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Report on the relevant infrastructure systems in the energy sector and reduced form representations of infrastructure costs in Energy System Models

Eoin Ó BROIN, Céline GUIVARCH [a]

[a] Société de mathématiques appliqués aux sciences humaines-Centre International de Recherche sur l'Environnement et le Développement (SMASH)

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1. Introduction

Global greenhouse gas (GHG) emissions from the transport sector have more than doubled since 1971, increasing at a faster rate than any other energy end uses sector to reach 7.0 GtCO2 in 2010. Over three quarters of this increase has come from road vehicles. Direct emissions from the transport sector were about 13.5% of total anthropogenic GHG emissions in 2010 or 22% of total global energy related CO2 emissions (Sims et al., 2014). Greenhouse gas mitigation scenarios that keep to 2°C of global warming suggest the need to reduce global emissions to net zero in the second half of this century (Edenhofer et al., 2014). **Thus significant reductions in emissions from the transport sector will be necessary as part of any mitigation strategy.**

Reducing transport emissions is however a daunting task given the ever increasing demand, the slow turnover of stock and infrastructure[1] and the huge sunk costs in the present transport system (Sims et al., 2014). The authors are highlighting the importance of both the actual transport technology e.g. light-duty vehicles, and the enabling infrastructure, e.g. roads. (Davis et al., 2010) calculate the emissions that will accrue from the use of the existing stock of vehicles (116 $GtCO_2$) and write that the average lifetime for a vehicle in the US is 17 years. (Guivarch and Hallegatte, 2011) on the other hand highlight the role of transport infrastructure, writing that transport infrastructure and assets locations create an inertia on transport emissions, which is larger than the inertia of the vehicles fleet itself. In other words the type of transport infrastructure in place can lock-in the sector to a particular pattern of emissions[2] that will be greater than the emissions from the vehicles calculated by (Davis et al., 2010). In their study (Guivarch and Hallegatte, 2011) extend the work of (Davis et al., 2010) to account for the neglection of the role of transport infrastructure in determining future levels of emissions. Focusing on physical infrastructure for transport and buildings itself (Müller et al., 2013) show that if the per-capita levels of all infrastructure enjoyed by people in Western countries was constructed globally using current technologies that the emissions from the construction alone would use up about 35−60% of the remaining carbon budget available until 2050 if the average temperature increase is to be limited to 2 °C. In other words the emissions from the construction of infrastructure are important as well. Globally, at least 25 million kilometres of new roads are anticipated by 2050; a 60% increase in the total length of roads over that in 2010 (Laurance et al., 2014). **Thus estimations of future emissions from the transport sector should consider not only the stock of vehicles, but in addition the 'induced demand' from the infrastructure and the emissions from the construction of the infrastructure itself.**

(Waisman et al., 2013) go further than the aforementioned authors by advocating for the consideration of behavioral determinants of transportation, which they write include (1) spatial organization at the

[1] The word infrastructure is itself relatively new in linguistic usage and it did not appear as a subject of interest in economics until the 1980's (Prud'homme, 2005).

[2] For example the construction of the interstate highway in the United States allowed for greater commuting distances and thus the suburban housing developments and the car-dependency that went with this (Lecocq and Shalizi, 2014).

urban level, (2) the level of investments in public transport and (3) the logistics organization which determine the transport intensity of production/distribution processes use of vehicles. The authors find that combining transport policies (e.g. dedicated investment in infrastructures for public modes) and a carbon price, can noticeably reduce the level of carbon tax necessary to reach a given climate target relative to a 'carbon price only' policy. (Waisman et al., 2013) write that to date E3 IAM modelling of global energy demand had not taken such issues into consideration. This is important because Integrated Assessment Models (IAMs) have become central tools for informing long-term global and regional climate mitigation strategies(EC, 2013a), and have evolved to typically incorporate all aggregated sectors of energy end use e.g. transport, industry, buildings and in some cases agriculture and land use change. For energy supply however the lack of inclusion of infrastructure could mean that solar power and natural gas are assumed to develop regardless of the existence or not of power lines. **For the transport sector this could mean that demand for transport services is modelled to evolve regardless of the existence or not of a road and rail infrastructure.**

In addressing greenhouse gas emissions from the energy system, sector focused modelling works and policy discussion documents have traditionally focused on end-uses of energy e.g. heating, lighting, driving and not so much on the enabling physical infrastructure. Notable exceptions to this are (Dulac, 2013) and (Laird et al., 2005). (Dulac, 2013)uses results from the IEA Mobility Model (MoMo) to model the infrastructure requirements to support projected road and rail travel through 2050, as identified in the IEA Energy Technology Perspectives 2012 (IEA, 2012). The author finds that net savings in expenditure on infrastructure of USD 50 trillion can be made in an 'avoid-shift' scenario where there is increased use of more sustainable modes of transport. (Laird et al., 2005) take a macroeconomic perspective and argue for the inclusion of transport infrastructure in modelling works because its deployment and network effects bring about accessibility, which stimulates development i.e. wages, prices outputs, labor and land markets and can help remove market imperfections.

A stocktaking exercise carried out for the ADVANCE project (EC, 2013a) to assess the level of infrastructure representation in IAMs and summarized below, revealed that infrastructure modelling to date in IAMs was rudimentary and mostly involves linearly related cost increments for deployed technologies. In five models, REMIND, IMACLIM, IMAGE, MESSAGE and TIAM-UCL, energy transmission and distribution infrastructure e.g. natural gas grid or CCS pipelines are included as individual technologies (McCOLLUM et al., 2013). The IMAGE model (van Ruijven et al., 2010) and REMIND (Pietzcker et al., 2014) also incorporate some network effects. These are that in IMAGE large scale hydrogen use is restricted until the supporting infrastructure has been modelled to exist while in REMIND the quadratic scale-up of an overlay grid is required for the scale-up of VRE. (Waisman et al., 2013) cited above, describe the incorporation of transport infrastructure into the IMACLIM-R Global E3 integrated assessment model, in order to analyze its role in facilitating modal shift or behavioral change towards more sustainable modes of transport. Their model includes road, public transport and air travel infrastructure. It was found that the other models only include the energy supply system for transport e.g. a hydrogen supply infrastructure.

This report summarizes a number of exercises that have been carried out with regard to further improving the modelling of infrastructure in IAMs. They are listed here and described fully in Sections 2 and 3.

1. Literature review to establish key questions regarding deployment and upkeep of infrastructure.
2. Stocktaking exercise to establish extent of infrastructure inclusion in Global Integrated Assessment Models
3. Reduced form description of the implementation of the modelling of overlay electricity grid for Variable Renewable Electricity generation. Includes 'rule of thumb' for relationship between VRE deployment and overlay grid requirement.
4. Reduced form description of the implementation of the modelling of infrastructure for the Transport Sector in the IMACLIM-R Global E3 IAM. Scenario results from the implementation of transport infrastructure in the IMACLIM-R Global E3 IAM

2. Background and Literature Review

2.1 Infrastructure Definition

Infrastructure is a relatively new word in linguistic usage and it did not appear as a subject of interest in economics either until the 1980's (Prud'homme, 2005). The author describes how the great economic writers of the 19th century assumed that output was a function of only two inputs, labor and capital, despite the fact that governments of the time invested heavily in infrastructure and later used cost-benefit analysis as a tool for estimating the economic and social contribution of infrastructure. Since the 1980's however, infrastructure has been the subject of numerous academic studies focusing on its economic role. Many of these studies have emanated from the World Bank due to the role of that institution in financing infrastructures-type projects for development (Prud'homme, 2005).

The (OECD and ECMT, 2007) describe infrastructure as 'a means for ensuring the delivery of goods and services that promote prosperity and growth and contribute to quality of life, including the social well-being, health and safety of citizens, and the quality of their environments'. This definition includes both physical infrastructure such as roads and virtual infrastructure such as so-called information highways. In a recent study (Wilbanks, 2014), describes built infrastructure (as contrasted, for instance, with social infrastructure) as including urban buildings and spaces, energy systems, transportation systems, water systems, wastewater and drainage systems, communication systems, health-care systems, industrial structures, and other products of human design and construction that are intended to deliver services in support of human quality of life. (Lecocq and Shalizi, 2014) describe infrastructure as a type of long-lived capital stock that can lock-in streams of emissions for extended periods of time.

These definitions of infrastructure cover different societal spheres i.e. economic, social, security and environmental but combined they highlight the role of infrastructure for 'sustainable development' or 'maintenance' of modern industrial society. The definitions also highlight the areas of communications, energy, transport and water as being consistently named as infrastructure.

2.2 The Societal Role of Physical Network Infrastructure

A review of contemporary reports and literature on the role of infrastructure have found the three most important questions to be:

- What is the role of infrastructure in economic development and growth?
- How the construction and maintenance of infrastructure can be financed going forward?
- The role of infrastructure in the face of climate change and the possibilities for its adaptation?

These three questions are described in the rest of this section.

The role of infrastructure in economic development and growth

With its new-found status since the 1980's in the discourse on economic growth and development, the key question being addressed was the extent to which **infrastructure was necessary for, or contributed to economic growth and productivity gains**? (Kessides, 1993) describes a debate on this subject using the chicken and egg metaphor i.e. whether infrastructure stimulates economic growth or vice versa[3]. The example of cars and highways is given i.e. did the construction of the inter-state highway system (IHS) in the USA enable mass auto-transit, or did the innovations and expansion of the automobile industry create the need for additional infrastructure? (Straub, 2007) carries out a comprehensive review 80 empirical studies most of which seek to establish **an elasticity of economic growth to the deployment of infrastructure**. The author writes that early studies found large positive feedback between the deployment of infrastructure and growth. However later studies employing more sophisticated econometric techniques to account for endogeneity i.e. mis- or under-specified models, suggested that the earlier findings of strong correlations should be revised downwards. The review carried out by (Straub, 2007) raises more questions than it answers for two reasons. First and mostly because of the difficulties he describes with carrying out empirical work regarding the impact of infrastructure and second because he suggests that empirical studies can easily overlook that there are spatial and temporal aspects of infrastructure that appear to be critical. For example the empirical evidence seems to suggest that for the decades immediately after WWII in the United States, that **the deployment of the IHS resulted in a one-time productivity increase**, however Straub argues that for a different country and a different decade a similar deployment may not have had the same effect. Reasons (Straub, 2007) gives as to why **the deployment of infrastructure might not result in productivity or growth gains** are; a lack of access in the region to capital for business people, trade-union power inhibiting changing work practices, an inconsistent legal framework such that business people cannot have faith that contracts will be honored and enforced and lastly that the reasons for the deployment of the infrastructure may in the first place be down to 'pork-barrel' politics as opposed to gains that cost-benefit analysis have suggested exist. In conclusion Straubs paper suggests that there are three important ideas regarding infrastructure around which there is no academic consensus regardless of results from empirical studies, but nonetheless must be considered on a case-by-case

[3] A similar chicken and egg discussion surrounds electric vehicles i.e. what comes first the charging stations or people buying the vehicles (Paine, 2013).

basis. They are that (i) Initial investments to establish e.g. a specific road or communication infrastructure, may only have a one-time effect on productivity (p.18), (ii) once basic infrastructure is in place, adequate investment in maintenance might actually have a higher rate of return than new investment (p.18) and (iii) productivity gains from the deployment of infrastructure may not kick-in until a certain threshold or network effect has been reached e.g. until there is widespread deployment of mobile telephony infrastructure the gains from its deployment are minimal (p.29). Obviously the first and third idea suggest different outcomes from the deployment of infrastructure but nonetheless should be considered.

(Prud'homme, 2005) argues that **the empirical research on the impact of infrastructure has been misplaced**. He offers compelling arguments as to why **the establishment of a correlation between the deployment of infrastructure and economic growth is problematic**. He presents arguments such as that (i) even where correlations have been found showing that the deployment of infrastructure lead to economic growth that additional infrastructure of the same kind does not necessarily lead to more economic growth, (ii) **many projects have a welfare focus** e.g. congestion elimination and so may not *ceteris paribus* lead to an increase in growth, (iii) **infrastructure are homogenous and difficult to value** e.g. how should one evaluate the lifetime contribution of the Suez Canal to economic output and (iv) it is the **usage of infrastructure rather than its deployment that should be assessed** and this is a function of whether infrastructure is priced/free of charge and is under-utilized/congested.

Nonetheless (Prud'homme, 2005) leaves the reader in no doubt that the right infrastructure in the right place have both economic and welfare benefits. Three benefits he cites are:

- Welfare improvements of householders by having more reliable access to energy, water and telecommunications. These improvements he notes may also have economic benefits by improving the health and thus productivity of citizens.
- Lowered costs of the inputs, energy, water and telecommunications for business.
- Increased access to markets (goods, labor, capital). Qualifying this point he writes that it has been established that the productivity of workers in a city increases the faster they can get to work and infrastructure obviously impacts on this.

In distinguishing between infrastructure that has economic and welfare benefits from infrastructure that does not (Prud'homme, 2005) frames the discourse as being around three issues, **(i) ownership, (ii) user-fees and (iii) the cost-benefit analysis of proposed projects.** The first issue revolves around whether a piece of infrastructure is in public or private ownership or a combination of both. The second issue concerns whether users pay directly for the use of infrastructure or via their taxes. Both issues have implications for the financial viability of projects. For the third issue he describes how it often happens that in evaluating proposals ex-ante that costs are underestimated and numbers of users over-estimated and that this frequently explains the cost overruns that are associated with infrastructure projects. Related to the above discourse is the question as to whether the economic gap between developed and developing countries could be explained by the lack of infrastructure in the latter. (Prud'homme, 2005) argument is essentially that in order for developing countries to get the three benefits of infrastructure cited above, the combination of the three criteria given in this paragraph have to be gotten right. He does not see econometric or production function studies of the kind described by (Straub, 2007) as making a strong contribution in this regard.

