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Sustainable global automobile transport in the 21st century: An integrated scenario analysis

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Abstract

Transport represents a significant threat to long-term sustainable development, and is one of the fastest-growing consumers of final energy and sources of greenhouse gas emissions. Moreover, transport is heavily reliant on petroleum, a limited resource that is also associated with geopolitical risks to security of supply. Together, threats to the global environment and limited resource availability warrant a closer examination of possible pathways to a sustainable transport system. This study describes a sustainable automobile transport scenario based on the SRES B2 scenario, but with key demographic and economic drivers updated to incorporate developments between 1990 and 2000, and revisions to population projections. Multiple sustainable development objectives are incorporated, including: i) continuing economic growth, with a moderate reduction in disparities in income between different world regions; ii) maintaining a buffer of oil and gas resources to enhance security of energy supply, both globally and in vulnerable regions; iii) abating greenhouse gas emissions to ensure atmospheric CO_2 concentrations do not exceed double pre-industrial levels; and iv) ensuring global mobility demands are met, without resorting to assumptions about a large counter-trend shift to public transport or lower travel demand. We then explore the technological, economic, fuel production and infrastructure implications of realizing this scenario over the long term. This provides a number of policy insights by identifying critical developments required for the emergence of a sustainable global passenger transport and energy system.

Keywords: Sustainable development; Climate change; Energy security; Technological change; Hydrogen; Transport; Automobiles

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1. Introduction

Realising the goals of sustainable development represents a significant challenge to humankind. The challenge of sustainable development—creating a livable future world in which human needs are met whilst maintaining the natural systems that support these needs—encompasses social, economic and environmental dimensions, and requires a long-term systematic perspective and the integration of many different elements. Critical among these elements are global energy and transport systems, and redirecting the development of these systems onto a sustainable path is becoming an increasingly important concern and policy objective [1–4].

The current development trajectory of the global transport system, which is one important part of the overall energy system, poses a number of threats to sustainable development. These threats include the possible impact of anthropogenic climate change and risks to long-term security of the global energy supply. Looking first at climate change, there is mounting evidence of human interference with the Earth's climate system and this has lead to concern about possible serious adverse impacts resulting from future global climate change [5]. Realising a sustainable transport system with a low impact on the global climate, but that still achieves other long-term development goals, may require profound and wide-reaching changes [6]. Security of energy supply, on the other hand, is seen as a more pressing concern given the current overall dependence of OECD countries on oil supplied from politically volatile regions (e.g. [2,7,8]). The combined impact of increasing global energy demand and eventual depletion of resources poses further serious long-term challenges to maintaining access to affordable and secure sources of energy, and appropriate policy responses may also require major changes to the global energy system.

Transforming global social and economic systems, including global transport systems, from their current structure to one that is compatible with sustainable development is likely to be a long-term process involving continual change to a range of physical, technological and institutional systems. Understanding how this long-term process might unfold may help guide policy responses aimed at achieving the long-term strategic goals of sustainable development. The objective of this study is to explore one possible trajectory for the transformation of the global energy and transport system by building a long-term (until 2100) energy–economy–environment (E3) scenario. Such scenarios are useful for enhancing our understanding of highly complex systems, such as the future development of the global transport system, and for guiding responses to long-term challenges. Importantly, however, scenarios are not intended to be predictions, but enable us to explore plausible questions of "what if" related to key future uncertainties.

In this study we use an E3 scenario based on the B2 storyline from the IPCC's Special Report on Emissions Scenarios [9,10] to explore a number of issues related to the role of private transport and personal mobility in sustainable development. One of the specific questions we will attempt to address with this E3 scenario is if and how satisfying demand for personal mobility in the developed regions of the world, and achieving the mobility aspirations of the developing world, can be compatible with long-term sustainable development—defined here as encompassing economic growth, climate change mitigation and maintenance of security of energy supply. This will at very least provide an indication of whether it may be necessary to restrict access to particular modes of transport, even though this may undermine other aspects of development and human welfare.

Importantly, in this analysis we explore in detail only one possible configuration of the future global E3 system, even though significant social, economic, environmental, technological and political uncertainties mean that many pathways are possible. However, a single scenario that is carefully defined, internally consistent and intuitively plausible can provide important additional insights about technological developments and possible targets for policy support.

Moreover, this approach focuses the analysis on to the role of future technology choices in a possible transformation to a sustainable world. In this analysis we investigate in detail the transport sector technologies and energy carriers most characteristic of sustainable development (see [11,12]). The early identification of technologies with the potential to accelerate, or help overcome potential barriers to, the transition to a sustainable energy system is essential for providing guidance to policy makers about the most appropriate forms of support needed to achieve long-term sustainability strategies [13].

Within this context there has been a substantial debate on the role and possible early introduction of hydrogen (H_2) fuel and fuel cell (FC) vehicles in a long-term sustainable transport system (see e.g. Keith and Farrell [14], Azar et al. [15] and Wokaun et al. [16]). However, given that H_2 and FCs are immature and expensive technologies and much of the necessary supporting infrastructure does not yet exist, it is unclear along which pathways a so-called ‘hydrogen economy’ could emerge. This is one of the many issues this analysis will seek to explore. Moreover, transport systems based on alternative fuels such as hydrogen may not necessarily be compatible with sustainable development, since they may rely on energy intensive synthesis pathways using fossil fuels. This highlights the importance of considering the transport sector in conjunction with the broader energy system, particularly fuel production.

Accordingly, for this long-term analysis we use ECLIPSE, an integrated policy assessment tool [17], to estimate key scenario variables and ensure engineering consistency within the energy and transport sector, and to incorporate economic feedbacks on energy and transport demand. ECLIPSE also includes endogenous technology change, and a detailed representation of transportation technologies. In this study we apply ECLIPSE to develop a technological road map to a sustainable transportation sector.

Given this overall plan, the remainder of this paper is organized as follows. In Section 2 we describe some of the main elements of the scenario used in this analysis, and describe key assumptions about the implementation of sustainable development. Section 3 then briefly describes the ECLIPSE modelling framework used in this analysis to generate the scenario results, which are presented in Section 4 where we focus on the role of new technologies and fuels. Section 5 discusses some policy and technology development insights, related particularly to potential targets for public support to facilitate the realization of a sustainable transport and energy system.

2. Scenario drivers

2.1. Basic scenario drivers

To explore the possible emergence of a sustainable transport system we start by selecting from a set of existing E3 scenarios a scenario with suitable demographic, economic and social driving forces. We then build on this scenario of basic driving forces to incorporate the elements necessary to investigate sustainable transport in more detail.

Importantly, many pathways of future demographic, social and economic development are possible, leading to many possible sustainable development outcomes. For example, among the 40 scenarios presented in the Special Report on Emissions Scenarios (SRES) from the Intergovernmental Panel on Climate Change [9], several describe future worlds in which the basic economic and social drivers are consistent with a number of the principles of sustainable development [18]. However, in exploring the potential emergence of a sustainable energy and transport system we want to avoid using a scenario that relies on heroic or utopian assumptions that are inconsistent with current institutions and driving forces, since such a scenario is less likely to offer useful policy insights.

