot be monetised.
  - When available, apply EU guidelines for monetisation of externalities to increase comparability between studies. → Handbook of External Costs of Transport (CE Delft et al., 2019)
  - Examine underlying simplifying assumptions in the limitations section of CBA studies.
  - Provide more detailed information on costs included and the assumptions and methodologies used to assess investment needs.

- **Consideration of distributional impacts:**

Place higher emphasis on distribution of costs and benefits of sustainability transitions as entailed in the CBA implementation steps in the Better Regulation Toolbox (EC, 2023) and *Better assessing the distributional impact of Member States' policies (EC, 2022)*.

- **Consideration of decision-making frameworks:**

Ensure balance between decision criteria effectiveness, coherence, proportionality and subsidiarity, rather than focusing purely on CBA net benefit and its effectiveness logic.

- **Accounting for methodological challenges of CBA:**
  - Careful consideration of insufficient risk analysis, the complexity of system transitions, technological progress, and other path dependencies is necessary to avoid overstating costs and understating benefits.
  - CBA alone can be suitable for incremental changes, but should be used alongside other decision-making tools for broader or more transformative policies e.g. multi-criteria-analysis, risk-opportunity-analysis.

5 List of abbreviations

Abbreviation	Name	Reference
BAU	Business as usual	
BMDV	Federal Ministry of Transport, Building and Urban Affairs (Germany)	
CBA	Cost-benefit analysis	
CIVITAS	City-Vitality-Sustainability (European Union Initiative)	www.civitas.eu
CO	Carbon monoxide	
CO_2	Carbon dioxide	
EEA	European Environment Agency	www.eea.europa.eu
EIT	European Institute of Innovation and Technology	www.eit.europa.eu
ELTIS	The EU Urban Mobility Observatory	www.eltis.org
ETC ST	European Topic Centre on Sustainability Transitions	www.eionet.europa.eu/etcs/etc-st
EU	European Union	
FCV	Fuel cell electric vehicles	
FTIP	Federal Transportation Infrastructure Plan	2030-federal-transport-infrastructure-plan.pdf (bund.de)
GDP	Gross domestic product	
GHG	Greenhouse gases	
IAM	Integrated assessment model	
ICEV	Internal combustion engine vehicles	
LCA	Life cycle analysis	
LULUCF	Land use, land-use change and forestry	
MCA	Multi-criteria decision analysis	
NOx	Nitrogen oxides	
pkm	Passenger-kilometer	
PM2.5	Particulate matter 2,5 micrometers	
TEN-T	Trans-European Transport Network	Trans-European Transport Network (TEN-T) - European Commission (europa.eu)
V2G	Vehicle-to-grid	
VOC	Volatile organic compounds	
VOLY	Value of life year	
VSL	Value of a statistical life	

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Annex 1

Table A1 Energy and mobility investment needs at EU level for a sustainability transition

Investment category	Sector	Scope of transition	Time horizon	Annual investment costs	Reference
Additional annual investment needs for delivering on European Green Deal (EGD) objectives	All necessary sectors, especially energy, transport and buildings	European Green Deal, net zero by 2050	2021-2030	EUR 522 billion	EC, 2022
Annual average climate investment need for the EU to reach its climate objectives in the energy, buildings, and transport systems	22 sectors that are critical for the transformation of energy, building and transport systems	European Green Deal, net zero by 2050	2024-2030	EUR 813 billion	I4CE, 2024
Investment needs for climate-relevant infrastructure until 2035	Energy & transport	European Green Deal, net zero by 2050	2021-2025	EUR 302 billion	Klaaßen & Steffen, 2023
Average annual investment needs in transport	Transport (road, rail, aviation, domestic navigation, international maritime, alternative fuel infrastructure)	S1: climate neutrality 2050 S2: reduction of 85% by 2040, climate neutrality 2050 S3: reduction of 90% by 2040, climate neutrality 2050 LIFE: no specific target	2031-2050	S1: EUR 870 billion S2: EUR 873 billion S3: EUR 869 billion LIFE: EUR 787 billion	EC, 2024
Average annual energy system investment needs	Energy	S1: climate neutrality 2050 S2: reduction of 85% by 2040, climate neutrality 2050 S3: reduction of 90% by 2040, climate neutrality 2050 LIFE: no specific target	2031-2050	S1: EUR 661 billion S2: EUR 664 billion S3: EUR 666 billion LIFE: EUR 619 billion	EC, 2024
Investment required to implement the TEN-T Regulation (multimodal transport network in the EU)	Transport	European Green Deal, net zero by 2050; objectives of the Sustainable and Smart Mobility Strategy	2021-2030 2021-2050	Investment in the core network: EUR 500 billion Investments for the whole network (incl. the core network) and other transport infrastructure projects: EUR 1.5 trillion	EC, 2021