(Kessides, 1993) argues for the **positive influence of infrastructure on economic growth but also on its role in improving quality of life**. This second point is similar to what (Prud'homme, 2005) describes as welfare gains. The main effect she cites is that infrastructure influences the marginal productivity of private capital. This in turn leads to reduced costs for production, a diversification of the economy, more efficient use of land, water and energy and improved worker productivity brought about by shorter commuting times and cleaner sources of water. The quality of life benefits she describes **include greater access to leisure amenities and communication possibilities**. In addition the author states that urban development can be constrained by a lack of infrastructure. (Straub, 2008) also takes up the quality of life dimension of infrastructure by emphasizing that infrastructure is essential for the provision of energy, water and telecoms to households and business. He writes that power outages lower productivity whereas internet connectivity increase it or **as in the African case, mobile communications increase the ability to do business**. In addition because the services provided by infrastructure make up such a proportion of the income of poorer households an improvement in the quality of infrastructure provides direct welfare improvements for them. (Kessides, 1993) describes gives five 'musts' for infrastructure to be successful. They are:

1. the acceptance that infrastructure cannot create economic potential only develop it
2. that the focus should not be on the investment, rather the service generated
3. that more productive investments should not be crowded out
4. that reliability and quality of service are essential
5. That user-charges should be included and they are good for protecting the environment and don't discriminate against the poor[4].

In summary the work of (Kessides, 1993; Prud'homme, 2005; Straub, 2007) suggest that there are multifaceted reasons for the deployment of infrastructure and that there are numerous criteria that must be satisfied for a particular project to be likely to contribute to economic growth.

How the construction and maintenance of infrastructure can be financed going forward

Whether publically owned or privately owned but regulated, the commissioning of the physical network infrastructure essential for economic development, have traditionally been the responsibility of government (LaRouche, 1995). In recent decades this has changed somewhat with the private sector taking a greater role in initiating and financing large-scale infrastructure projects (WEF, 2010) or

[4] Lecocq (in personal communication with the authors) highlights the trade-offs between equality and incentivisation that occur when urban and rural dwellers are charged the same user fees for utility services e.g. electricity and water, despite the cost premium inevitable in the delivery of such services to rural areas.

partnering with the state to do so via so-called public private partnerships (PPP). In a detailed report on infrastructure needs to 2030 the (OECD, 2007), write that the existing infrastructure in OECD countries needs to be maintained, upgraded and replaced. Reasons outlined for this are the need for improved economic performance and competitiveness, the increasingly networked economy, the aging society, and the onset of climate change. (US Census Bureau, 2012) estimate that the population of the USA is expected to grow from 310 million in 2010 to 400 million in 2050 thus pointing to additional reasons for additional deployment of infrastructure there. For developing countries (McKinsey & Company, 2013) write that access to water and sanitation is the critical driver of infrastructure building. Nonetheless they estimate that at current trends universal access to sanitation and improved water is more than 50 years away in most African countries. Focusing on the same point ("Physical Capital," 2012) estimate that $72 billion will be needed to meet millennium development goals for water and 7% of developing country GDP will be needed to fill the 'infrastructure gap' to bring developing country levels of infrastructure up to OECD levels[5].

(McKinsey & Company, 2013) however write that such deployment of infrastructure is '*simply not happening*' at the rate that it should be and that existing infrastructure is not being adapted to climate change. At the same time the (OECD and ECMT, 2007) warn that, "a gap is opening up in OECD countries between the infrastructure investments required for the future, and the capacity of the public sector to meet those requirements from traditional sources", and the (WEF, 2010) write that "many countries, developing and developed, are facing significant infrastructure deficits, owing to growing populations, urbanization, changing demands and ageing assets." Reasons given (McKinsey & Company, 2013) for this are that an increasing amount of government budgets are going on social expenditures including public health, governments not being able to keep up with the complexity and size of the infrastructure that has been deployed, and tighter public budgets. The (OECD, 2007) write that gross fixed capital formation (GFCF) in OECD countries fell from 9% of GDP in 1990 to 7% in 2005 while at the same time social expenditure increased from 16% to 21%. Problems the (OECD, 2007) say that the failure to keep up with infrastructure requirements has implications for are living standards and quality of life via, increased congestion, unreliable supply lines, blunted competitiveness, and growing environmental problems. The US Chamber of Commerce decry the drop in spending on infrastructure in the USA between 2005 and 2009 and have started the 'let's rebuild America' campaign (U.S. Chamber of Commerce, 2011) which promotes the benefits to the economy of physical infrastructure. (The Economist, 2014) blame the banks for escalating the problem by not releasing capital or only offering 70% of costs since the financial crisis. A similar situation is reported for Australia (KPMG, 2011) with a large proportion of the infrastructure there reaching the end of its useful life and bottlenecks at container ports, inadequate rail systems, congestion on urban roads, struggling public transport, water shortages in our cities, over-allocated rural water systems and an increasingly straining electricity network. The EU write that investing in natural ecosystems as part of societal infrastructure may be long-run beneficial but the funding is not there now (EC, 2013b).

[5] The Indonesian government have recently announced plans (Yulisman, 2013) to offer up to 30 sizeable infrastructure projects (e.g. projects on dams, airports, railways, ports, toll roads and power generators) totaling US$32.74 billion to investors starting next year, under a public-private partnership (PPP) scheme

The solution according to the (WEF, 2010) is to allow private investment to do what governments are fiscally constrained from doing. On this point (The Economist, 2014) write that there should be a natural match between the long term nature of infrastructure projects and the timeframes of pension funds, insurance and sovereign wealth funds. For the case of the US IHS, (Geddes, 2014) write that funding maintenance through gasoline taxes is no longer working[6] as inflation has decreased the value of the taxes and less gasoline is being purchased anyway because drivers are switching to smaller cars or ethanol fueled cars. They write that it is not politically feasible to address this by increasing gasoline taxes and that in any case congressional administered maintenance and infrastructure funding is prone to inefficiencies in its allocation brought about by the 'pork barrel' or 'earmarking' system (Winston, 2014). They propose an alternative funding system known as 'Mileage-based user fees' (MBUFs), whereby usage of the road is taxed rather than fuel usage. In addition they advocate that the MBUF schemes be privately managed so as to keep monies collected away from 'rent-seeking' politicians. However in the comments to (The Economist, 2014) the point is raised that such schemes merely allow for private monopolies to assume the role of 'rent-seeker' off projects that the taxpayer has historically paid for the construction of. (Lecocq and Shalizi, 2014) highlight that infrastructure investments are mostly lumpy, and thus large capital outlays and commitments are necessary for their actualization regardless of who provides financing. The (WEF, 2010) write that regardless of ownership being public or private that three requirements for successful infrastructure are that projects are that they are:

1. part of an economic vision for a country or region
2. somehow involve the private sector to benefit from efficiency gains
3. socially inclusive

The (OECD, 2007) write that 3.5% of GDP per annum is needed for investments in telecoms, roads, rail, water, electricity, oil coal and gas to 2030. They write that although this can be offset somewhat by increased tax revenue from more migrants in employment, more productivity and more consumption taxes, that the offset will not be significant .(Winston, 2014) suggests more tolls and user fees can help while (McKinsey & Company, 2013) see room for efficiency improvements as they write that infrastructure productivity has not improved in the US for 40 years. (McKinsey & Company, 2013) estimate that $57 trillion investment in infrastructure will be required from 2012 to 2030 to keep up with GDP growth, although that this is 60% more than what has been spent in the previous 18 years (1994 to 2012). In addition the (OECD, 2007) state that as well as the problem of infrastructure financing, there are the triple economic, social and environmental goals, that need to be optimized for maintenance and improving the efficiency of construction and operation.

For the purposes of this report the key finding here is that the financing the maintainence of infrastructure is as important as financing new construction.

[6] This is despite the fact that (RFF, 2009) write that 50% of the $60 billion federal infrastructure budget is spent on the IHS.

The role of infrastructure in the face of climate change and the possibilities for its adaptation

The third issue with infrastructure concerns how it should be adapted in light of climate change, its vulnerability to same, and its role in mitigating the impacts of climate change. This first two issues cover both the impact of climate change on individual pieces of infrastructure but also on the impact on the different engineering and economic systems that the infrastructure is part of. The key issues in this regard are cascading system failure (Wilbanks, 2014), ripple effects and resilience.

Cascading system failure arises because of the dependency of sectors of the economy and society on one another and thus that a failure of one piece of infrastructure, say, a bridge has implications for more than just the transport sector. An outline of the dependencies of the energy, ICT, transport and water sectors on one another elucidates this. The modern ICT sector is wholly dependent on the functioning of the energy sector for its power supply. In turn energy production is increasingly dependent on ICT for control and switching purposes and on water supply for cooling purposes. The ICT, energy production and water supply sectors are all dependent on the transport sector for getting their operatives to work (UK Department for Environment, Food & Rural Affairs, 2011). This outline shows how a failure in one sector has implications beyond the immediate sector (See also Figure 1 while (EC, 2013b) provide a table of risks divided by region of the EU). A straightforward example of such cascading system failure is where an electricity black-out stops waste-water pumps working and this leads to waste-water infiltrating the fresh-water-supply system (UK Department for Environment, Food & Rural Affairs, 2011). A recent catastrophic example of cascading system failure was the unintended consequences of the tsunami in Japan in 2011 causing failure of both the main and the auxiliary power supply to the cooling system at the Fukushima power plant. The implication of cascading system failure is that if there is more likelihood of systems failure in a changed climate that this is an issue for infrastructure that should be addressed[7].

[7] In the UK case the chief threat from climate change is increased flooding and subsequently the potential of flooding to cause the cascading failures described above (UK Department for Environment, Food & Rural Affairs, 2011). For the case of Australia increasing water shortages and bushfires are also highlighted as being the most likely threats to infrastructure from climate change (State of Victoria, Department of Sustainability and Environment, 2006).

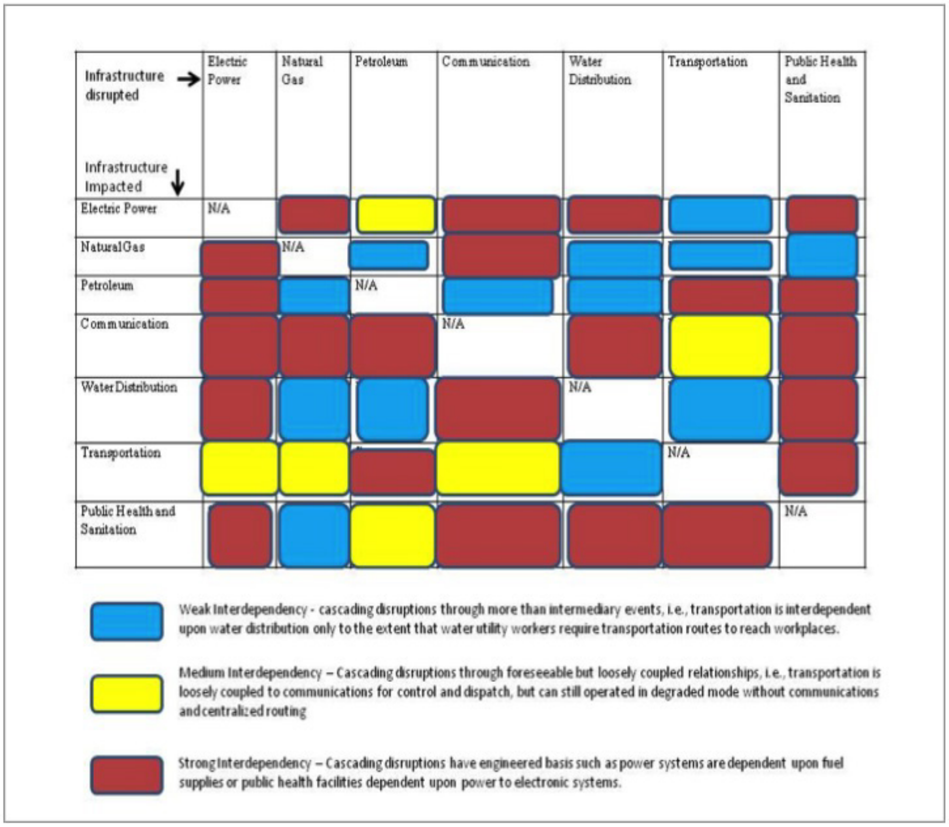


Figure 1 : Infrastructure and System dependencies and vulnerabilities (Wilbanks, 2014).

The threat of climate change having an international ripple effect is also highlighted in the literature e.g. flooding in South Korea effecting US computer manufacturing by the loss of key components, droughts in Russia or USA affecting global agri-business and car manufacturing in Detroit being defendant on supply lines from Mexico. A positive ripple effect is also described for example the widening of the Panama Canal increasing business for the Port of Miami in Florida (Revello, 2014) and the boom in demand for mineral resources in Australia leading to the construction of $100's of billions of dollars of infrastructure there (KPMG, 2011).

The threats from cascading system failure and international ripple effects suggest that planning and deployment of infrastructure now needs to proceed within the new framework of climate change and the associated risks. (UK Department for Environment, Food & Rural Affairs, 2011) state that policy will have to change anyway because the existing infrastructure has been engineered for the current climate (which is going to change) and new infrastructure will last for the next 50 to 100 years. ("Physical Capital," 2012) write that there is an urgency with addressing these issues given that there is such a huge potential for regret with infrastructure choices. In this regard they contrast Atlanta and Barcelona which are two cities of equal population but vastly different population densities. (State of Victoria, Department of Sustainability and Environment, 2006) write that dense cities are less vulnerable to shocks in energy supply because of their transport infrastructure. (Royal Academy of Engineering, 2011) on the other hand write that urban areas are particularly at risk of supply chain disruption and from flooding because increasing areas under concrete means there are less places for rain water to go.