For this reason, as a starting point we selected the B2 storyline from the SRES [9,10]. The B2 storyline describes a world in which demographic, economic and technological drivers are in the centre of the range of SRES storylines. However, the economic and demographic trends in B2 also reflect some of the elements of a sustainable development scenario, including continued economic development and some convergence in global incomes. B2 also represents a world where there is a strong emphasis on local solutions to economic, social and environmental sustainability, which makes it well-suited for examining sustainable development [9]. Importantly, the B2 scenario does not diverge significantly from historical and prevailing trends, and relies on existing institutional frameworks. By using such a scenario we can assess whether these frameworks and trends are incompatible with sustainable development, and hence whether there is a need to break from existing structures. Nonetheless, future developments are highly uncertain, and no single scenario can encapsulate the inevitable and unpredictable political and other developments likely to occur over the timeframe of this analysis. However, by restricting the socio-political scope of this analysis to a scenario based on existing institutions and current trends in many world regions, the results presented in subsequent sections may have greater near-term relevance and can be directly understood in terms of current institutions and drivers.

For this analysis we updated the B2 scenario driving variables to account for actual changes between the base year used in the SRES (1990) and 2000, and to include revisions to future population projections [19]. Specifically, we used the actual year 2000 population estimates and the latest UN medium

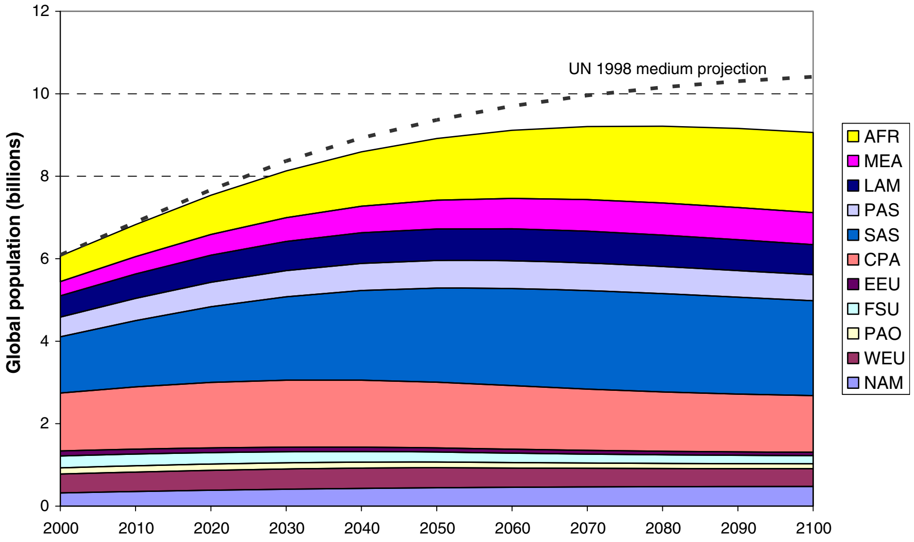

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Fig. 1. Global population scenario, UN 2004 medium projection. (Source: UN [19]).

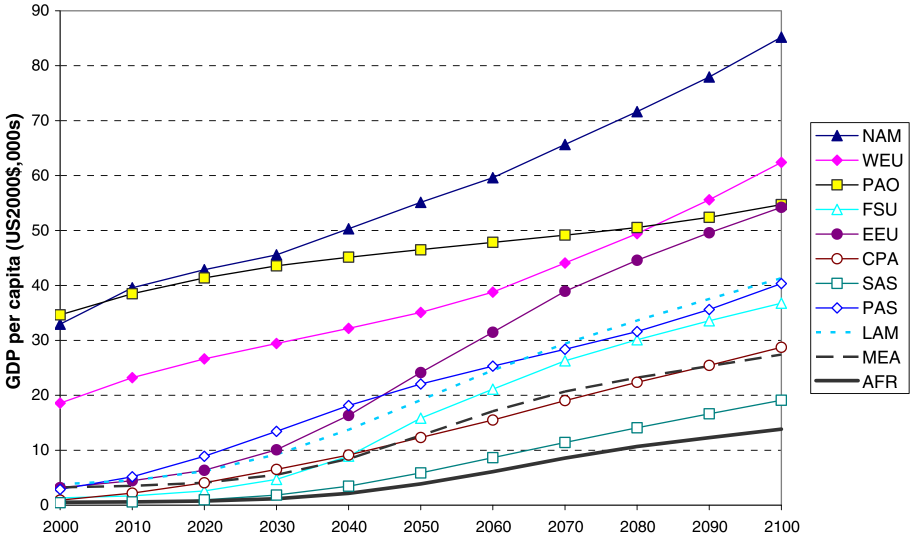

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Fig. 2. Economic growth scenario, based on SRES B2 (Source: derived from Miketa [21], Riahi and Roehrl [10] and Riahi [22]).

population projections to 2100 instead of the 1998 UN medium projections adopted in the SRES for long-term population growth under the B2 scenario. This ensures that the scenario used here is consistent with up-to-date median population growth trajectories. Fig. 1 shows the population in each world region over the period 2000–2100 under this scenario, and compares the total population with the SRES B2 population scenario.

In addition, we applied B2 economic growth rates from the year 2000 onwards, and used actual estimates of GDP in 2000 rather than the SRES-projected levels of GDP (for a comparison between the SRES and actual developments between 1990 and 2000, see van Vuuren and O'Neill [20]). Economic growth in each world region is presented in Fig. 2. We also calibrated the scenario to year 2000 energy demands [23,24], and used B2 energy intensity projections to calibrate the modelling framework described in Section 3.

2.2. Transport scenario

Future transport demand is uncertain, but there is an expectation that transport activity will experience rapid growth over the 21st century as incomes in developing countries rise, with a concomitant increase in energy consumption.[1] In passenger transport, without either a substantial reduction in demand for mobility or a shift towards public transportation (mass transit), both of which run counter to current global trends, curtailing this growth in energy demand is a significant challenge.

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[1] For example, some of the nearer-term projections suggest that global transport energy demand could increase to 120–135 EJ by 2020 [25,26], with the lower estimate consistent with consumption of 145 EJ by 2030 [26], compared to around 80 EJ in 2000.

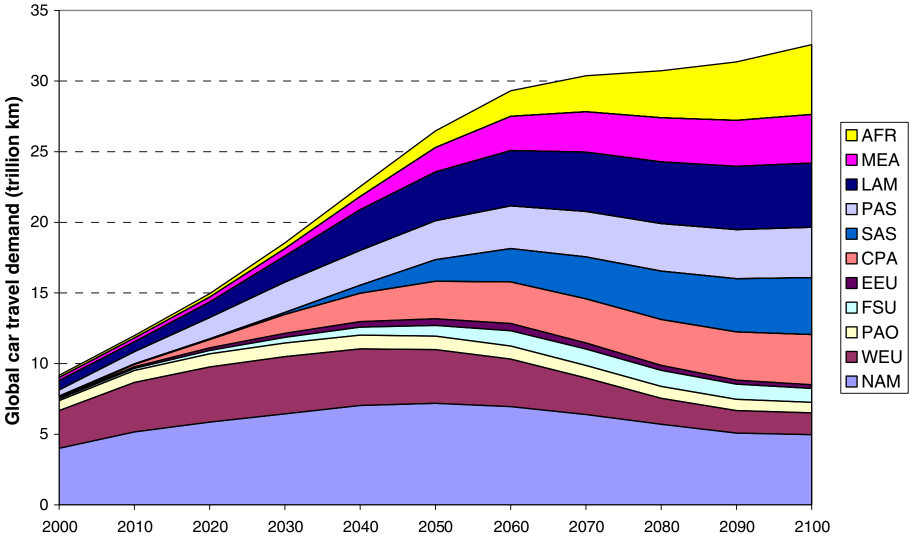

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Fig. 3. Automobile transport, calibration scenario.