Annex 2

Table A2 Cases for Cost-Benefit Analysis for mobility transition in the EU or EU member countries

Scope of CBA analysis	Market internal costs & benefits considered	External costs & benefits considered	Reference
EU (all 779 EU27 cities) **Decarbonisation of urban mobility, 2030 and 2050 (cumulated from 2019)**	City total costs and revenues: Public Administration and External Providers; External Providers defined as providers of services that are not directly operated by the public administration (e.g., car sharing, bike sharing, public transport, etc.)	CO_2 -emissions, air pollutant emissions NOx, VOC, CO and PM2.5), noise and as well as fatalities and injured people caused by accidents	Borgato et al., 2021
Austria (Graz, Wien, Linz) **Decarbonisation of urban mobility 2025 targets compared to baseline 2010**	Investment and operating costs	direct and indirect health benefit[26] from improved air quality and increased physical activity, intangible health benefits (VOLY & VSL)	Wolkinger et al., 2018
Denmark **Electric vehicle deployment, including and excluding "vehicle-to-grid" (V2G)**	Private costs of electric vehicles	CO_2 -emissions, health	Noel et al., 2018
Hydrogen-based transport in Europe Replacement of ICEVs with Fuel Cell Vehicles that use hydrogen gas as a fuel source	Total Costs of Ownerhip (Purchase Price, Running Costs, Infrastructure Investment for Hydrogen Refueling Stations)	CO_2 -emissions, additional platinum depletion for fuel cell vehicles	Cantuarias-Villessuzanne et al., 2016
Germany **CBA for transportation infrastructure planning until 2030 in Germany (Federal Transportation Infrastructure Plan 2030)**	Investment costs, operating costs, change in operating and maintenance costs of transport routes	Travel time, transport time benefits of cargo, reliability, implicit benefits, traffic safety, noise pollution and exhaust emissions, lifecycle emissions of greenhouse gases from infrastructure, change in local separation effects (waiting times and detours for pedestrians), benefits of competing modes of transport	BMDV, 2016
EU **Impact Assessment on the use of railway infrastructure capacity in the single European railway area, amending Directive 2012/34/EU12 and repealing Regulation (EU) No 913/201013**	Administrative costs, adjustments costs and adjustment costs savings; increase in capacity (additional traffic) and increase in punctuality; macroeconomic assessment in terms of positive impacts on GDP and employment	CO_2 -emissions, air pollutant emissions and road accidents (fatalities and serious injuries), as well as the external costs of congestion social impacts in terms of impacts on employment, public health, road safety and fundamental rights	EC, 2021a
Austria **Ground based passenger transport (all modes), year 2040**	Privately born costs: vehicle costs, other	Accidents, air pollution, climate change, congestion, noise, well-to-tank-emissions, habitat damage, health benefits, barrier effects (barrier to switch to active modes of transportation), travel time costs across travel modes	Maier et al., 2023

[26] As explained before in Chapter 2.2: Health benefits are not purely externalities. For instance, the health benefits derived from active mobility are internal benefits from the cyclist's perspective. However, health benefits from active mobility also lead to reduced government healthcare spending which is an external benefit. To maintain brevity and because health impacts are predominantly considered as market external costs, health benefits are referred to as external benefits in the rest of the study.

Annex 3

Table A3 Cases for Cost-Benefit Analysis for energy and food sector transition in the EU or EU member countries

Scope of CBA analysis	Market internal costs & benefits considered	External costs & benefits considered	Reference
EU **EU's transition to climate neutrality until 2040**	Mitigation costs: Energy system cost, Non-CO_2 and LULUCF costs	(Avoided) costs of climate change and air pollution	EC, 2024
EU **EU's energy system transformation**	Investment needs; benefits from investments; benefits from EU ETS and Taxonomy Regulation; benefits from a more integrated EU energy market, development of renewable energy and an increased energy efficiency, benefits from a fair transformation	(Avoided) costs of climate change	Heflich & Saulnier, 2021
Italy **Decarbonisation scenario of the energy system in Italy**	For energy sector: investment costs and saved energy costs	For energy sector: benefits from reduced air pollution, morbidity, and mortality	Sofia et al., 2020
Global **Food System Transformation**	Investment needs; safety net support to keep food affordable for the poorest	Costs of GHG emissions, freshwater use, land use conversion, nitrogen pollution, under- and over-nourishment, poverty, and dietary risks	Ruggeri Laderchi et al., 2024
Netherlands **Tax on meat and subsidy on fruit and vegetables**	Tax income and subsidy expenses; changes in productivity and consumer surplus	Health effects; Environmental effects: costs of GHG emissions, acidification, eutrophication of salt and fresh water, and land use	Broeks et al., 2020

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