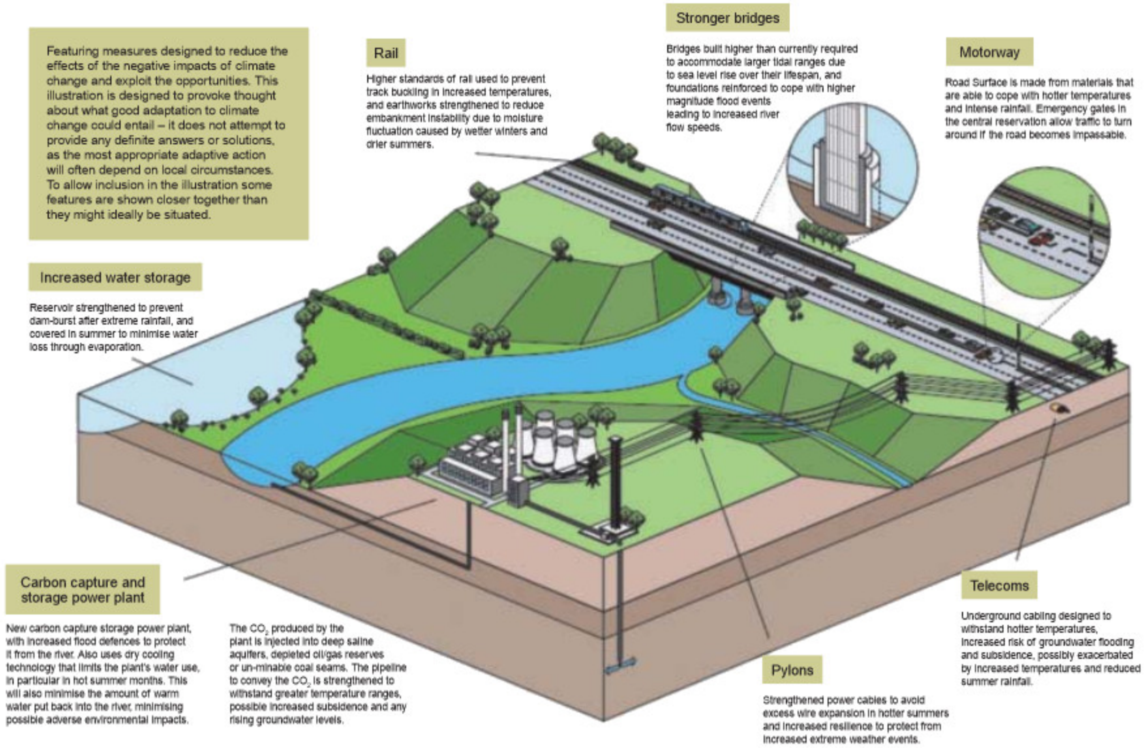


Figure 2 : Solutions to make infrastructure more resilient and adapted to climate change (UK Department for Environment, Food & Rural Affairs, 2011).

(Royal Academy of Engineering, 2011) write that infrastructure, or the systems they are part of, need resilience to shock events and adaptation to higher levels of water. (State of Victoria, Department of Sustainability and Environment, 2006) write that coordinated infrastructure planning and built in redundancy is needed to increase resilience, and that forecasts of climate change must be meaningfully incorporated into infrastructure planning. (Wilbanks, 2014) writes that more drainage will be needed if there is going to be more rainfall. ("Physical Capital," 2012) however suggest that there may be a trade-off between building right (to adapt to climate change) and building more (to meet demand brought about by increased urbanization) which highlights again the question of financing. In this regard (EC, 2013b) write that climate change does not alter the need for infrastructure but it may increase the cost. Figure 2 shows some approaches for adapting infrastructure and increasing resilience for the case of the UK.

(Hallegatte, 2008) however suggest an alternative approach. Because adaptation is costly and it is difficult to estimate the cost correctly given the uncertainty associated with climate change and freak events, he advocates what he calls, soft adaptation. For the case of adaptation to the increased possibility of flooding he calls hard adaptation the construction of a preventative sea wall while soft adaptation he describes as where no sea-wall is constructed but instead early warning systems are improved thus saving the money for other welfare expenditure. His point is salient in light of the increased difficulties in funding new infrastructure outlined in the previous section. On the debate of how to adapt, (EC, 2013b), write that Coastal forest rehabilitation and dike building are better than constructing seawalls while (Hallegatte and Dumas, 2009) write that on some occasions natural disasters may be a blessing in disguise as they allow for a renewal of infrastructure.

In terms of mitigating the effects of climate change it is clear that infrastructure is critical. The IPCC AR5 (2014) citing (Müller et al., 2013) describe an "infrastructure gap" between the existing per capita physical infrastructure in industrialized countries and that which has yet to be constructed in developing counties. This is the same gap attributed to the OECD in the previous section. Merely the construction of this infrastructure[8] i.e. not counting its use, is estimated by the authors to account for 30 % of the emissions budget calculated to keep global warming at the 2°C limit. This highlights the potential of the construction of new infrastructure to vastly exacerbate the climate problem. In summarizing findings of their Urban Infrastructure Initiative (WBCSD, 2014) write that the pursuit of sustainability will typically necessitate major transformations in the design, construction and operation of a city's infrastructure systems – including buildings, energy, mobility, telecommunications, water, sanitation and waste management services – and optimizing the inter-linkages between these systems. ("Physical Capital," 2012) also highlight that car ownership increases dramatically at annual household incomes of $6,000–$8,000, thus providing a threshold after which infrastructure needs for transport could be expected to increase in the absence of a transport policy that anticipates this demand growth. On this point (EC, 2013b) write that modal shift in transport needed because technical change can only bring about so much. In addition low price elasticity means that demand reduction through price increases is difficult. Thus the example of Atlanta and Barcelona given above by ("Physical Capital," 2012) is relevant for the long term infrastructure choices being made to fill the infrastructure gap given the level of urbanization currently under way in the developing World. It also highlight's the spatial planning dimension of infrastructure i.e. the location of settlements and the implications for resource allocation and greenhouse gas emissions. Related to this ("Physical Capital," 2012) write that 'getting infrastructure "right" is at the heart of green growth'. However 'getting it right' also involves trade-offs between the ability of infrastructure to or solve a problems e.g. the reduction in greenhouse gas emissions possible from the construction of renewable energy systems on the one hand, and the disutility that can occur for people living in their path of such systems the other. This highlights the so-called NIMBY or not-in-my-back-yard issue.

While it is difficult to accurately account for increased spending on infrastructure that will be necessary for mitigation and adaptation purposes the key finding here is that for low-carbon scenarios to succeed there will have to be increased financing directed towards infrastructure that deals with these needs.

[8] Physical infrastructure projects by their very nature cause the emission of greenhouse gasses from the extraction of materials and the use of large quantities of concrete and steel for their construction. These emissions are separate from those that occur from the use of infrastructure and are can be measured using the so-called embodied energy of the infrastructure.

3. Task Outputs

This section describes three of the four outputs from this task. The first output described is a **synthesis of a stocktaking exercise** where five of the modelling teams from the ADVANCE project filled out a questionnaire on how they currently model infrastructure and how they consider it could be undertaken in the future. The second output is a reduced form model of grid requirements for VRE deployment which includes a '**Rules of thumb**' for the relevant relationship. The third is the description of a **reduced form model of transport infrastructure** and its associated costs as developed for the IMACLIM-R Global E3 IAM. This includes the results of **scenarios explored** using the IMACLIM-R Global E3 IAM. The literature review described in Section 2 is the fourth output from the task. In addition to the four outputs a generic table of infrastructure costs used in four IAM models has been assembled. Thisis described in the Discussion section.

3.1 Task Output: Synthesis of a stocktaking exercise

Six teams behind the following models participated in the stocktaking exercise: IMACLIM-R, IMAGE, MESSAGE, REMIND, TIAM-UCL and GEM-E3. The exercise itself consisted of a ten-page questionnaire that included general and specific questions about the approach to modelling infrastructure adopted by each team and also their respective visions for how modelling should develop. The full answer from each team plus, a synthesis of replies is given in the appendices/supplementary material. The following section provides a summary of responses received.

Summary of replies to stocktaking exercise by six modelling teams

Views expressed on how modelling infrastructure should develop ranged from those of the minimalist to those of the expansionist. According to the former, one outcome of Task 5.4, could be the finding that modelling infrastructure in global IAMs is not necessary. If this is found to be the case it must be that demand in e.g. the transport sector, can be modelled satisfactorily regardless of the necessary underlying infrastructure e.g. based on the number of vehicles and shares of different modes in use. Supporting this idea, David Green's presentation to the ADVANCE meeting at IIASA, suggests that modelling the infrastructure itself may be too complicated to be worth the effort. One of the modelling teams have suggested in their reply that this may be the case. Against this view another of the teams have stated that: we suggest that the representation of infrastructure is quite important in Integrated Assessment energy-economy models in particular for assessing mitigation costs as the lack of the appropriate infrastructure might act as barrier to entry for new technologies. The exact modelling that should be adopted can potentially range from a very simplistic representation of additional costs for infrastructure to implementing certain investment projects in a detailed infrastructure model.

If infrastructure is to be modelled, the most basic way to do so, according to the replies received, is that the costs of and barriers to infrastructure deployment are included and that year on year the costs change linearly. Barriers can be overcome once a threshold level of deployment is reached or surpassed. This is already done in the IMAGE model where investments into the electric grid are described and add to the costs of electricity. Electric vehicles for example are then only introduced in IMAGE at a rate that is consistent with the expansion of the corresponding infrastructure to provide power. Data for such an exercise is available from an IEA database containing data for more than 1300 individual projects in 110 countries (See IRF, UIC, ITDP, and EMBARQ).

Four of the six modelling teams, REMIND, TIAM-UCL, MESSAGE and GEM-E3 advocate a more detailed approach to modelling infrastructure. Some propose the use of infrastructure specific sub-modules to do this. Key areas connected to the role of infrastructure that the modelling teams are interested to examine are; barriers and bottlenecks to deployment of low carbon energy and transport solutions, costs, network effects (non-linear/S-shaped), path dependencies and lock-ins, embodied energy, effect on price of energy, feasibility of mitigation options and financing. Niche critical infrastructure suggested to model are; LNG terminals, T&D lines, CCS pipelines, access to electricity (electrification), integration of large amounts of RES and EV/H_2 deployment.

	IMACLIM	IMAGE	MESSAGE	REMIND	TIAM-UCL
Communications	NI	NI	NI	NI	NI
Water	NI	Irrigation pipes	Planning to work on water pipelines for utility scale energy production	Planning to work on water pipelines for irrigation and fresh water supply	NI
Energy	Following modelled implicitly. • HVDC/HVAC national and international grid connections (investments accounted for) • CCS pipeline grid (diffusion follows S-Shaped)	Following modelled spatially :as linear functions of demand • Natural gas grid • H_2 grid • RES sites (renewable infrastructure) • CCS pipeline grid :as non- linear functions of demand • HVDC/HVAC national and international grid connections • LNG Terminals In addition they are planning to model HVDC/HVAC inter - continental grid connections and have some data available	Planning to work on following • HVDC/HVAC national, international and intercontinental grid connections • RES sites • CCS pipeline grid • Underground CO_2 storage sites	Construction and maintenance of following modelled as linear functions of demand. Have some data to share. • Natural gas grid • District heating and cooling grid • H_2 grid • RES sites • CCS pipeline grid • Underground CO_2 storage sites In addition HVDC/HVAC national and international grid connections are modelled non-linearly and they are planning to model HVDC/HVAC inter -continental grid connections	Construction and maintenance of following modelled as linear functions of demand. Have data, can share. • Natural gas grid • LNG Terminals • H_2 grid • CCS pipeline grid • Underground CO_2 storage sites
Transport	Following modelled as linear functions of demand: • Airports • Motorways and link roads • BRT and Rail • EV	Following modelled as linear functions of demand: • EV recharging infrastructure • Fuel stations (oil products, biofuels, LPG)	None currently modelled. Working on including the following: • EV recharging infrastructure • Fuel stations (oil products, biofuels, LPG)	Construction and maintenance of following modelled as linear functions of demand. • EV recharging infrastructure • Fuel stations (oil	Construction and maintenance of following modelled as linear functions of demand. Have some data to share: • EV recharging infrastructure

	• Car-focused or public transport-focused city form	• H_2 refueling structure Planning to work on • Car-focused city form • Public transport-focused city form	• H_2 refueling structure	products, biofuels, LPG) • H_2 refueling structure Planning to work on a spatial dimension for the above.	• Fuel stations (oil products, biofuels, LPG) • H_2 refueling structure Planning to work on • Airports • Bike lanes • BRT (Bus Rapid Transport) • Footpaths • Motorways • Link Roads • Car Parking • Rail tracks
'Must-have' infrastructure in IAMs (based on order of preference given for different infrastructure) Note that three of the modeling teams (IMAGE, REMIND and TIAM-UCL) list the same 'must-have' infrastructure in IAMs: (1) EV recharging infrastructure, (2) Fuel stations (oil products, biofuels, LPG)and (3) H_2 refueling structure		• EV recharging infrastructure • Fuel stations (oil products, biofuels, LPG) • H_2 refueling structure	• HVDC/HVAC national and international grid and inter - continental grid connections • RES sites	• EV recharging infrastructure • Fuel stations (oil products, biofuels, LPG) • H_2 refueling structure • HVDC/HVAC national and international grid connections • Natural gas grid • District heating and cooling grid • H_2 grid • CCS pipeline grid • Underground CO_2 storage sites	• EV recharging infrastructure • Fuel stations (oil products, biofuels, LPG) • H_2 refueling structure

Table 1 : Summary of infrastructure modelled or planned to be modelled. NI = not important.

1. DEFINITION: Sectorial enabling physical infrastructure (of the energy, transport, water and communications sectors.)

All teams are happy with this definition although IMAGE add that boundaries might need to be specified in communication.

2. THEORETICALLY NECESSARY TO REPRESENT INFRASTRUCTURE IN GLOBALLY FOCUSED IAM MODELS?

IMAGE says that it is important to take infrastructure costs in to account but cite Korner and Green to say that modelling the transition to an alternative transport infrastructure is very challenging and might be not be necessary in IAMs. MESSAGE say water and energy infrastructure are relevant for their model but that road infrastructure would be beyond their scope.

Both MESSAGE and GEM-E3 say that lack of infrastructure can be a barrier to the economic potential of infrastructure for energy technologies e.g. HVDC transmission lines, recharging/refueling stations for EV (road transport electrification), gas or H_2 vehicles, and thus the costs of removing such barriers should be considered. In this vein TIAM-UCL say that representation of infrastructure is necessary to address some questions e.g. whether energy supply infrastructure will be a bottleneck for different energy futures.