In this subsection, we apply the broad socioeconomic drivers from the updated B2 scenario described above to develop a long-term scenario of automobile transport demand. It must be noted, however, that in developing this transport scenario we deviate from the B2 storyline, which relies on very optimistic developments in passenger transportation. Specifically, under the B2 storyline "[u]rban and transport infrastructure is a particular focus of community innovation, contributing to a low level of car dependence and less urban sprawl" (Section 4.3.4 in [9]). However, given other elements of the B2 storyline this represents a somewhat courageous assumption. In particular, the gradual changes in demographics, geopolitics, productivity, technology and other "salient scenario characteristics" in the B2 scenario (Section 4.4.2.4 in [9]), do not appear to be consistent with rapid changes in systems with high inertia, such as transport infrastructure and urban form. Moreover, the B2 storyline envisages a continued reliance on current institutional frameworks (Section 4.3.4 in [9]) which have generally shown themselves unable to shift trends in personal mobility towards lower car dependence.[2]

Accordingly, we developed for this study a scenario of future passenger transport demand to 2100 that reflects a continuation of current trends. This scenario is constructed using the work of Turton and Barreto [27] who developed a scenario of transport demand based on a B2 scenario using an enhanced version of the passenger transportation demand model of Schafer and Victor [28].[3] This model estimates future

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[2] In addition, if one simply makes the assumption that there will be low levels of car dependence, than one can solve many of the potential challenges to sustainable development immediately. This provides very few policy insights, and so is not particularly helpful.

[3] The original model of Schafer and Victor [28] projects total demand for passenger travel (in passenger-km), shares of various modes and vehicle occupancy rates to 2050 for the IS92a/e scenario [29] based on stable time and money share budgets. It was necessary to modify the original model to extrapolate these projections beyond the original income range to cope with a different income scenario and timeframe.

demand based on passenger travel money budget shares of income and time budgets, which are historically and cross-regionally stable [30]. Importantly, this model does not project freight transport demand, and this demand is instead modelled in aggregate using the growth rates in total transport energy demand from the B2 scenario [10,22].

Using this approach, and the basic B2 scenario drivers described in Section 2.1, we developed the automobile transport demand projection presented in Fig. 3, in which total demand increases by around 250% over the century (an average of 1.26% pa). Most of this growth occurs in developing regions, whereas in developed regions a combination of low population growth (or a decline), and a shift to faster modes of transport mean that total demand in 2100 is at around the same level as in 2000. Since these regions accounted for more than 80% of demand in 2000, the demand projection presented in Fig. 3 implies an average 15-fold increase in developing country automobile travel demand. In conjunction, we developed an air transport scenario consistent with this automobile demand projection, in which global air transport demand increases by more than 21-fold between 2000 and 2100 (not shown). This multi-modal scenario differs to that presented in Turton and Barreto [27] because an updated population projection is used here, as discussed above. Importantly, this 'what if' transport scenario does not envisage a major shift to greater use of public transport (mass transit), a redesign of urban areas, or any significant attenuation of demand growth arising from information or communications technology. In many ways, this is consistent with other aspects of the B2 storyline.

Having developed this scenario, we use it to calibrate the models used in this analysis, as discussed in Section 3.

2.3. Sustainable development objectives

Another key driver assumed in the sustainable transport scenario described in this study is sustainable development. As discussed in the introduction, we focus on three key aspects of sustainable development. The first of these is continuing economic growth, with a moderate reduction in income disparities between different world regions. This is represented by the economic growth trajectories presented in Fig. 2. Although substantial differences in income persist under this growth scenario, there is a considerable improvement in distribution of income. For instance, it is possible to calculate a global Gini index [31] from the information in Figs. 1 and 2, and this index improves substantially from around 71.5 in 2000 to 36.7 by 2100.[4]

The second element of this sustainable development scenario is related to the need to ensure access to energy supplies, which implies a need to manage effectively long-term threats to security of energy supply. This encompasses reducing exposure to the risk of supply disruptions by a combination of diversification, demand reduction, and maintaining domestic production capacity and resources. In developing this scenario, this is assumed to be implemented on a regional level and global level. Regionally, those regions most dependent on oil and gas from external sources are assumed to maintain an aggregate resources-to-consumption ratio of 20 years and maintain capacity to ramp up production rapidly in the first half of the 21st century, as described in more detail in Turton and Barreto [33]. Globally, it is assumed that the resources-to-production ratio (Rsc/P) for oil

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[4] Although not directly comparable to within-country Gini indices, for illustrative purposes the level of the global index in 2000 exceeds the level in some of the countries with the largest income disparities, such as Namibia, Colombia and Sierra Leone, while the index in 2100 is similar to countries with more moderate distributions such as Australia and the United Kingdom [32].

and gas is maintained above 30 years throughout the century as a hedge against unforeseen requirements or supply disruptions.[5] Clearly, resource assumptions affect the stringency of measures aimed at achieving this goal. In this scenario, we apply resource estimates from Rogner [34] for oil and gas that include conventional reserves and resources, enhanced recovery, identified unconventional reserves and unconventional resource estimates (Categories I–VI using Rogner's notation)—for oil this is equivalent to roughly 5500 billion barrels, which is consistent with other recent estimates (for example, see Odell [35]).

The third element of sustainable development included in this analysis is the need to mitigate climate change through greenhouse gas emissions abatement. In developing the scenario described in this paper, we assumed that global efforts seek to limit atmospheric carbon dioxide (CO_2) concentrations to 550 ppmv or below throughout the 21st century, with concentrations declining at the end of the century.

In the next section we describe the methodology applied to combine these scenario drivers and thereby explore the possible emergence of a sustainable transport system.

3. Modelling and scenario framework

3.1. The ECLIPSE integrated assessment model

The possible transition towards a sustainable passenger transport system cannot occur in isolation to developments in the overall energy system or broader economy. To ensure that such developments and interactions are considered in our analysis we employ the ECLIPSE (*E*nergy and *Cli*mate *P*olicy and *S*cenario *E*valuation) integrated assessment model that incorporates the detailed bottom-up energy systems model ERIS with macroeconomic and passenger transport demand models [17]. ECLIPSE models and integrates feedbacks between economic activity, transport demand and the energy system iteratively. In addition, ECLIPSE is linked to the MAGICC climate model [36,37]. This combination of features makes this integrated model ideally suited to analyzing the technological, economic, resource and environmental implications of future transport demand. We briefly describe the main elements of the modelling framework below.

3.1.1. The ERIS model

ERIS (*E*nergy *R*esearch and *I*nvestment *S*trategies) is a "bottom-up" energy optimization model that includes a detailed representation of technologies and technology dynamics. ERIS is a global multi-regional model that endogenizes technological learning curves [27,38–41]. It models energy demands and technologies in electric and non-electric sectors, covering transportation and thermal needs, in addition to fuel production technologies, specifically for hydrogen,[6] alcohols and Fischer–Tropsch liquids production. For transportation, ERIS distinguishes 17 distinct technology–fuel combinations, including 10 technology–fuel combinations for the private automobile (see Turton and Barreto [27]), making it well-suited to studying the potential impact of technological change on the possible emergence

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[5] It should be noted that this resources-to-production ratio differs from the commonly quoted 'reserves-to-production ratio', which is calculated based on identified reserves at a given point in time (which is a function of, among others, technology and prices), rather than ultimately recoverable resources.

[6] Now also including electrolysis using baseload electricity (based on data from [42]).

of a sustainable transport system, particularly sustainable automobility. ERIS also models other aspects of sustainable development, including resource availability (based on Rogner [34]) and GHG abatement options for several non-CO_2 greenhouse gases [43], as well as geological and forest sinks [44].

3.1.2. Macroeconomic model

ERIS is linked with the macroeconomic model described in Turton [17]. The development of this macroeconomic model was guided by previous work by Messner and Schrattenholzer [45], Manne et al. [46,47] and Kypreos [48]. In this model, the broader economy in each world region is modeled using a production function with constant elasticity of substitution between nested non-linear Cobb–Douglas functions of capital and labour, and energy and freight transport (see Turton [17]). Economic output is divided between consumption, investment and expenditure on energy (and freight transport), with the model seeking to maximise discounted utility (a function of consumption) in each world region.

This element in the modelling framework ensures that feedbacks between energy system and economic development are incorporated. Consequently, freight transport and energy demands respond to changes in fuel prices, and the overall economic impact of particular developments can be gauged.

3.1.3. Transport module

As mentioned above, the macroeconomic model estimates freight transport demand, but passenger transport is assumed not to be an input into economic production. Passenger transport demand is instead estimated using a model based on the work of Schafer and Victor [28], who estimated future demand for passenger transportation according to consumer money and time budgets, and the price and speed of different transport modes. Importantly, the transport model in the ECLIPSE framework does not project future transport demand, but examines how a scenario of future transport demand responds to changes in energy prices. Accordingly, we use the automobile and air transport scenario in outlined in Section 2.2 and presented in Fig. 3 (based on Turton and Barreto [27]) to calibrate the passenger transport model and estimate consumer travel budgets, which are used to estimate the share of income devoted to private motor vehicle and passenger air travel in each time period (and in each region). The travel money budget shares and time budget are then assumed to be independent of energy prices and economic growth.

As mentioned above, the macroeconomic, transport and ERIS sub-models described above are integrated in ECLIPSE to incorporate feedbacks between economic activity, transport demand and the energy system. This framework has similarities to other integrated models such as MERGE [46] and MESSAGE-MACRO [45], but with additional transport sector detail.

The next section presents the scenario developed using the key drivers described in Section 2, with the methodology discussed above.

4. Scenario results

4.1. Sustainability indicators

The main driving forces under this scenario include continuing economic growth, climate change mitigation, and enhancement of long-term energy resource security (see Section 2). To illustrate the impact of these drivers, a number of key indicators of sustainable development are presented in Fig. 4, including atmospheric concentrations of CO_2, the global resources-to-production ratios (Rsc/P) for oil and gas, and economic growth. These macro indicators are calculated from the output of the modelling framework described in Section 3, based on the scenario described in Section 2. Fig. 4 shows that under the sustainable transport scenario developed in this analysis, global atmospheric CO_2 concentrations peak at 550 ppmv in around 2085, global Rsc/P ratios stay above 40 years throughout and are increasing at the end of the century—that is, they stay above the 30 year policy target described in Section 2.3—and economic growth continues throughout the century.

For comparison, in the absence of sustainable development drivers, global atmospheric CO_2 concentrations would reach over 800 ppmv by 2100, and global Rsc/P ratios would fall well below 20 years using the same modelling assumptions (results not shown). On the other hand, under the assumptions applied here global economic output would be around 2% higher by the end of the century without the sustainable development drivers, although this estimate excludes the possible negative economic impacts of climate change or reduced supply security. This 2% difference in economic output can be compared with the 750% increase in global GDP over the century (equivalent to 88% of the 2100 level).

This implies that it is possible to achieve some aspects of long-term sustainability in the energy system for a relatively small economic cost over the course of the 21st century. We now turn to the focus of this study, which is to explore the implications of this scenario for the global transport system.

4.2. Global transport energy consumption

As outlined earlier, future passenger travel demand poses a potentially significant challenge to sustainable development. However, the results above show that it is possible to describe a long-term transition to a sustainable energy system, implying that it may be possible to overcome this challenge. We now look in more detail at the transport sector within this scenario, to identify key developments required for long-term sustainability.

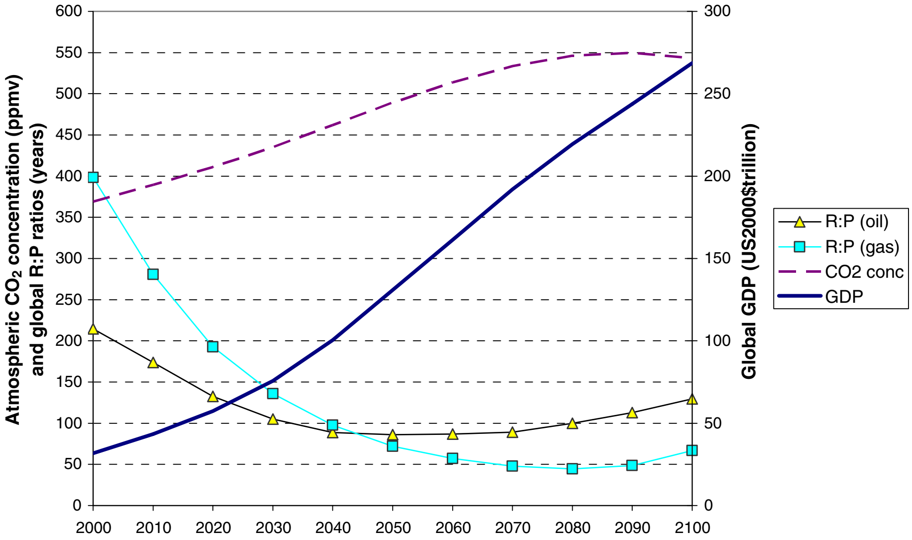


Fig. 4. Sustainable development indicators.

Fig. 5 presents energy use in the transport sector, under this scenario, and shows both the transition from petroleum products to a more diverse fuel mix and broad technological developments. Fig. 5 shows that total global transport energy demand increases roughly 200% over the 21st century, although without improvements in efficiency across all modes of transport this would be much higher—in this scenario it is assumed that average car efficiency improves slowly at a rate of 2% per decade (to account for efficiency improvements being offset by a shift to larger vehicles with more on-board systems), air transport efficiency converges towards 0.9 MJ/pkm, and other modes follow the overall transport sector efficiency improvements implied in the original B2 scenario, in which total transport energy demand also grows by around 200% [10]. Further efficiency improvements arise as a result of the deployment of new transport technologies, and this is partly illustrated by the increasing role of fuel cells shown in Fig. 5, which contribute to a slight decline in energy consumption towards the end of the century.

The introduction of the fuel cell technologies begins around 2010, although initially in very limited quantities, but their share gradually increases such that they become an important technology by the end of the 21st century. Looking at energy carriers, first natural gas, then alcohols and hydrogen displace an increasing share of petroleum. Importantly, however, Fig. 5 shows that there is scope within a sustainable development scenario for petroleum products to continue to play a substantial role in the transport system, and most of this petroleum is used in air transport towards the end of the century (along with direct combustion of hydrogen).

Air transport is a large consumer of energy in 2100 under this scenario, with energy demand increasing almost 450% over the century, as shown in Fig. 6, which presents transport demand for three main sectors—automobiles, air transport and freight. In comparison, automobile transport demand increases 4-fold and freight transport energy demand 3-fold over the century. It should be noted that the transport demands presented in Fig. 6 differs from the calibration demands discussed in Section 2.2, and presented in Fig. 3 for automobile transport. These calibration demands are represented by dashed lines in Fig. 6.