REMIND look at other aspects such as the embodied energy in infrastructure, the Path dependencies infrastructure creates, and how the deployment of infrastructure can change the influence of carbon taxes if the infrastructure has itself changed the profile of energy use in a sector.

All six modelling teams agree that the costs of infrastructure should be included to allow proper accounting and correctly describe the costs of transition.

3. SHOULD INFRASTRUCTURE BE REPRESENTED IN YOUR OWN MODEL?

IMAGE think that the level of detail would be limited to infrastructure costs, and barriers/constraints. IMACLIM say yes infrastructure should be represented because it requires a significant share of global investments but also to make sure that the deployment scenarios for new technologies are "plausible". Both IMAGE and IMACLIM agree that the representation of infrastructure should not be too detailed, however MESSAGE say they could create *an infrastructure sub-module* to account for their required level of aggregation and GEM-E3 would be happy with detailed sectorial representation if the data for infrastructure was available. TIAM-UCL also mention the possibility of linking to other more detailed modules but also that for a given research question e.g. modelling modal shift possibilities in transport, that detailed modelling of transport may be appropriate. REMIND remind us that the feasibility of future power systems with high shares of renewable supply are contingent on an increase in long-distance electricity transmission from sites with favorable renewable resources to demand centers. However they add that a full representation of this aspect would require explicit modeling of individual supply and load centers in each global region, which would again make a long-term non-linear optimization model like REMIND too complex for solving and that the high level of aggregation in Global IAM models mean that stylized representations of infrastructure are necessary. However because they consider the role of infrastructure to be so critical to, (i) the deployment of new technologies, (ii) transport modal shift and (iii) lock-ins delaying climate policy, REMIND would like to take this as far as possible.

4. HOW WOULD YOU RANK ENERGY, TRANSPORT, WATER, COMMUNICATIONS?

All six models place energy first. Four place transport second, while MESSAGE places water second and IMAGE considers water to be equally important with transport. No model ranks Communications above 4th, however IMACLIM mentions that the possibilities for communication infrastructure replacing transport requirements could be important.

5. DOES YOUR MODEL INCLUDE ANY ENABLING INFRASTRUCTURE?

IMACLIM, MESSAGE and REMIND include energy transmission/distribution as a technology. For IMAGE investments into grid and the distance between potential renewable supply and load centers are described and add to the costs of electricity in the model. Access to electricity (% connected in developing countries) is also considered in the IMAGE model. TIAM-UCL include the costs of CCS pipelines whereas IMAGE include a spatial element to site costs for CCS by factoring in the distance from a model region to a storage site. REMIND increase the deployment of the CCS technology with increasing levels of storage.

For transport, REMIND currently only have energy distribution infrastructure modeled, but no modeling of road/rail infrastructure. IMACLIM have an aggregated representation of transport infrastructure (airports, roads for private cars, public transport) where their maximum capacity limits the mobility increase in the respective mode. Combined with this, IMACLIM have a maximum share of electrified vehicles (evolving in time as an S-shaped curve) that can be interpreted as representing infrastructure development needs to accompany the technology deployment. For IMAGE, electric vehicles are only introduced at a rate that is consistent with the expansion of corresponding infrastructure to provide power. This delay factor is modelled using a smoothing function affecting the portfolio of investments.

Both TIAM-UCL and IMAGE represent H_2 infrastructure while TIAM-UCL also represent oil refineries, primary energy mines/extraction technologies.

No model seems to represent water or communications infrastructure.

Based on the questionnaire it would appear that IMAGE has progressed furthest with representing infrastructure in their model. The representation of H_2 technology in IMAGE is worth highlighting for its similarity with S-Curve technology diffusion theory. In the start years of the model only small-scale H_2 options are available. However when the capacity gets above a certain threshold, large-scale options become available thus providing the option of much lower costs of H_2 production.

Based on the questionnaire it would also appear that the default representation of infrastructure in the models seems to be to treat it like a technology with costs.

6. DOES YOUR MODEL INCORPORATE NON-LINEAR NETWORK EFFECTS OF THE DEPLOYMENT OF ENABLING INFRASTRUCTURE e.g. AN INCREASE IN MOTORWAY CAPACITY LEADS TO A FACTOR GROWTH IN TRANSPORT EMISSIONS?

IMACLIM's use of an S-Curve for the deployment of EV's and their maximum capacity per transport mode are both nonlinear. In IMAGE HVDC/HVAC national and international grid connections, exogenous change of LNG share, and underground CO_2 storage sites are modelled non-linearly.

REMIND use geometric principles to develop a conservative estimation of long-distance grid costs arising from a given share of a VRE source in the electricity mix. The VRE overlay grid required to meet new VRE production is considered to be proportional to [Share of VRE in electricity production * VRE electricity production]. They refer to Eq. 5 in, Pietzcker et al, (2014) - Applied Energy. doi:10.1016/j.apenergy.2014.08.011.

7. DOES YOUR MODEL INCORPORATE SPATIAL NETWORK EFFECTS OF INFRASTRUCTURE DEPLOYMENT e.g. PROXIMITY OF SOURCES OF RENEWABLE ENERGY TO ELECTRIC LOAD PROXIMITY TO SITES FOR UNDERGROUND STORAGE OF CO2?

For solar, wind, ccs and H_2 IMAGE takes into consideration the geographic location of resources, sinks and loads. This is a form of a network effect. IMAGE also restricts deployment of both EV and H_2, at a rate at which matches the deployment of the necessary infrastructure, which itself is a network effect. REMIND distinguish between the VRE potentials of regions with an even distribution of resources (Japan, India, Europe) and other regions, in modelling how the necessary grid is deployed, which is a form of a spatial network effect.

8. **IF YOUR IAM MODELS THE NETWORK EFFECTS OF INFRASTRUCTURE DEPLOYMENT CAN YOU BRIEFLY OUTLINE HOW THIS IS IMPLEMENT (FUNCTIONAL FORM , PSEUDO CODE ETC) E.G. MODELLING A RELATIONSHIP BETWEEN THE CONSTRUCTION OF CO_2 PIPELINES FOR CCS AND DEMAND FOR FOSSIL FUELS?**

The threshold effects for the deployment of EV and H_2 outlined for IMAGE in the previous question give their modelling approach to these network effects.

REMIND have a quadratic scale-up of an overlay electricity grid for the scale-up of VRE.

9. DO YOU CONSIDER THAT IMPROVING THE REPRESENTATION OF INFRASTRUCTURE DEVELOPMENT IN GLOBAL IAMS WOULD INCREASE THEIR POLICY RELEVANCE AND THEIR ABILITY TO ASSESS ENERGY AND CLIMATE POLICIES AND PRODUCE IMPACT ASSESSMENTS OF MITIGATION POLICIES?

Five of the models agree that improving the representation of infrastructure development in global IAMs would increase their policy relevance. However there is not clear alignment on how this would happen. GEM-E3 on the other hand write that policy relevance is only possible if a sufficient level of detail and bottom-up data for investments and costs of energy and transport related infrastructure were properly incorporated in the multi-sectoral CGE modeling framework. IMAGE think results could influence timing and/or policy advice on infrastructure investments. REMIND emphasize the role of government in the provision of infrastructure which inherently gives such results policy relevance. They also emphasize the role of highlighting the negative role of new carbon-intensive infrastructure on future mitigation efforts. MESSAGE however consider that it is too early to say if results would be relevant because detailed studies on the importance of infrastructure have not yet been carried out by IAM's.

TECHNICAL QUESTIONS

1. ARE THERE NON-LINEAR SCALING RATIOS BETWEEN THE DEPLOYMENT OF RENEWABLES AND THE LOCATION, CAPACITY AND LENGTH OF THE ELECTRICITY GRID? IN THEORY AND IN YOUR MODEL.

In theory yes. In modelling only in REMIND and IMACLIM. For the latter renewable deployment is constrained by a S-shaped curve for its deployment over time while for the former see above. For IMAGE and MESSAGE costs increase linearly, while GEM-E3 may adapt a non-linear cost of integration of VRE from the PRIMES model (i.e. integration costs increase non-linearly when the share of VRES exceeds a certain threshold). From WP5.1 the REMIX model may be able to show the dependence of transmission on VRE share.

2. **ARE THERE ESTABLISHED LEVELS OF POPULATION DENSITY OR OTHER PARAMETERS e.g. CONGESTION, WHERE MODE SWITCHING FROM PRIVATE TO COLLECTIVE TRANSPORT OCCURS OR WHERE CERTAIN MODES BECOME VIABLE? IN THEORY AND IN YOUR MODEL.**

None of the models take this into account. MESSAGE write that this would be difficult to model in a global IAM. IMACLIM write that such thresholds are important as exemplified by Hong Kong where almost 80% of trips are made by public transport. GEM-E3 write that congestion plays an important role in determining the consumers' utility from public transport; this is not represented in GEM-E3, but that they can include the PRIMES-TREMOVE mechanism. IMAGE models the saturation of % GDP spent in the transport sector (TMB based on work of Zahavi), with an increasing share of car and faster modes.

Schafer, A., Heywood, J., Jacoby, H., Waitz, I., 2010. Transportation in a Climate- constrained World. MIT Press, Massachusetts.

Zahavi, Y., Talvitie, A., 1980. Regularities in travel time and money expenditures. Transportation Research Board.

3. IS THERE A RELATIONSHIP BETWEEN GROWTH IN AIR TRAVEL AND THE NUMBER AND CAPACITY OF AIRPORTS? IN THEORY AND IN YOUR MODEL.

IMACLIM is the only model that considers these two effects.

4. FROM A MODELLING PERSPECTIVE DO YOU CONSIDER THAT GROWTH IN TRANSPORT (IRRESPECTIVE OF MODE) FOLLOWS AN S-SHAPED DIFFUSION CURVE? IF SO DOES THE DEPLOYMENT OF INFRASTRUCTURE AFFECT THE POSITION ON THE CURVE. IN THEORY AND IN YOUR MODEL.

IMAGE agrees that growth of transport technologies does follow an S curved shape but in their model deployment of infrastructure does not affect the position of the curve. MESSAGE write that transport modal demands should be modelled to reach a saturation point, but that it is not necessary to model the infrastructure that supplies this demand and the demand itself does not need to be modelled as an S-shaped diffusion process. GEM-E3 write that the level of passenger cars per capita usually follows S-shaped diffusion curves and the deployment of the related infrastructure can have an impact on the position and the elasticity of the curve. Furthermore, there is a particularly strong correlation between road transport electrification and the provision of the related recharging infrastructure. IMACLIM write that growth in transport is not necessarily S-shaped and their model reproduces the pattern from Andreas Schaefer's papers. REMIND proposes the example that e.g. for BEV: if no recharging infrastructure is built, BEVs will never leave the "demonstration phase". If substantial infrastructure were provided for, the growth could be much faster than in a normal "market scenario"

Collantes, G., Melaina, M.W., 2011. The co-evolution of alternative fuel infrastructure and vehicles: A study of the experience of Argentina with compressed natural gas. Energy Policy 39, 664–675. doi:10.1016/j.enpol.2010.10.039

5. ARE THE POSSIBILITY OF TECHNICAL BREAKTHROUGHS IN INFRASTRUCTURE UTILIZATION e.g. HVDC (HIGH VOLTAGE DIRECT CURRENT) ELECTRICITY LINES TO BRING SOLAR ELECTRICITY FROM NORTH AFRICA TO EUROPE (e.g. DESERTEC) OR INCREASED INTEGRATION OF TRUCK AND RAIL FREIGHT TRANSPORT IN EUROPE (e.g. CARGOBEAMER) TOO SMALL TO CONSIDER IN GLOBAL IAM'S? IN THEORY AND IN YOUR MODEL.

GEM-E3 highlight that the role of HVDC lines for global IAM modeling highly depends on the level of regional/country disaggregation of the models, e.g. if the EU and the North Africa regions are explicitly modeled, then the issue of HVDC transmission becomes important especially in the context of decarbonisation. REMIND on the other hand think that a better understanding the possibility to have freight transport use electricity or H_2 is much more important than trade in electricity to MENA as freight transport is one of the bottlenecks of decarbonization in most IAMs. Both IMAGE and MESSAGE think it would be interesting to model both Desertec and Cargobeamer although MESSAGE would require the development of more detailed sub-models to do this.

6. IS THERE AN INTERACTION BETWEEN GAS PIPELINES AND LNG TERMINALS AND INTERNATIONAL GAS TRADE? IN THEORY AND IN YOUR MODEL.

All models agree that this relationship holds in theory.

For modelling IMAGE assumes that infrastructure exists and only account for costs.

MESSAGE can choose between (i) developing natural gas production within a given region (and building the requisite pipeline infrastructure, in a generic way) and (ii) building LNG terminals to import the gas from abroad (or to export it). There is no spatial component to these infrastructure installations, however; everything is done at the macro-region level.

GEM-E3 say that it is rather difficult to be modeled in the CGE framework due to the extensive data requirements and the very different national circumstances that affect international trade of natural gas (pipelines, liquefaction and regasification terminals, storage facilities) and gas import prices (spot prices, long term contracts prices based on oil indexation, LNG import prices, regulated prices in several parts of the world).

In IMACLIM a proxy to represent this relationship is under development.

REMIND write that such infrastructure in highly politicized e.g. Gas pipelines to EU from Russia that bypass Ukraine, and the US ban on export of shale gas, but at the same time wonder whether this is important for long-term modelling.

Holz, F., von Hirschhausen, C., Kemfert, C., 2008. A strategic model of European gas supply (GASMOD). Energy Economics 30, 766–788. doi:10.1016/j.eneco.2007.01.018

7. WATER IS ESSENTIAL FOR COOLING IN POWER PLANTS AND IRRIGATION OF BIOMASS. IS THIS HOWEVER AN ISSUE THAT CONCERNS INFRASTRUCTURE? AFTER ALL, FOR EXAMPLE, POWER PLANTS ARE USUALLY LOCATED CLOSE TO WATER SOURCES.

GEM-E3 and IMACLIM do not think this to be important for IAM's. REMIND say there is too little information to decide whether it is really relevant although they think it might be relevant for long distance water transport infrastructure. MESSAGE write that it could be an issue for certain technologies, like CSP, that might be located in more arid environments. In IMAGE, the only model that currently includes water, water demand of power plants is added to the regional water demand while water demand for biomass is based on balances in 0.5 x 0.5 degree grid cells. They do not include water infrastructure.

8. INFRASTRUCTURE PROJECTS EMBODY SIGNIFICANT AMOUNT OF ENERGY AND CARBON THAT HAVE BEEN UTILIZED IN THEIR PRODUCTION AND THE EXTRACTION OF THEIR COMPONENT MATERIALS. IN A GENERAL EQUILIBRIUM MODEL THIS ENERGY USE IS CAPTURED IN THE EVOLUTION OF TOTAL DEMAND FOR ENERGY. IN A PARTIAL EQUILIBRIUM IT MAY BE CAPTURED BY THE EVOLUTION OF DEMAND FOR MATERIALS IN THE INDUSTRY SECTOR. DO YOU CONSIDER HOWEVER THAT IT WOULD BE POSSIBLE OR USEFUL TO EXPLICITLY MODEL OR QUANTIFY THE EMBODIED ENERGY IN YOUR MODEL?

The MESSAGE model could account for the embodied energy and emissions in infrastructure. However, they are not sure if they would model infrastructure requirements in the first place. GEM-E3, IMACLIM and REMIND think embodied energy it is important and could be useful to examine. REMIND suggest that the methodologies being discussed in WP5.2 for own energy consumption of energy technologies could be relevant supply while IMAGE think that this would probably be mostly important for building stock. TIAM-UCL undertake other work where it is possible to consider indirect/embodied emissions of energy.

Federici, M., Ulgiati, S., Basosi, R., 2008. A thermodynamic, environmental and material flow analysis of the Italian highway and railway transport systems. Energy 33, 760–775. doi:10.1016/j.energy.2008.01.010

Federici, M., Ulgiati, S., Basosi, R., 2009. Air versus terrestrial transport modalities: An energy and environmental comparison. Energy 34, 1493–1503. doi:10.1016/j.energy.2009.06.038

9. ACCORDING TO THE OECD, GOVERNMENTS IN OECD COUNTRIES ARE HAVING INCREASING DIFFICULTY IN FINANCING THE MAINTENANCE AND CONSTRUCTION OF INFRASTRUCTURE. IF THIS SITUATION CONTINUES AND PRIVATE CAPITAL DOES NOT FILL THE DEFICIT, THERE WILL BE A SUB-OPTIMAL DEPLOYMENT OF INFRASTRUCTURE. IS THIS ANYTHING THAT CAN BE CONSIDERED IN YOUR IAM?

For the detailed bottom up models; TIAM-UCL, IMAGE, MESSAGE and REMIND, who generally assume well-functioning markets, such a scenario would require a more detailed, multi-sector macro-economic model, than they currently have. For the two general equilibrium models, IMACLIM considers that such a scenario could be possible while GEM-E3 state that: a neutral way to include public financed infrastructure investments is to assume that the government would retain a balanced budget or a solvent debt (i.e. by redirecting funds from other sources). If any of the two conditions is not met then sub-optimal infrastructure should lead to lower total factor productivity of the economy and in particular in the energy/transport related sectors.

10. The motorway infrastructure and its maintenance is obviously critical to the just-in-time approach. As the IPCC highlight 'returning to more localized sourcing and relaxing just-in-time pressures,' as a possible mitigation and risk abatement measure, is this anything you think can be considered in IAM's?

Although IMAGE could incorporate freight demand reduction due to localized sourcing, this will not impact the installed motorway infrastructure or maintenance as they are not explicitly modelled. MESSAGE think that the same modelling could be best done by CGE style IAM's but they caution that there could be a net increase in energy demand from more localized production because of local industry being less efficient than global. REMIND think that there are too little micro studies examining these questions for the data to be there to examine the question properly in IAM's. GEM-E3 think modelling this effect would be difficult while IMACLIM say that they can adjust the input-output coefficient of transport demand by sectors in their production process.

11.Based on the previous question do you think that IAM's can be used to highlight the actual purpose of use of infrastructure or the drivers of growth in infrastructure construction?

Both MESSAGE and IMACLIM agree that IAM's are not the best tools to analyze such questions although some crude representations (e.g., increased vehicle-km demand) could be made. GEM-E3 highlight that CGE IAMs can quantify the macro-economic and employment impacts of alternative scenarios assuming different deployment of infrastructure. IMAGE does not link evolution in transport demand to evolution in infrastructure. They agree that such a relationship is possible but does not align with their model structure.

12.Given that there are diverse drivers of deployment of infrastructure e.g. alleviation of congestion, meeting demand, just-in-time, mitigation of climate change, increased connectivity, welfare improvement; does it make sense when modelling in IAM's to go beyond linear cost-markups? A 'linear' scenario for infrastructure expansion could assume "policies lead to optimal infrastructure build" while a 'non-linear' scenario could assume "policymakers do not plan ahead,

thus relevant infrastructures are not in place, thereby reducing growth in related transport/energy".

Both TIAM-UCL, MESSAGE and IMAGE agree that this would be difficult in IAM's. TIAM-UCL propose some stylized representations of questions of special interest. REMIND suggest that modeling the long-term vintage structure of infrastructure is more important than additionally modeling non-linearities in the infrastructure deployment. The first one (vintages) is necessary to realistically represent the costs of radically changing energy use in "delayed mitigation" scenarios. REMIND add however that if for example the initial part of infrastructure build-up would lead to substantially higher costs per final energy, then modeling this initial hurdle might be necessary for realistic scenarios, especially in recursive-dynamic models that don't care about the intertemporal optimum.

13.**Do you think there are infrastructure bottlenecks that would fundamentally constrain growth in the transported quantities, such as an upper limit to car/truck transport due to congestion and no further space to build roads (first in cities, possibly also in intercity travel) at high population densities? Do you model them?**

No team models such effects at the moment. IMAGE and MESSAGE question whether congestion at an urban level has an impact on long term transport demand. IMACLIM suggest that there are probably no "physical" constraints but some might be voluntarily engineered by policies that disincentivise the use of car/truck transport. Both GEM-E3 and REMIND think that such constraints are relevant. GEM-E3 would like to see this analyzed as part of ADVANCE. REMIND already assume a saturation in the demand for transport energy as incomes increase.

14.**Do you differentiate between expansion of infrastructure that is driven by national, regional (e.g. Benelux, Scandinavia) and international trade/transport demand? If yes, how do you determine the ratios between the different categories?**

Apart from IMAGE no other model makes this distinction. IMAGE differentiates between national and international shipping of freight, and treat them as two different modes in the model. The demand for these modes in IMAGE is based on historical data, similar to the method applied to project the demand for the other transport modes.

PREVIOUS and CURRENT WORK

1. CAN YOU SUGGEST ANY REFERENCES TO WORK, NOT NECESSARILY IN IAM'S, WHERE THE MODELLING OF INFRASTRUCTURE HAS BEEN UNDERTAKEN AT A REGIONAL OR GLOBAL SYSTEMS LEVEL?

H_2 infrastructure:
N. Johnson, (2012), Detailed spatial modeling of coal-based hydrogen infrastructure deployment with carbon capture and storage: methods, implications, and insights, doctoral dissertation.
N. Johnson and J. Ogden (2012), A spatially-explicit optimization model for long-term hydrogen pipeline planning. International Journal of Hydrogen Energy, 37(6): p. 5421-5433.

CCS infrastructure:
N. Johnson and J. Ogden, Detailed spatial modeling of carbon capture and storage (CCS) infrastructure deployment in the southwestern United States, poster presentation at the International Conference on Greenhouse Gas Technologies (GHGT), Amsterdam, The Netherlands, Sept. 19-23, 2010, in Energy Procedia. 4: p. 2693-2699.
R.S. Middleton, J.M. Bielicki, A scalable infrastructure model for carbon capture and storage: SimCCS, Energy Policy, 37 (2009) 1052-1060.

HOLZ, F., VON HIRSCHHAUSEN, C., 2013. THE INFRASTRUCTURE IMPLICATIONS OF THE ENERGY TRANSFORMATION IN EUROPE UNTIL 2050 — LESSONS FROM THE EMF28 MODELING EXERCISE. Clim. Change Econ. 04, 1340006. doi:10.1142/S201000781340006X

Gas: Holz, F., von Hirschhausen, C., Kemfert, C., 2008. A strategic model of European gas supply (GASMOD). Energy Economics 30, 766–788. doi:10.1016/j.eneco.2007.01.018

H_2: Stiller, C., Bünger, U., Møller-Holst, S., Svensson, A.M., Espegren, K.A., Nowak, M., 2010. Pathways to a hydrogen fuel infrastructure in Norway. International Journal of Hydrogen Energy 35, 2597–2601. doi:10.1016/j.ijhydene.2

Murthy Konda, N.V.S.N., Shah, N., Brandon, N.P., 2011. Optimal transition towards a large-scale hydrogen infrastructure for the transport sector: The case for the Netherlands. International Journal of Hydrogen Energy 36, 4619–4635. doi:10.1016/j.ijhydene.2011.01.104009.04.003

Paolo, A., 2007. Hydrogen infrastructure for the transport sector. International Journal of Hydrogen Energy 32, 3526–3544. doi:10.1016/j.ijhydene.2007.02.016

CCS: Jung, J.-Y., Huh, C., Kang, S.-G., Seo, Y., Chang, D., 2013. CO2 transport strategy and its cost estimation for the offshore CCS in Korea. Applied Energy 111, 1054–1060. doi:10.1016/j.apenergy.2013.06.055

Eccles, J.K., Pratson, L., 2014. A "carbonshed" assessment of small- vs. large-scale CCS deployment in the continental US. Applied Energy 113, 352–361. doi:10.1016/j.apenergy.2013.07.002

HOLZ, F., VON HIRSCHHAUSEN, C., 2013. THE INFRASTRUCTURE IMPLICATIONS OF THE ENERGY TRANSFORMATION IN EUROPE UNTIL 2050 — LESSONS FROM THE EMF28 MODELING EXERCISE. Clim. Change Econ. 04, 1340006. doi:10.1142/S201000781340006X

Schaber, K., Steinke, F., Mühlich, P., Hamacher, T., 2012. Parametric study of variable renewable energy integration in Europe: Advantages and costs of transmission grid extensions. Energy Policy 42, 498–508. doi:10.1016/j.enpol.2011.12.016

Bioenergy: See BeWHERE model (Sylvain Leduc, IIASA) and GBSM (Nathan Parker, UC-Davis)

LCA-relevant references:

Jorge, R. S. and E. G. Hertwich. 2014. Grid infrastructure for renewable power in Europe: The environmental cost. Energy 69: 760-768.

Arvesen, A., R. Nes, D. Huertas-Hernando, and E. Hertwich. 2014. Life cycle assessment of an offshore grid interconnecting wind farms and customers across the North Sea. The International Journal of Life Cycle Assessment 19(4): 826-837.

Turconi, R., C. Simonsen, I. Byriel, and T. Astrup. 2013. Life cycle assessment of the Danish electricity distribution network. The International Journal of Life Cycle Assessment: 1-9.eg

Bergerson, J. A. and L. B. Lave. 2005. Should We Transport Coal, Gas, or Electricity:? Cost, Efficiency, and Environmental Implications. Environmental Science & Technology 39(16): 5905-5910.

Edgar G. Hertwich, Thomas Gibon, Evert A. Bouman, Anders Arvesen, Sangwon Suh, Garvin Heath, Joseph D. Bergesen, Andrea Ramirez, Mabel Vega Coloma, Lei Shi, 2014. Integrated life cycle assessment of electricity supply scenarios confirms global environmental benefit of low-carbon technologies, PNAS

2. CAN YOU SUGGEST ANY SYNERGIES BETWEEN THIS TASK AND OTHER TASKS IN THE PROJECT? THE FOLLOWING TASKS FOR EXAMPLE HAVE BEEN MENTIONED AS HAVING OVERLAP: DATA (2.1), HYBRID MODELING (2.3), BEHAVIOR (3.1), VRE (5.1), LCA (5.2) AND WATER (5.3). PLEASE DESCRIBE BRIEFLY THE SYNERGIES YOU SEE POSSIBLE (EVEN WITH THE TASKS NAMED IN THE PREVIOUS SENTENCE).

TIAM-UCL: Behavior (transport and mode shift)

MESSAGE : Behavior (3.1) could have some synergies in that infrastructure availability (namely for refueling/recharging) contributes to decisions to purchase particular alternative fuel vehicles. VRE (5.1) has several synergies. First, an accounting of the transmission costs for connecting remote VRE may reduce the economic potential or increase the cost. Second, transmission can be used to reduce integration costs by minimizing curtailment and matching VRE supply with demand. Finally, infrastructure can have implications for water availability and thus has synergies with Water (5.3).

REMIND: WP5.1: REMIX is modeling grid requirements for Europe in dependence of VRE shares. Currently, there is no work yet on the geographical influence on electricity grids in different regions – if WP 5.4 could provide anything in this direction, it would be very helpful. WP5.2: It would be great if the "LCA-cards" that are prepared for the main Energy conversion technologies were also prepared for the main types of infrastructure.

GEM-E3: Synergies perhaps with task 5.1 (integration of variable RES) and hybrid energy-economy modeling and split of IO tables (task 2.3)

IMAGE: Increase in VRE penetration (5.1) is expected to result in an increasing demand in infrastructure.

DATA

1. CAN YOU SUGGEST ANY WAY IN WHICH THE COST OF DEPLOYMENT OF INFRASTRUCTURE CAN BE ESTIMATED? OR SOURCES OF CURRENT DATA?

MESSAGE: In MESSAGE, it is currently introduced as a variable operating cost that increases with VRE deployment. To do it right, you'd have to do regional spatially-explicit modeling of infrastructure deployment.