The differences between the calibration and actual scenario are most obvious for air and car transport, but also occur for freight transport, and arise because achieving the sustainable development objectives

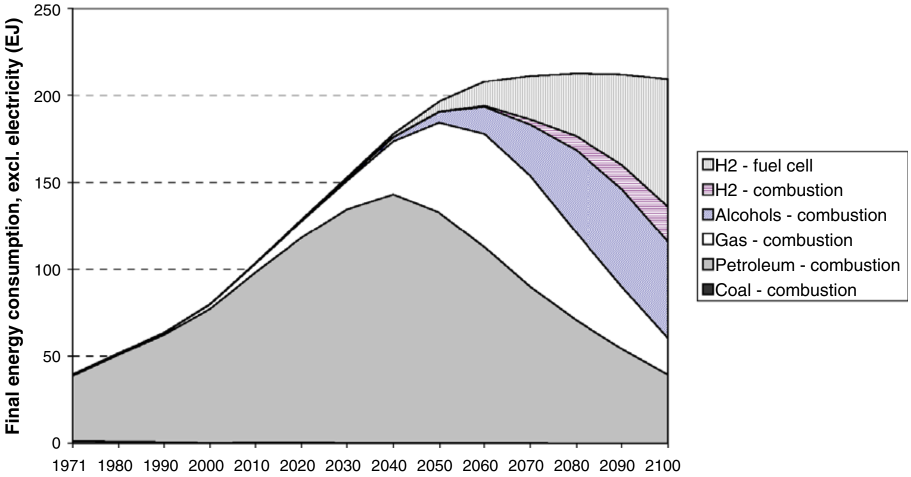


Fig. 5. Transport energy consumption, historical and scenario. (Source (historical statistics): IEA [23,24]).

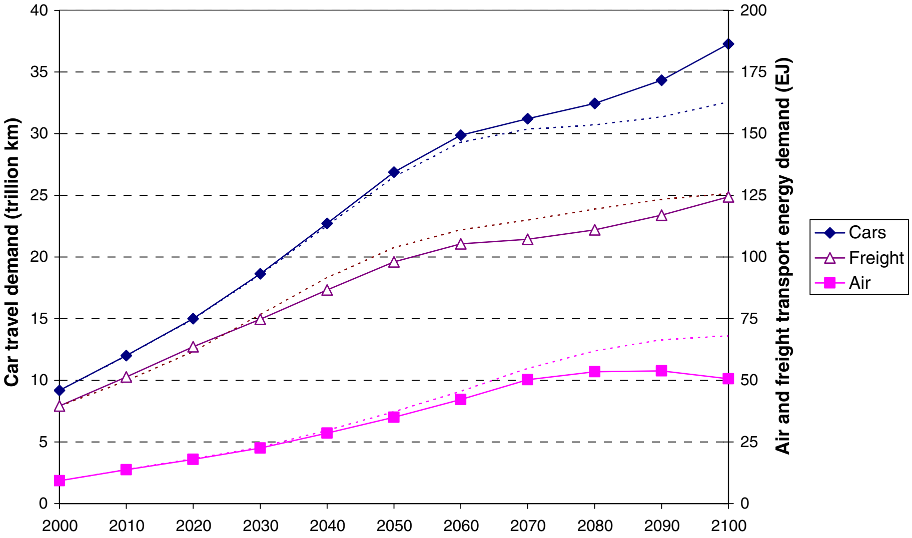


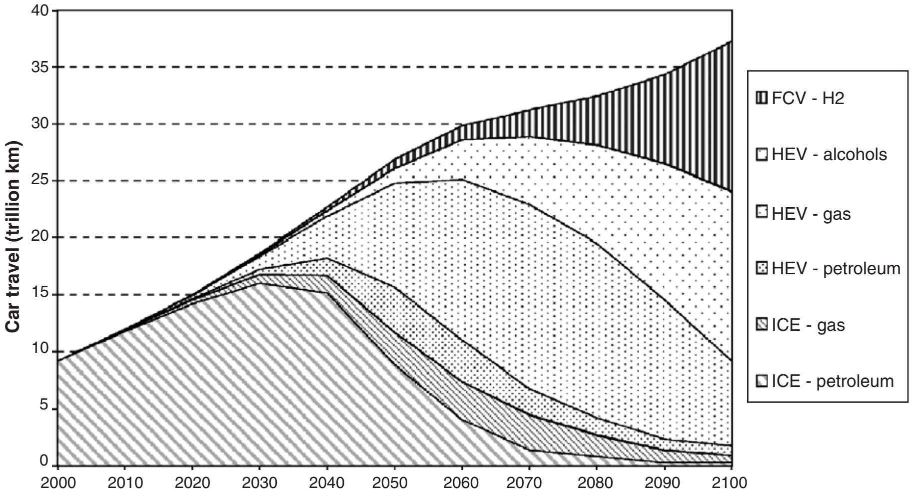
Fig. 6. Transport demand, sustainable development scenario and comparison with calibration baseline.

increases the cost of energy. Among other impacts, this leads to substitution of energy and freight inputs in economic production, resulting in a slight decrease in freight energy demand. For car and air transportation, the increased energy cost reduces the purchasing power of the travel money budget—resulting in a shift away from more hypexpensive air travel to less-expensive car travel. It is important to stress that this impact arises not because of different relative increases in the cost of one mode compared to another, but instead as a consequence of the overall reduced purchasing power of the travel money budget, which tends to favour the cheaper transport mode. This is an important finding, because it shows that an even greater increase in car transport demand (than presented in Fig. 3) can still be compatible with sustainable development, but it also implies that policies aimed at the two sustainable development drivers analysed in detail here—climate change mitigation and security of energy supply—may lead to negative impacts in terms of congestion and urban air pollution. However, new car technologies and fuels also have the potential to alleviate urban air pollution, along with reducing greenhouse gas emissions and reducing risks of energy supply disruptions. We now look at the choice of car technologies and fuels under this scenario in more detail.

4.3. Car transport

New technologies have the potential to play a major role in any transition towards a more sustainable transport system. The automobile technologies and fuel most compatible with sustainable development under the scenario described in this paper are illustrated in Fig. 7, which disaggregates total automobile transport demand into different technologies and fuels.

Fig. 7 shows that in the first half of the 21st century hybrid ICE-electric technologies slowly begin to challenge the dominance of the petroleum ICE, and by 2030 account for almost 10% of travel. This increases to almost 55% in 2050, and peaks at 78% in 2070. Hybrid electric vehicles (HEVs) fueled with natural gas are initially the most attractive, with smaller shares of petroleum and alcohol HEVs also playing a role. The initial attraction of natural gas HEVs can be attributed to their low



Abbreviations are as follows: ICE – conventional internal combustion engine vehicle; HEV – hybrid ICE-electric vehicle; and FCV – hybrid fuel cell-electric vehicle.

Fig. 7. Technologies and fuels for automobile transport.

emissions and cost, and their reliance on a fuel that is more abundant than petroleum. However, towards the end of the century they are replaced by alcohol HEVs as the dominant hybrid technology, driven mainly be efforts to manage the depletion of gas resources, and to further reduce greenhouse gas emissions.

Around the same time as alcohol HEVs start playing an increasingly important role in automobile transport, hydrogen-fuelled fuel cell vehicles (FCVs) begin to be deployed in this sector on a larger scale. Under this scenario, the first transport applications in which hydrogen is deployed on a large scale are in heavy transport, where on-board storage and refueling do not represent as great a barrier as in private automobile transport. The freight sector (including heavy transport) remains an important consumer of hydrogen throughout the century, and by 2100 accounts for almost half of global H_2 demand. By this time, more than one-third of the passenger fleet is powered by hydrogen fuel cells. Fuel cells powered by other fuels—such as methanol or petroleum—do not play a significant role in this scenario, mainly because they face additional technical barriers associated with reforming the input fuel. Conversely, the role played by hydrogen fuel cells in automobile transport is limited for much of the century because of the availability of a number of alternative automobile technology–fuel combinations that can achieve high levels of sustainability, and also by limited availability of H_2. It is important to note, however that in this study we focus on a limited set of sustainability criteria, and efforts to address other sustainability issues—such as local air pollution—may increase the attractiveness of those transport technology options that are uncompetitive under this scenario.