REMIND: We had an intern calculate costs for distribution and transmission grids in Germany, using data published by the TSOs, which was not always self-consistent. Hydrogen infrastructure:

Köhler, J., Wietschel, M., Whitmarsh, L., Keles, D., Schade, W., 2010. Infrastructure investment for a transition to hydrogen automobiles. Technological Forecasting and Social Change 77, 1237–1248. doi:10.1016/j.techfore.2010.03.010

GEM-E3: http://ppi.worldbank.org/

Jonas Egerer, Clemens Gerbaulet and Casimir Lorenz, "European Electricity Grid Infrastructure Expansion in a 2050 Context", Deutsches Institut für Wirtschaftsforschung, 2013

IMAGE: IEA database containing data from IRF, UIC, ITDP, and EMBARQ. In particular, the database includes cost data for more than 1300 individual projects in 110 countries. IEA ETP 2012.

3.2 *Task Output: Rules of Thumb' on Long-distance transmission grid requirements from variable renewable energies*

An overlapping theme between the workpackages 5.1 and 5.4 of ADVANCE is the need to extend the long-distance transmission grid for integrating variable renewables into the power system. When the amount of wind and solar in a power system increases, the variability between high and low supply increases. As weather patterns are limited in size and demand schedules also depend on regional specificities, pooling generation and demand across larger spatial regions can flatten the residual load and reduce the demand for backup capacities and other flexibility options.

WP5.1 studied the different challenges of integrating variable renewable energies (VRE) with the help of the detailed hourly dispatch and investment model REMix (Scholz, 2012), which ran a large number of scenarios to map the dependence of different challenges on the share of wind and solar in the generation mix. As REMIX represents most EU countries individually and endogenously calculates cost-optimal investments into grid infrastructure between the countries, these scenarios can also be used to derive generalized rules for additional long-distance transmission from wind and solar.

Model Description:

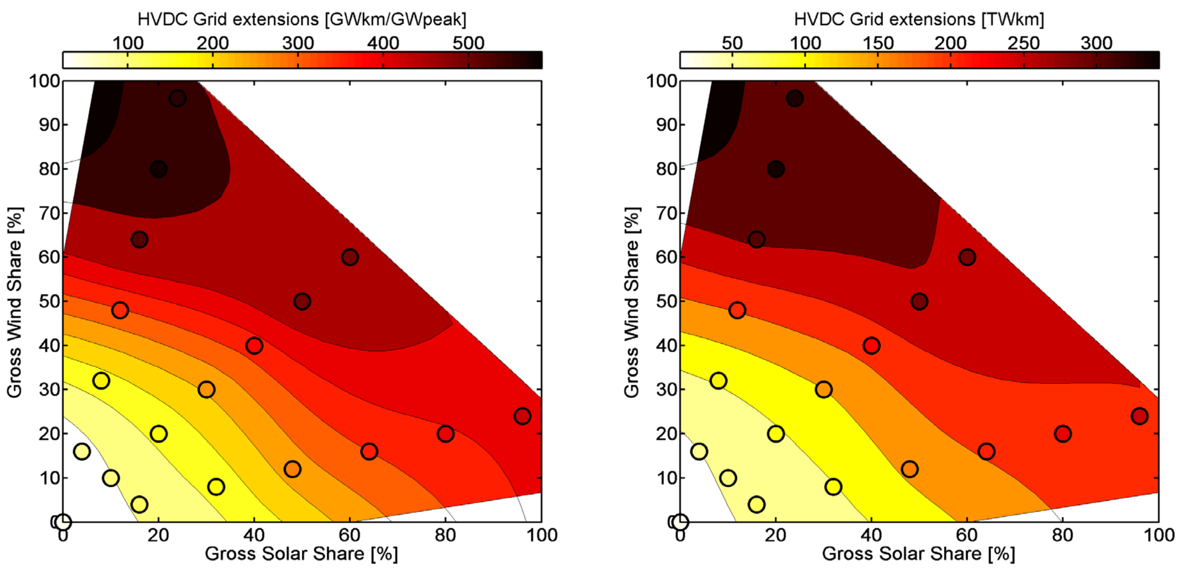
REMix is a deterministic linear optimization program realized in GAMS that minimizes total power system costs given certain boundary conditions. It has been developed as core element of the REMix modelling environment, with the aim of providing a powerful tool for the preparation and assessment of future energy supply scenarios based on a power supply system representation in high spatial and temporal resolution. Power generation, storage and grid technologies are represented by their available and maximum installable capacity, investment and operation costs, as well as efficiency. Investments in new capacities consider the technology costs, as well as an amortization time and interest rate, allowing for the calculation of proportionate capital costs for the chosen optimization interval.

REMix-OptiMo is a multi-node model. Demand and supply within predefined regions are aggregated to model nodes, which can be connected through electricity grids. Within the nodes, all generation units of each technology are grouped and treated as one single power or heat producer. The model relies on a perfect foresight modelling approach and optimizes over the overall time horizon, which is typically one year, with hourly resolution.

REMix accounts for the three main benefits from transmission grid extensions, namely a) reduced peak capacity requirements, b) reduced curtailment of VRE, and c) higher utilization rates of conventional power plants. It also represents the costs as well as transmission losses associated with high-voltage direct current (HVDC) lines and converter stations: The model assumes DC transmission power losses of 0.45%/100 km on land and 0.27%/100 km in sea cables. Additional 0.7% is lost at conversion from and to AC. Investment costs differ substantially for overland lines on the one hand and sea cables on the other: values of 490 k€/km and 1953 €/km are applied, respectively. Additional costs of 162 000 k€ each arise from the installation of converter stations. All components have an amortization time of 40 years and annual fixed operational costs equivalent to 0.6% of the investment (Scholz et al., 2015). The grid capacity expansion is limited to point-to-point DC connections between neighbouring model regions. HVDC lines with a nominal power of 1.5 GW can be added up to an overall capacity of 30 GW per connection.

Results:

Figure 3 shows the resulting cost-optimal transmission grid expansion in dependence of the theoretical share of wind and solar in the scenarios with a CO_2 price of 150€/tCO_2. While some grid expansion compared to today's level is beneficial even at 0% wind and solar, one can clearly observe how the transmission grid becomes more relevant for the EU power system as VRE deployment increases.



1

Figure 3: DC transmission capacity installation total (left) and relative to peak demand (right) in the scenarios with a carbon price of 150€/tCO_2. The wind and solar shares on x- and y-axis are the share of gross wind/solar production (before curtailment) in total electricity demand, thus values >100% are possible (Net shares stay below 100%)

Figure 4a shows the resulting total costs for the transmission grid extension, while Figure 4b displays the grid costs per unit of used VRE electricity. It also presents a linear regression of grid costs on wind and solar shares which can easily be incorporated in any integrated assessment model.

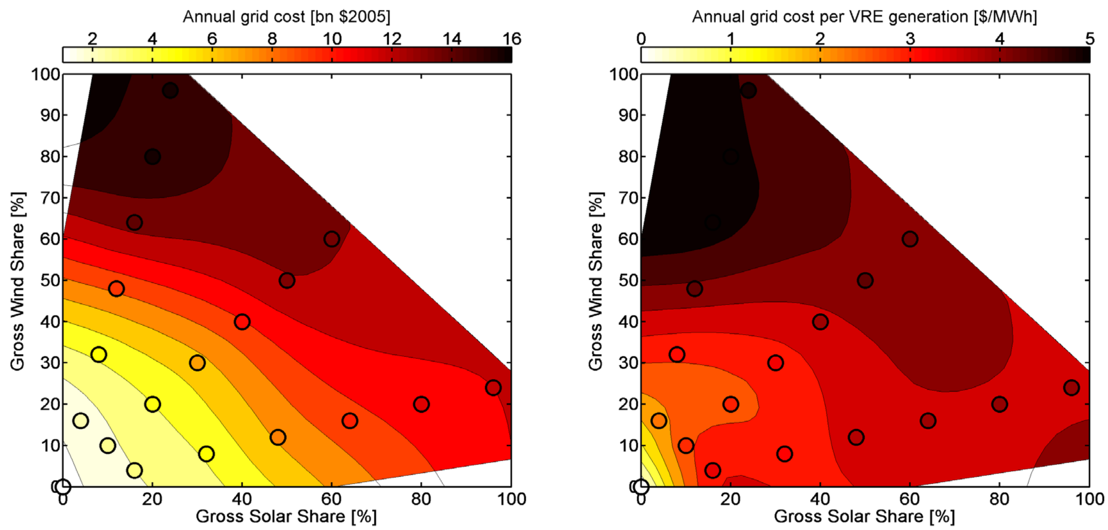


Figure 4: Costs for transmission grid expansions in scenarios with a carbon price of 150€/tCO_2. Total annual costs for expanded transmission grid (left), average annual grid expansion costs per MWh of net VRE generation (right). The depicted wind and solar shares are the share of gross wind/solar production (before curtailment) in total electricity demand, thus values >100% are relevant (Net shares in all depicted scenarios stay below 100%) ..

Deriving a "rule of thumb" for the grid requirements from VRE:

From the REMIX results, it is possible to derive simplified equations that represent the additional costs for long-distance transmission grids from the deployment of VRE. These equations can then be included in IAMs to improve the consistency of the IAM scenario results.

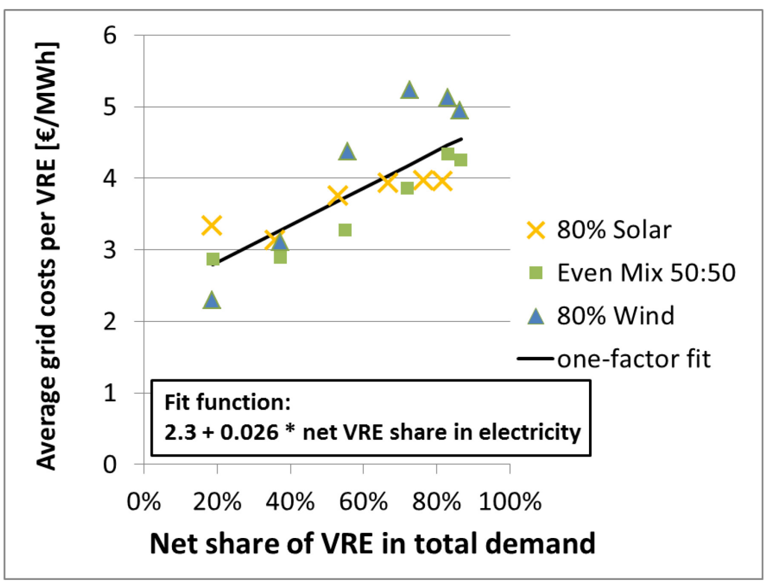


Figure 5a: Average integration costs for transmission grid extension per unit of net VRE over net share of VRE in total demand (markers). The plotted fit is the linear regression of the costs on the combined net wind and solar shares.

We here derive two equations of different complexity, to allow modelers to choose which level of accuracy they want to achieve, and which computational price they are willing to pay. We first develop an a representation where the required long-distance transmission expansion depends only on the amount and share of VRE electricity, but not on the mix between wind and solar (see Figure 5a):

Average grid costs per VRE production [$/MWh]= 2.3 [$] + 0.026 [$/%] * net VRE share [%]

Total grid costs [$] = 2.3 [$] + 0.026 [$/%] * net VRE share [%] * total net VRE production [MWh].

The more detailed representation displayed in Figure 5b also includes the impact of the mix between wind and solar. As can be seen in Figure 4, deploying wind increases the grid requirements faster than deploying solar. Accordingly, the more detailed equations are:

Average grid costs per VRE production [$/MWh]=

0.053 [$/%] * net wind share [%] - 0.002 [$/%] * net solar share [%]

+ 0.035 [$/%] * share of solar in (solar + wind) [%] + 0.011 [$/%] * share of wind in (solar + wind) [%]

Total grid costs [$] =

(0.053 [$/%] * net wind share [%] - 0.002 [$/%] * net solar share [%]) * total net VRE production [MWh]

+ 3.5 [$/MWh] * total net solar production [MWh]+ 1.1 [$/MWh] * total net wind production [MWh]

With this formulation, one clearly sees that wind requires less grid at low shares, but the requirements increase fast with rising wind share, while for solar the grid requirements start high at low solar shares and stay relatively flat as the solar share increases.

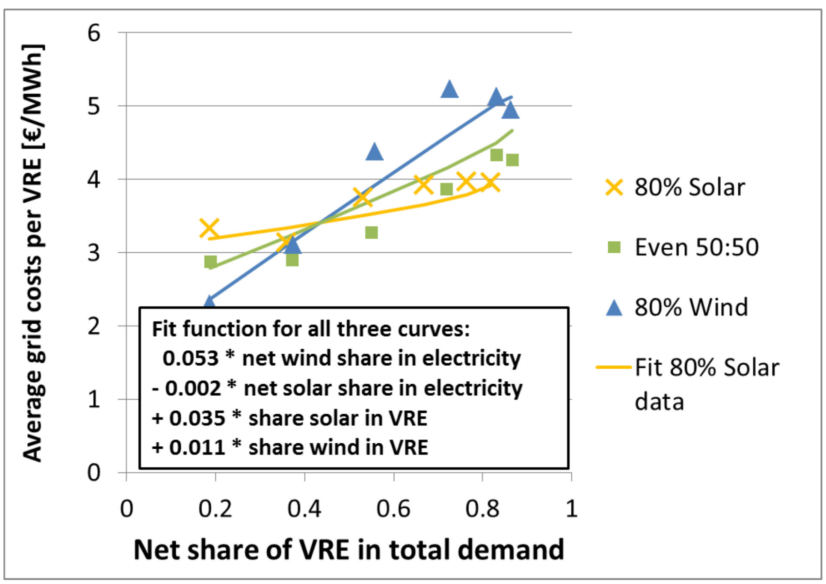


Figure 6b: Average integration costs for transmission grid extension per unit of net VRE over net share of VRE in total demand (markers). The three lines result from applying the regression equation to the different scenarios with a 50:50, 20:80 and 80:20 mix between wind and solar.

3.3 Task Output: Reduced form model of transport infrastructure

This section describes the model developed to analyze the role of infrastructure and the various scenarios explored. The methodology can be said to involve model development and scenario implementation.

The IMACLIM-R model used in this exercise is a hybrid dynamic general equilibrium model of the world economy that covers the period 2001–2100 in yearly steps through the recursive iteration of annual static equilibria and dynamic modules. The annual static equilibrium determines the relative prices, wages, labour, value, physical flows, capacity utilization, profit rates, and savings at a year *t* as a result of short-term equilibrium conditions between demand and supply of goods, capital, and labour markets. The dynamic modules are sector-specific reduced forms of technology-rich models, which take the static equilibria at a year *t* as an input, assess the reaction of technical systems to the economic signals, and send new input–output coefficients back to the static model to allow computation of the equilibrium for year *t* + 1. (Waisman et al., 2013; Winning, 2015)describe the architecture of the IMACLIM-R model in more detail.

Transport infrastructure in the IMACLIM-R Global model is represented by a variable called *Captransport* and as the name suggests it represents the available transport capacity for various modes. *Captransport* combines three vectors of transport modes (air, public, road) per IMACLIM global region into a matrix. Public transport is made up of both bus and rail transport and has the label *OT* (other) in the model. Infrastructure for freight transport is not considered. The units of *Captransport* are passenger kilometers (*pkm*). In the model to date (pre April 2015) its values of *pkm* were initialized for the year 2001 (calibration year of the IMACLIM model) by assuming that the capacity of each mode is twice the respective measured *pkm's*. For example, for China for 2001, 142 Billion *pkm's* of air transport were measured as being flown. Thus the capacity of air transport in China in 2001 is assumed to be 284 Billion *pkm*. For subsequent model years (2002 to 2100) the *Captransport* variable is always kept at twice the size of whatever number of *pkm's* the model has calculated. This can be understood as conforming to a congestion avoidance scenario. In addition to this, the construction and maintenance of infrastructure has happened cost free to date. In other words although varying levels of transport infrastructure were deployed each year, there were no costs assigned to this deployment[9].

The number of *pkm's* per mode per year is calculated as part of the model static equilibrium, whereby a representative household in each model region, maximizes their utility (U_k) under constraints of income and a travel time budget. The first step in this process is the definition of, $S_m^{(0)}$, the minimum needs of mobility for commuting and shopping. The amount of additional mobility, $S_m - S_m^{(0)}$, purchased by the representative household, is a factor of income, levels of congestion, a time budget and the price of alternative goods and services. As income increases the representative household can travel further within mode or by switching mode, within a fixed time budget of 1.1 hours and thus obtain more utility from transport. Equation 1 shows how mobility (*S*) , for region (*k*), is the sum of four modal

[9] The model assumed a constant level of investment in construction each year but this was not linked to infrastructure deployment (See Figure 8 below). In the model development described this link has been established.

choices, the proportion of each being determined by a region-specific elasticity (η) of substitution to the increase in total mobility and (b) represents a proportion of basic transport needs.

$$S_{k,mobility} = \left(\left(\frac{pkm_{k,air}}{b_{k,air}} \right)^{\eta_k} + \left(\frac{pkm_{k,public}}{b_{k,public}} \right)^{\eta_k} + \left(\frac{pkm_{k,cars}}{b_{k,cars}} \right)^{\eta_k} + \left(\frac{pkm_{k,nonmotorized}}{b_{k,nonmotorized}} \right)^{\eta_k} \right)^{-\eta_k} \quad (1)$$

The substitution between modes and thus the total pkm travelled in each mode within the time travel budget is constrained by the level of congestion in the supporting infrastructure. As the utilization rate of e.g. roads, increases, congestion increases and speed decreases thus limiting the distance that can be travelled and ultimately the level of utility from transport. This development is shown in Figure 1.

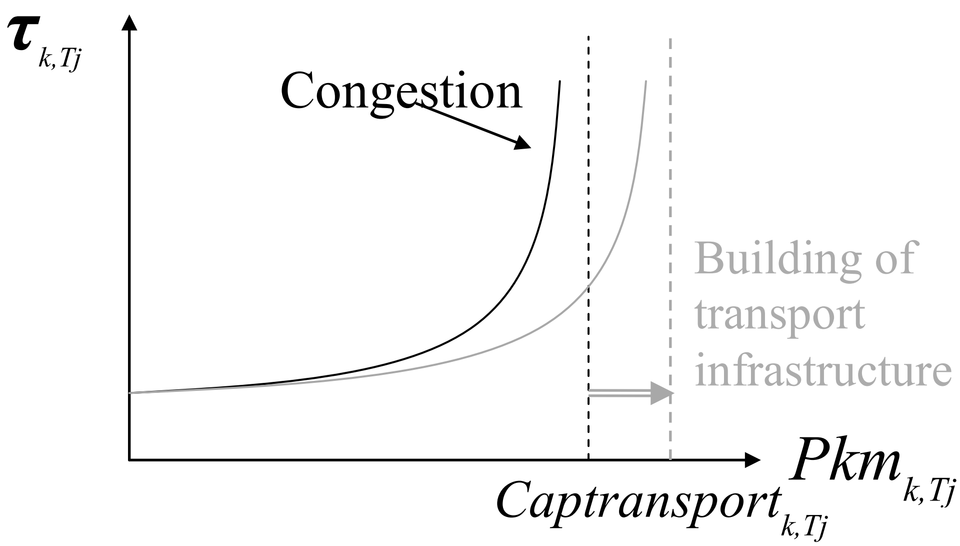


Figure 7 : Marginal efficiency in transport time (the time necessary to travel an additional passenger.kilometer with mode Tj in region k)

The total level of mobility (Sk) is calculated in a trade-off with its cost and the cost of other goods, subject to a regional specific elasticity of utility to the increase in income (ξ) as shown in Equation 2. The steps involved in calcuating the division of income between transport and other services and thus the maximum utility (Uk) occur in one general equilibrium calcuation.

$$\boldsymbol{U_k}\left(\vec{C}_k, \vec{S}_{\boldsymbol{k}}\right) = \prod_{\substack{\text{goods } i \\ \text{services } j}} \left(\mathrm{C_{k,i}} - bn_{k,i}\right)^{\xi_{k,i}} \left(S_{\mathrm{k,j}} - bn_{k,j}\right)^{\xi_{k,j}} \quad (2)$$

Starting in April 2015 an exercise has been conducted as part of the ADVANCE project (Work package 5.4) in which a new approach to updating the *Captransport* variable has been implemented. In addition the costs associated with infrastructure have been included in the model. In the new implementation, the change in *Captransport* for each mode is modelled to change linearly according to the change in *pkm's* travelled in the previous two years. For roads (used for automobiles but not public transport i.e.

for the purpose of modelling it can be understood that public transport (bus + rail) has a separate infrastructure) however the change in *Captransport* is also subject to the following six constraints, of which numbers 4 to 6 are new introductions to the model:

1. The utilization rate of the road network .
2. The change in the stock of vehicles.
3. Other drivers of road construction, such as upgrading.
4. The construction capacity in the region. See parameter 3 in Table 2.
5. The density of the existing road network. See parameter 5 in Table 2.
6. The maximum percentage of GDP that can go to infrastructure.

The first point emphasizes that existing roads may be underutilized and thus an increasing number of vehicles on the road or KM's driven does not necessarily mean that new roads are needed. The second point reflects that an increasing stock of vehicles can lead to increased travel use and pressure to build infrastructure. The third point reflects factors such as the desire to pave roads, or upgrade them to motorway, or to connect cities to ports, that drive construction regardless of apparent capacity. The fourth point seeks to incorporate the limits of the construction industry itself i.e. that a ramp-up in levels of construction can only happen if the requisite labor resources, and technical knowhow exist. The fifth point provides a realistic alternative to scenarios of linear growth of infrastructure capacity. In such linear growth scenarios the density of road infrastructure in India can reach the same level as that of Manhattan, New York, by 2050, a clearly implausible outcome (Dulac, 2013). The final point emphasizes the average percentage of GDP that has been spent on infrastructure to date. Of the six constraints listed above we considered two to be the main drivers of automobile infrastructure deployment: the target infrastructure utilization rate and the annual change in the stock of vehicles (linked to changes in personal income).

It is assumed that each region is striving for a roadway utilization rate of 50% (*UR_automobile_ideal*). Utilization rate in this sense is a modelling construct whereby the number of pkm's travelled is divided by the infrastructure capacity (also measured in pkm's) and measures levels of congestion. 50% is chosen as an average between the current high levels of utilization (90%) in Brazil i.e. a high level of road congestion and low levels (15%) in India i.e. a low level of road congestion[10].

[10] The data on road utilization (Dulac, 2013) are averages for regions, and thus the high levels of congestion in some urban districts should not be confused with these averages.

Road occupancy per region is calculated using paramaters 4 and 6 in Table 2.It is further assumed that for a region with a high utilization rate that it would take a number of years for the infrastructure expansion necessary to reach the the 50% target to be rolled out. To ensure this in the model it is assumed that a regions progress towards this target cannot change by more than 2% per year (*UR_automobile_inertia*). For a country with a utilization rate of nearly 90% e.g. Brazil, the massive investment in infrastructure that would be necessary to bring this down to 50% is modelled to only happen over 20 years (2% X 20 = 40%). Likewise for a region with a low utilization rate e.g. India, this *UR_automobile_inertia* parameter ensures that construction takes place regardless of the surplus capacity in the existing network i.e. an implementation of the third constraint listed above. Combining the existing utilization rate and, the change allowed given inertia, produces a target utilization rate (*UR_automobile_target)*. In parallel it is assumed that the number of *pkm's* for the following year (*pkmautomobile_anticip)* is anticipated to increases linearly as a function of the current and previous years *stock of vehicles and their average pkm's driven*. A combination of this anticipated pkm increase and the target utilization rate (as described in previous paragraph) gives the planned *Captransport(automobile)* for the subsequent year as follows:

capautomobile_target=pkmautomobile_anticip/UR_automobile_target (3)

This result is then compared against the fourth and fifth constraint listed above : (i) The construction industry capacity in the region, and (ii) The density of the existing road network. These are two checks on the amount of new road infrastructure that the model estimates. In both cases the idea with the constraint is to avoid the model proposing unrealistic levels of infrastructure expansion.

A variable *New_road*s is then defined as the difference between *Captransport(automobile)* from the previous year and that calculated according to the aforementioned constraints. *New_roads* is then added to *Captransport(automobile)* from the previous year to update this metric. Testing has shown that the updated value of *Captransport(automobile)* is often of the same size as *capautomobile_target*.

A final constraint on *Captransport(automobile)*, the sixth listed above, the amount of investment that can go on infrastructure (*Max_Infra_Road_Invest*), is then introduced. This has initially been set at 2% of the value of GDP. The 2% cap covers the cost associated with road infrastructure (construction, upgrade, O&M and parking spaces). Given the substantial road networks in place in OECD countries upgrade, O&M and parking spaces (Paramater 9 in Table 2) can combined make up over 50% of spending on road infrastructure. Model testing has shown that this constraint also prevents the capacity of road transport rising too fast. Despite the aforementioned constraints this can still occur in the model. This is because the increased capacity modelled for *Captransport* allows greater distances to be travelled (*pkmautomobile*) within the travel time budget (as modelled in the static equilibrium of IMACLIM), and thus *pkmautomobile_anticip* (see above) which is the basis for *capautomobile_target,* can increase rapidly. If it is found that the combined cost of roads, *C_roads*, exceeds 2% of GDP, the variable *New_roads* is recalibrated to be the length of road that would be possible to construct for the difference between 2% of GDP and the combined cost of road O&M, upgrade and parking spaces.

The method used for the deployment of infrastructure for public transport and airports has not been changed in the new version of the model, however the costs of their deployment have been included.

Note that the budget cap does not cover public transport or airports as their infrastructure costs should not be low as compared to GDP, but also because doing so would necessitate a decision as to how to allocate budget between road, public transport and air. In an alternative scenario other budget caps on spending for public transport or airports infrastructure could be introduced.

Thus to summarize Captransport (automobile) increases to meet the anticipated change in utilization rate, but within the bounds of a realistic level of construction, non-utilization centered motivations for increasing Captransport e.g. upgrade to motorway, the construction industries capabilities, the existing road density and the budget available for road infrastructure. The key parameters outlined above are presented in Table 2.

Table 2 : Modelling parameters for road infrastructure in IMACLIM-R Global model.

	Parameter Name	Value	Unit
1	UR_automobile_inertia	2	% increase or decrease in *UR_automobile_target* /year
2	UR_automobile_ideal	50	% pkm/Captransport
3	constr_limit	30 – 355[a]	Lane-km/year in thousands
4	occupancy_road_vkm	300 – 1150[a]	VKM/Lane-km in thousands
5	density_limit	1-6[a]	Lane-km per km^2 land
6	maxoccupancy_road	1200	Vkm/lane-km in thousands[b]
7	conv_pkm_lanekm	$4\text{-}5 \times 10^{-7}$	Lane-km/pkm
8	Max_Infra_Road_Invest	2	% of GDP
9	park_space	2X15 – 3X18[a]	Square Metres where 2x means two parking spaces
10	share_rail_OT	5 - 70[a]	%

[a]Varies depending on regional circumstances [b]Variable converted to pkm/lane-km using *conv_pkm_lanekm*

The above described constraints and costs for the roll-out of new automobile infrastructure are based on an approach carried out by (Dulac, 2013) for the IEA. Dulac's goal is to model realistic expansion of road infrastructure. The author has also carried out an extensive survey to establish average costs for road, and rail construction, upgrade and O&M for various World regions. Dulac's costs are used in this work to provide calibration values for the cost of infrastructure for the model calibration year, 2001. Costs for road infrastructure are made up of new roads and parking spaces, upgrade of existing roads and O&M for existing roads and parking spaces. Costs for construction and O&M of Air infrastructure (airports) were estimated independently using data from the (OECD, 2015). Table 3 lists the transport infrastructure costs as applied in this work. Dulac's models the expansion of transport relative to an ex-post evaluation of the increase in passenger service demand (pkm) between 2010 and 2030. In this work however, although the costs and principles of expansion are similar, the model works recursively year on year with attendant feedbacks such as changes in prices of energy.