4.4. Fuel production

The deployment of the sustainable vehicle technology–fuel combinations described above depends critically on transitions in the global fuel production system, particularly the increasing availability of alcohol fuels and hydrogen. Initially, alcohol fuels have a number of advantages over hydrogen—they can be handled relatively easily and distributed utilizing some of the existing fuel delivery infrastructure—and so play an important role in improving sustainability in this scenario before hydrogen supply infrastructure is fully developed, and fuel cells are mature. Importantly, throughout much of the century alcohols and hydrogen complement one-another, rather than compete, as they increasingly substitute for fossil fuels in surface transport. This is illustrated in Fig. 8 which compares global petroleum production (refining) with production of alternative fuels over the century under this scenario. Again illustrating the continuing importance of oil, refinery throughput exceeds alternative fuel production for much of the century under this scenario, and it is not until 2080 that combined production of alcohols and hydrogen becomes larger the petroleum production.

The continuing reliance on petroleum fuels in this scenario occurs partly because of barriers to the mobilization of technologies and sufficient resources for large-scale non-fossil synthetic fuel production and distribution, particularly from biomass. For instance, hydrogen is initially synthesised from natural gas, which is a more technologically mature production path relying on a conventional feedstock. Later, synthesis from biomass becomes the preferred production route for both hydrogen and alcohols. Under this scenario, hydrogen synthesis from biomass is also combined with carbon capture and storage (CCS) technologies, resulting in a fuel with net negative emissions.

Given the importance of biomass in this scenario it is worth briefly mentioning the biomass resource potentials assumed in the ERIS model. These potentials are based on estimates from Rogner [49], who identified an annual global potential in 2050 of between 250 and 400 EJ, mostly in Africa and Latin America—which is similar to other estimates, such as in Fischer and Schrattenholzer [50]. In this scenario we assume that this potential can only be fully exploited towards the end of the century, and that in 2020 only 125 EJ is available, rising to 235 EJ in 2050 and 320 EJ by 2100.

4.5. Well-to-wheels emissions

The penetration of zero- or negative-emissions alcohol and hydrogen fuels synthesized from biomass into the transport sector can be seen as an important element in the transition to a sustainable transport

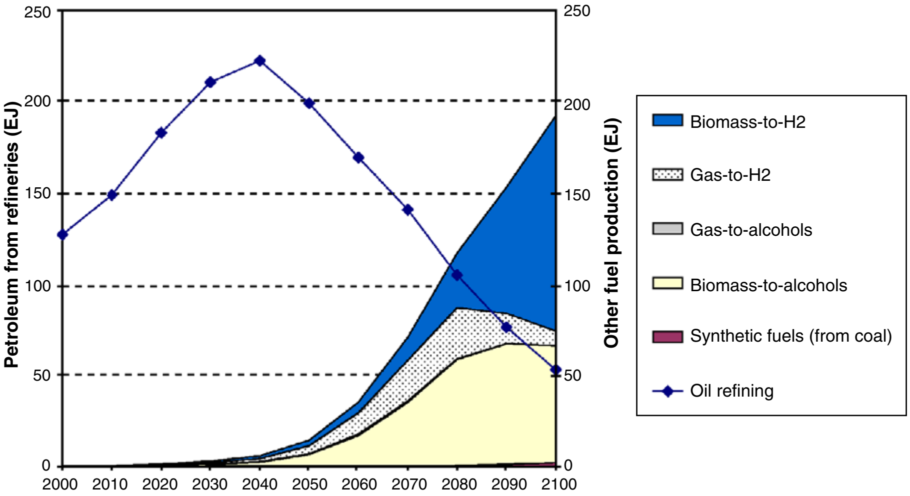


Fig. 8. Global fuel production.

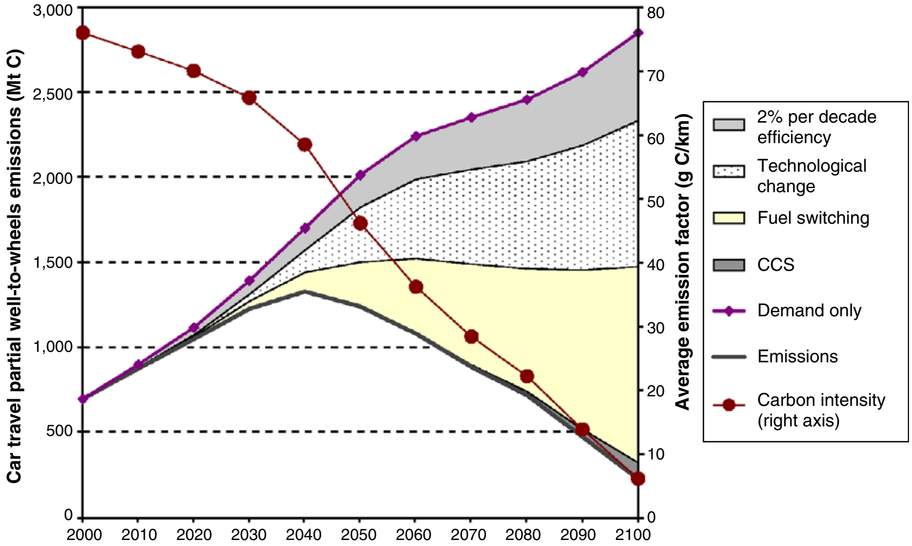


Fig. 9. Partial well-to-wheels emissions for automobiles.

system. The overall impact of this transition on greenhouse gas emissions from automobile transport is illustrated in Fig. 9, which shows partial well-to-wheels emissions,[7] and the specific emission factor of car travel under this scenario. Fig. 9 also shows the impact of some of the other factors discussed above including improvements in efficiency, new technologies, fuel switching, and carbon capture and storage. Without any of these factors, emissions would have simply increased in line with car travel demand (which is shown in Fig. 6) to over 2.8 Gt of carbon (C) in 2100. However, Fig. 9 shows that the efficiency improvements unrelated to energy technologies assumed for this scenario—2% per decade (being the combined impact of factors such as reduced rolling resistance, better aerodynamics, lighter materials, etc., partly offset by consumer preferences for larger vehicles)—reduce this by around 500 Mt C. Emissions are further reduced by the deployment of new efficient vehicle technologies such as hybrids and fuel cells, and by 2100 these technologies are responsible for almost 900 Mt C of annual abatement. As alluded to earlier, the single largest impact arises from a shift to low emissions fuels, which reduces emissions by over 1.1 Gt C in 2100, down to just above 300 Mt C. Carbon capture and storage in hydrogen production reduces this by around a further 100 Mt C, such that automobile CO_2 emissions in 2100 are less than one-third of their 2000 level.

The combined effect of these factors reduces the average emissions per kilometre of travel by over 90% between 2000 and 2100. By many indicators automobiles become an increasingly sustainable transport option as the century unfolds in this scenario.

4.6. Other energy system developments

It is important to remember that the emergence of a sustainable transport system does not occur in isolation to other developments in the global energy market. This has already been discussed in terms of

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[7] Partial well-to-wheels emissions presented in Fig. 9 include emissions from fuel production and losses in transmission and distribution, but exclude non-CO_2 emissions (which arise, for instance from fertilizers used for biomass production, or from venting of gases during oil extraction), and emissions produced in the transport of fuels.

a shift to synthesis of alternative fuels, and is further illustrated by exploring developments in other energy sub-sectors. This helps to show how developments in the transport sector are part of a consistent and co-ordinated transition towards a more sustainable energy system. Fig. 10 presents electricity generation and direct thermal consumption according to fuel in 2000, 2050 and 2100 under this sustainable development scenario. Apart from a strong shift towards greater use of electricity, because of its flexibility and convenience for the end user (which is an element of the B2 storyline [9]), Fig. 10 illustrates a number of other important changes. In electricity generation, there is a transition away from coal initially towards natural gas and nuclear generation, and eventually nuclear and renewables. Although much of this nuclear generation is from inherently safe third and fourth generation reactors, this technology must overcome a number of other major barriers before it can be considered an option for sustainable development, related mainly to waste management and safety, public acceptance, and weapons proliferation. Looking at other fuels, only a small amount of hydrogen or biomass is used in electricity generation, because these fuels are required in other sectors. In comparison, the fuel mix used to satisfy direct thermal energy needs changes less over the century, with oil and gas remaining important, but surplus electricity and hydrogen being used in preference to coal and biomass.

These developments are equally important for the emergence of a sustainable transport system, since they ensure that these other sectors do not overly compete with transportation for the fuels required to make the transition to sustainability. The main elements of an overall energy system compatible with sustainable development include:

- a fuel synthesis sector based on biomass, producing alcohols and hydrogen;
- a transport system based on alcohols and hydrogen (with petroleum persisting for air transport);
- an electricity sector based predominantly on nuclear and renewables (other than biomass); and
- direct thermal needs supplied mainly by a combination of gas, hydrogen and additional electrification.

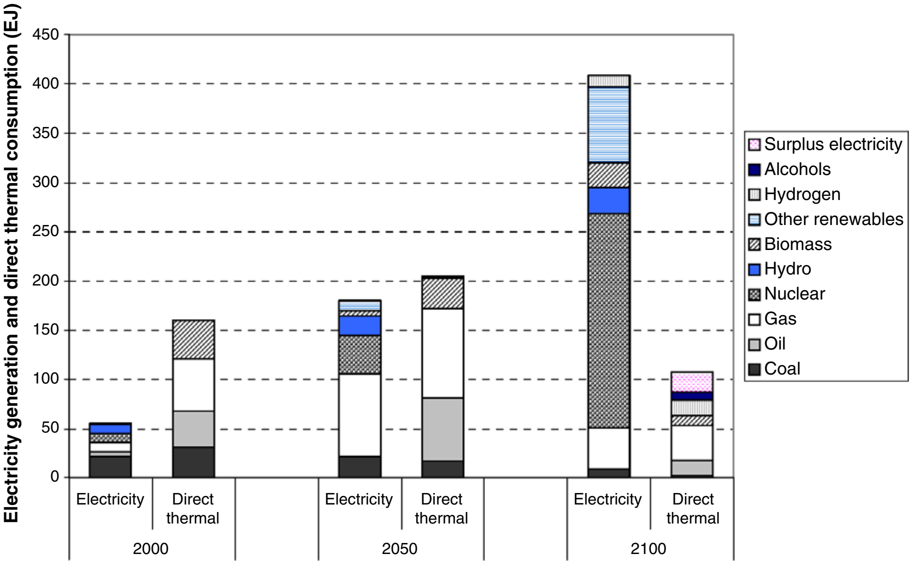

Fig. 10. Global electricity generation and direct thermal combustion, by fuel.

We now discuss in more detail some of the key developments required for the emergence of a sustainable transport system, and identify areas for public support or policy intervention.

5. Discussion

The objective of this study is to firstly understand pathways to a sustainable global transport and energy system, and secondly, to identify key technological developments necessary for the emergence of such a system. By doing so, we seek to provide insights into key targets for public support, and identify areas requiring near-term intervention to shift the energy system's development trajectory onto a more sustainable pathway, particularly given the inertia of energy system development.

With these goals in mind, the scenario described in this paper illustrates one pathway towards a global sustainable transport system, and describes in detail this transition using an integrated modelling framework that includes energy system detail and interlinkages. However, a single scenario can only represent one configuration of the future, and significant social, economic, environmental, technological and political uncertainties mean that future developments are almost certain to follow an alternative pathway. Nonetheless, even a single scenario can provide a robust illustration of where, and the type of conditions under which, long-term challenges to sustainable development may emerge and the possible nature of these challenges. Moreover, the scenario presented here is based on drivers, including economic, institutional and technological, that are consistent with current and historical experience, and so may be well-suited to providing credible nearer-term policy insights for addressing longer-term challenges, despite future uncertainties.

5.1. Integrated framework

We have explored the emergence of a sustainable energy and transport system with an integrated modelling framework that includes a detailed bottom-up energy systems model with technological learning, a consumer-budget transport demand model, a top-down macroeconomic model and a climate model. Accordingly, the sustainable development scenario presented here incorporates important feedbacks between energy prices, energy demand and economic activity, while also capturing the potential impact of technological change on the transport system. In addition, the comprehensive energy model helps illustrate how all energy sectors develop towards sustainability in a consistent and complementary manner.

One key finding arising from the application of this framework is that a sustainable energy system can emerge over the long term at relatively little cost over the century (roughly 2% of GDP by 2100). In addition, and more interestingly, these results imply that the higher per unit energy costs under a sustainable transport system may result in a shift from air transport towards additional automobile transport compared to an equivalent scenario where sustainable development objectives are not pursued, as consumers respond to higher prices by exploiting relatively cheaper transport modes. Importantly, this finding is based on the assumption that current institutional and economic drivers of transport demand (as discussed in Section 2.2) remain in place, and alternative modes such as high-speed railways do not significantly replace air or car transport.

However, there are a number of key uncertainties in this analysis including the pace and direction of technological change, the size of ultimately recoverable global oil and gas resources, and the required level of greenhouse gas abatement to avoid the worst impacts of climate change. If some of the technological developments envisaged here do not materialise, if more pessimistic assessments of global resources turn out to be accurate, or if more stringent abatement is required, then achieving the goals of sustainable development would require an even faster transition to new fuels and technologies than envisaged in the scenario presented here, probably at greater economic cost. Given that the scenario presented here already involves a number of radical changes to the energy and transport system, a faster and more extensive transformation poses further challenges and may require additional action to discourage certain transport modes and reduce the volume of transport and energy demand.

5.2. Transport technology transitions

Deployment of new technologies plays an important role in realizing a sustainable transport system. In this scenario, in automobile transport there is initially an almost total transition from internal combustion engine vehicles to hybrid-electric vehicles, and eventually a shift towards hydrogen fuel cell vehicles.

Importantly, hybrid vehicles are already commercially available and have gained relatively widespread consumer acceptance, often supported by government initiatives (for example, tax deductions in the USA and grants and exemptions in the UK [51,52]). However, HEVs still only account for a very small share of the passenger car market (with cumulative global sales over 8 years estimated to be below 1 million). The question remains whether current market drivers alone will be sufficient to promote a complete transition to these vehicles over the next 50 years or so. To ensure the full potential of this technology to contribute to sustainable development is realized there may be a role for public support to ensure economies of scale in production are achieved, and key barriers—such as battery costs and storage—can be overcome. Accordingly, there may be scope for government rebates, subsidies or procurement programs to create additional confidence in this technology.

Deployment of H_2 fuel cell vehicles is the other major technology development under this scenario. Although adoption is greatest later in the century, this only arises because of critical small-scale experience from as early as 2010 in heavy vehicles and 2020 in passenger vehicles. This early experience is essential for fostering technological improvements and cost reductions essential for later large-scale deployment. However, the immaturity and current high cost of fuel cells implies that market drivers alone will be unlikely to lead to socially optimal investment in this technology, highlighting the role for public support [27]. This may involve R&D funding and co-ordination, government-sponsored demonstration and procurement programs, and support for deployment in specific niche markets—including in non-transport applications where improvements in the technology may lead to spillovers to transport. As this technology becomes more commercially viable, more demand-based support mechanisms, such as subsidies, rebates, standards and voluntary agreements will form an important complement.

In the context of the major technological transitions described in this scenario, it is worth restating that there exist significant uncertainties related to energy technology development, ultimately recoverable energy resources and other elements of the energy system. Although the analysis presented here covers in detail energy system interlinkages, we restrict this analysis to a realistic set of technologies, energy resources and market conditions to illustrate how a sustainable transport system can be realized without relying on highly unpredictable technology breakthroughs. Nonetheless, the possibility of such technology developments cannot be ruled out.

For example, one such revolutionary technology that is excluded is fuel cell vehicle-to-grid systems, where the fuel cell engines in stationary automobiles are used to provide electricity generation services, including for peak power and system stability [53–55]. These technologies still face a number of technical hurdles, but may potentially play an important role in the future. Importantly, support for fuel cell technologies also supports the possible emergence of these more radical energy systems.

5.3. Fuel production and other requirements

In addition to developments in transport technology, two complementary fuel production trends emerge in the sustainable transport scenario described here. The first is an increasingly important role of biomass as a primary feedstock, and the second, somewhat related, is the development of a hydrogen and alcohol-based energy system. Creating the production and distribution infrastructure required for large-scale deployment of these fuels poses a number of challenges.

In the case of alcohols some of these challenges may be relatively easily overcome, since alcohol fuels have some advantages in that they can be distributed using similar infrastructure to that employed for petroleum fuels. However, the emergence of a sustainable transport and energy system may well require the deployment of hydrogen-based technologies. To supply these technologies with fuel, it is likely that major capital-intensive investment in hydrogen production and distribution infrastructure will be necessary. Moreover, as is often cited, much of this infrastructure will need to be developed before there exists sufficient demand to make it commercially viable [14]. However, because of the significant social benefits of sustainable development that may arise from H_2 deployment it is important that adequate investment is directed towards this infrastructure. This identifies an important role for public support, or innovative schemes to share the risk of large-scale capital-intensive infrastructure investment. Moreover, given the likely monopoly nature of a hydrogen distribution network, there exists an important role for government in overall strategic co-ordination of investment to guarantee an efficient network, in addition to more traditional roles in regulation.

In the sustainable transport scenario presented here, both alcohols and hydrogen are synthesised predominantly from biomass. This is despite the fact that creating an energy system in which biomass is one of the main primary feedstocks poses a number of significant challenges. Biomass is favoured because without major technological breakthroughs—for example, that result in a large surplus of cheap renewable energy for large-scale electrolysis, or very large-scale carbon capture and storage—there are relatively few long-term cost-effective alternatives to biomass for transport fuel synthesis. One possibility not included in the modelling framework applied here is hydrogen produced from high-temperature nuclear reactors (for example, see DOE [56]), although nuclear energy is already heavily exploited for electricity generation in this scenario suggesting there may be limited scope for further applications.

The challenges facing large-scale sustainable biomass mobilization relate particularly to finding sufficient productive land to devote to fuel production, while satisfying increasing human needs for food and fibre, and at very least maintaining environmental amenity. The scale of biomass production is best illustrated by considering that the resource potential identified by Rogner [49] (and used here) was based on the availability of an additional 1.3 billion ha of land globally. Clearly, biomass production on a scale of this order of magnitude must address other aspects of sustainable development, including effective water and soil management, nutrient recycling and preservation of organic matter [57]. In addition to a significant transformation to land management systems, and utilization of all organic waste streams, sustainable biomass production faces other challenges. Harvesting and transporting biomass to fuel synthesis plants represents a significant logistical challenge, although this may promote smaller-scale decentralized alcohol and hydrogen synthesis close to the feedstock source. Such decentralization, however, may merely shift logistical difficulties further down the production chain. On the other hand, there may also be benefits compared to today's relatively centralized oil industry because fuel production and demand centres may be proximate (compared to today's oil industry which relies on long-distance transport), and the fuel production system will no longer necessarily depend on a small number of large critical infrastructures—such as pipelines, shipping terminals and refineries—but instead on a less vulnerable network of energy producers.

However, developing such a sustainable biomass-based energy production system is likely to require a long-term overall strategic vision and substantial investment, and face long lead-times before becoming profitable. This highlights the need for innovative approaches to investment, including public–private partnerships (for example, see PCAST [58]), and a role for governments in providing the strategic framework in which private sector expertise can be exploited to realize long-term social goals, whilst ensuring other aspects of sustainability are addressed. Moreover, the major transformations to the energy and complementary systems described here may be particularly challenging in the developing world, where many of the systems may need to be established from scratch. Accordingly, realizing long-term sustainability is likely to also require major international partnerships to promote technology transfer and investment in new energy, transport and supporting system infrastructure.

5.4. Market drivers

Achieving the technology and fuel production requirements discussed above involves overcoming both technical and market barriers. So far we have focused predominantly on technology-specific measures, but there is also a strong case for the application of broader-based policy instruments to encourage a transition to a more sustainable energy system such as that envisioned in this paper. These may include taxes and tradable permit schemes, although alone these measures would need to be fairly stringent and costly to achieve the required technology transition. However, they can still play an important role even at low levels initially by discouraging those technologies and fuels least compatible with sustainable development, and by creating market conditions that lower the commercial barriers to the adoption of new sustainable technologies.

5.5. Climate change and security of supply

As a final point, we have presented in this analysis a scenario in which two major challenges to sustainable development—climate change mitigation and maintaining security of energy supply—are confronted and managed to reduce long-term risks. Importantly, there are synergies between these two policy goals when pursued together—illustrated best perhaps in the scenario presented here by the deployment of alternative fuels such as alcohols and hydrogen that can help achieve both policy goals. However, as shown by Turton and Barreto [33], it is important to appreciate that these synergies may not be realized cost-effectively if one policy goal is pursued whilst ignoring the other. Such an approach runs the risk of locking the energy system onto a development trajectory that may be incompatible with uncertain future challenges. This highlights the need for a long-term strategy to incorporate multiple policy objectives, and consistent with this requirement, we have presented and analysed here a scenario that integrates a number of elements of long-term sustainable development.

6. Conclusions

The sustainable transport scenario presented in this paper illustrates one possible configuration of a future global energy system that restricts atmospheric CO_2 concentrations to below 550 ppmv, maintains resource-to-production ratios for oil and gas above 40 years, and satisfies a rapidly growing global demand for transport, all at a cost of around 2% of GDP by 2100. Moreover, this scenario helps elucidate the possible pathways along which a sustainable transport system may emerge, and begins to lay out a technological and infrastructure roadmap illustrating one pathway, including key challenges. In doing so we identify critical roles for hybrid-electric and fuel cell technologies, and alcohol and hydrogen fuels synthesised from biomass, all of which may be potential candidates for strategic public support and coordination of private investment. This highlights the potential importance of innovation, both in terms of technology and policy support, in a transition to sustainability. Given the slow rates at which energy and transport infrastructure develops, and the need for a major transformation of the energy system indicated in this study, this analysis provides further support to the notion that early and consistent action is necessary to achieve sustainable mobility. Furthermore, because the scenario presented here is based on many current trends and institutional drivers it may provide credible nearer-term insights for today's policymakers, despite substantial future uncertainties.

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