Table 3 : Infrastructure costs assumed. O&M: Operations and maintenance.

IMACLIM REGION	Road Construction	Road Upgrade	Road O&M	Parking Construction	Parking Upgrade	Parking O&M	Public Transport Construction	Public Transport O&M	Air Construction	Air O&M
USA	1.2	0.2	0.03	300	240	9	0.5	0.05	0.25	0.0025
Canada	1.2	0.2	0.03	300	240	9	0.5	0.05	0.25	0.0025
Europe, Turkey	1.2	0.2	0.03	300	240	9	0.5	0.05	0.25	0.0025
JANZ, Korea	1.3	0.25	0.04	250	200	7.5	0.5	0.05	0.25	0.0025
CIS	1.2	0.2	0.03	250	200	7.5	0.5	0.05	0.25	0.0025
China	1.2	0.2	0.035	150	120	4.5	0.5	0.05	0.25	0.0025
India	1	0.15	0.03	150	120	4.5	0.5	0.05	0.25	0.0025
Brazil	1.1	0.2	0.035	150	120	4.5	0.5	0.05	0.25	0.0025
Middle East	1	0.15	0.03	175	140	3.6	0.5	0.05	0.25	0.0025
Africa	1.2	0.2	0.035	120	95	5.3	0.5	0.05	0.25	0.0025
Rest of Asia	1.1	0.15	0.033	150	120	4.5	0.5	0.05	0.25	0.0025
Rest of Latin America	1.1	0.2	0.035	150	120	4.5	0.5	0.05	0.25	0.0025
Unit	M$US2010/ lane-km	M$US2010/ lane-km	M$US2010/ lane-km	$US2010/ m^2	$US2010/ m^2	$US2010/ m^2	$US2010/ pkm	$US2010/ pkm	$US2010/ pkm	$US2010/ pkm
Notes	1	2	3	4	5	6	7	8	9	10

1. Data in Table 6 (Dulac, 2013) matched to IMACLIM regions
2. Data in Table 6 (Dulac, 2013)matched to IMACLIM regions. Assumed to occur every 20 years.
3. Data in Table 6 (Dulac, 2013)matched to IMACLIM regions. Assumed to occur every 4 years.
4. Data in Table 7 (Dulac, 2013)matched to IMACLIM regions. Assumed to occur every 20 years.
5. Data in Table 7 (Dulac, 2013)matched to IMACLIM regions. Assumed to occur every 3 years.
6. Data in Table 7 (Dulac, 2013)matched to IMACLIM regions
7. First lowest value from Table 13.5 (IEA, 2012) for capital construction per pkm assumed for each IMACLIM region. This assumption is based on the fact that public transport in IMACLIM is for both rail and busses whereas the data obtained is for rail. Note that although the data listed in Table 13.5 of (IEA, 2012) is given in Millions for pkm this is mistaken and the values should be in thousands. The data used is divided in two to reflect that it is for pkms, whereas in IMACLIM the cost of pkm for Captransport is wanted and Captransport for public transport is calibrated in 2001 to be two times the number of pkms.
8. First lowest value from Table 13. 5 (IEA, 2012) for O&M per pkm assumed for each IMACLIM region. This assumption is based on the fact that public transport in IMACLIM is for both rail and busses whereas the data obtained is for rail. Note that although the data listed in Table 13.5 is given in Millions for pkm this is mistaken and the values should be in thousands. The data used is divided in two to reflect that it is for pkms, whereas in IMACLIM the cost of pkm for Captransport is wanted and Captransport for public transport is calibrated in 2001 to be two times the number of pkms.
9. Time series data on investments in airport infrastructure from OECD (http://stats.oecd.org/Index.aspx?DataSetCode=ITF_INV-MTN_DATA) divided by data for air pkms from Schaffer.
10. Time series data on maintenance in airport infrastructure from OECD (http://stats.oecd.org/Index.aspx?DataSetCode=ITF_INV-MTN_DATA) divided by data for air pkms from Schaffer.

In IMACLIM-R costs are made up of price and volume. For the model calibration year (2001) the price of construction (for all sectors) is set to 1 while the volume is a dimensionless unit of construction, equal in absolute value to total investment in construction (infrastructure plus other construction investments). The price, as with the prices of in other sectors, evolves in the IMACLIM-R in response to the macroeconomic components of the model. Because both the prices and the size of the infrastructure evolve, the costs of infrastructure evolve too. Thus while the costs of infrastructure are defined for 2001 (see previous paragraph) they are scaled for each subsequent year by an index which represents the change in prices of the construction sector. For the costs some adjustments were needed. For example the costs for public transport seemed initially to be too high. This was found to be because they are for rail whereas the IMACLIM public transport variable also includes bus transport which is relatively cheap. Thus it was decided to multiply the costs for public transport construction by the share of rail in public transport (see parameter 10 in Table 2). It was also assumed that this share increases by 0.5% per annum for eight of the twelve IMACLIM global regions. The shares for USA, Canada, the EU and Japan were kept static. The notes under Table 3 give more detail on cost calibration issues.

For the baseline scenario GDP, population growth, and active population structure were harmonized to SSP2 projections. This is a new development in the IMACLIM model. Previously population growth was based on exogenous projections from the UN. GDP is an endogenous variable in IMACLIM which means that in order to ensure that GDP growth conformed to the SSP2 GDP scenario other parameters such as energy efficiency, fossil fuel resources and labour productivity needed to be adjusted. In addition process emissions from the production of cement have been added in the model so as to be able to measure embodied emissions resulting from infrastructure deployment.

The following steps thus summarize the model development.

- **Step 0**: Add industrial process emissions and harmonize population and GDP growth to SSP2. and harmonize population and GDP growth to SSP2.
- **Step 1**: Add costs for infrastructure deployment as per Table 3.
- **Step 2**: Add additional constraints on deployment of road infrastructure
    - The construction capacity in the region i.e. the workforce capability
    - The maximum road density in a region
    - The maximum percentage of GDP that can go to road infrastructure – set to 2%

The implementation of the above model improvements are described in the next section.

Scenarios of Transport Infrastructure deployment explored

This section presents results from the implementation of the model developments described in the previous section. This involves the implementation of a number of scenarios in the

IMACILM-R Global E3 model. The model, updated to include costs and the three additional constraints on expansion of *Captransport (automobile)* described in the previous section, was run to establish four baselines: with and without costs, and with and without constraints, on the deployment of infrastructure. The idea with these four variants was to isolate the effect of the introduction of costs and constraints on general baseline scenarios i.e. how significant an impact do the introduction of these additions have on the baseline that had heretofore been used. In addition a carbon constraint scenario and a carbon constraint plus restricted infrastructure scenario were run with all constraints and costs of infrastructure included. These latter runs were to investigate the role of a carbon price in isolation and also to see if non-price polices, such as restricted infrastructure expansion could have an effect. In detail this involved the implementation of the following two carbon budget scenarios.

1. CO_2 emissions constrained to 550ppm to 2100 plus costs for and constraints on the deployment of infrastructure being included.
2. CO_2 emissions constrained to 550ppm to 2100 and infrastructure deployment for roads and air travel constrained to 70% of what it was projected to be in Carbon Budget Scenario 2.

This section discusses results by focusing on key indicators such as GDP, CO_2 emissions, mobility (pkm's), modal shift, and infrastructure construction and its costs. It is divided into three parts that describe (i) variations on a baseline, (ii) model runs with carbon budgets and (iii) a section on infrastructure costs.

Baseline developments with improved modelling of infrastructure.

Figure 7 shows how the infrastructure in place for transport changes with the inclusion of first costs and then constraints and then both. It can be observed that the addition of costs for transport does not significantly change the amount of infrastructure deployed. This means that in the model that the investment needed to meet the demand for infrastructure is not a limiting factor. The investment made can be seen in Figure 8. On the other hand when the constraints (4 to 6 on page 36) are included it can be seen in Figure 7 that the amount of automobile infrastructure decreases while that for public transport and air travel increases. The trips not taken in cars are either avoided or taken in public transport or air travel instead and the infrastructure needed to meet this demand is rolled-out. The trajectory of distances traveled in each mode are very similar to those for infrastructure roll-out shown in Figure 7 with little impact of costs and significant impact from constraints. The magnitude of the increased demand for public transport and air travel is also helped by the fact that lowered demand for automobile transport lowers demand for oil and this energy prices. These are a small fraction of total costs for public transport and air travel and thus increase the desirablity of these modes for transport trips. It can also be observed that construction of new public transport and automobile infrastructure levels off after about 2060. This is as a consequence of large increases in oil prices brought about by reduced oil resources that occur after this date.

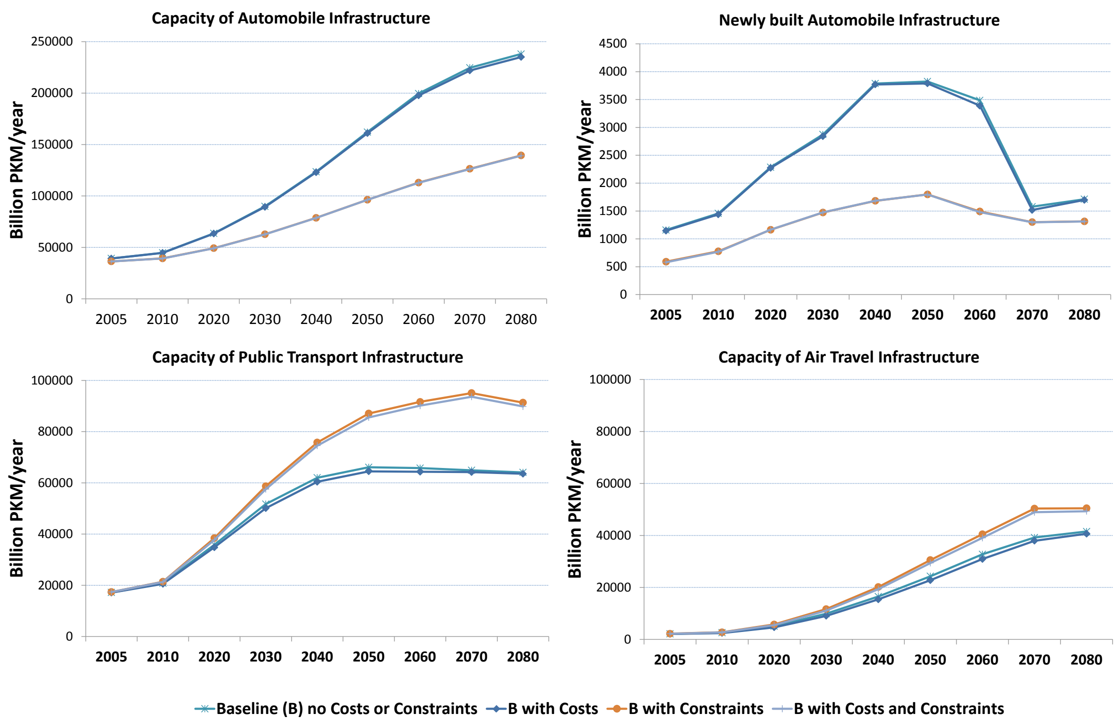


Figure 8 : Transport infrastructure deployment in Baseline Scenarios

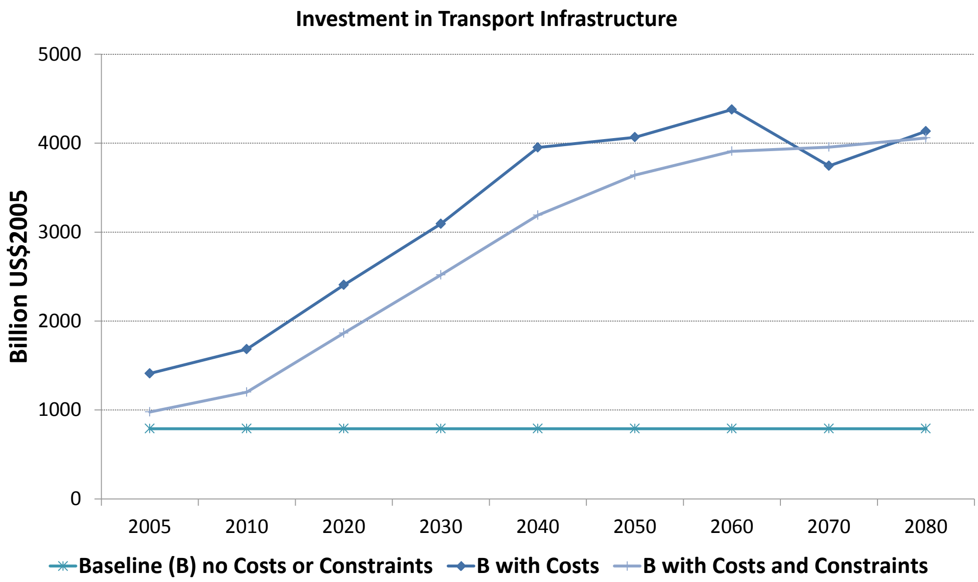


Figure 9 : Investment in Infrastructure in Baseline Scenarios

Figure 9 on left shows that the investment that needs to be made in infrastructure lowers total GDP slightly – the blue line is higher than the gold line. This can be interpreted as that the investment in infrastructure has been taken from more productive areas of the economy and has thus led to GDP being lowered. When constraints on the deployment of infrastructure are included, in addition to the costs, GDP actually rises. Although more investment is made in infrastructure in this case than in the no costs baseline, the lowered oil price that results from the decreased demand for automobile transport gives a boost to the economy. Thus although energy prices ultimately rise in the later decades of the scenario period because of decreased crude oil resources, this increase is lower in the constrained infrastructure deployment scenario than in the no-cost and just cost baseline thus increasing GDP relative to these two cases. Figure 9 on right hand side shows that the reduced demand for automobile transport in the restricted infrastructure baseline lowers CO_2 emissions from the sector relative to the two other baselines shown. Ultimately the increasing oil prices due to limits in oil resources lowers emissions for all of these scenarios after 2060.

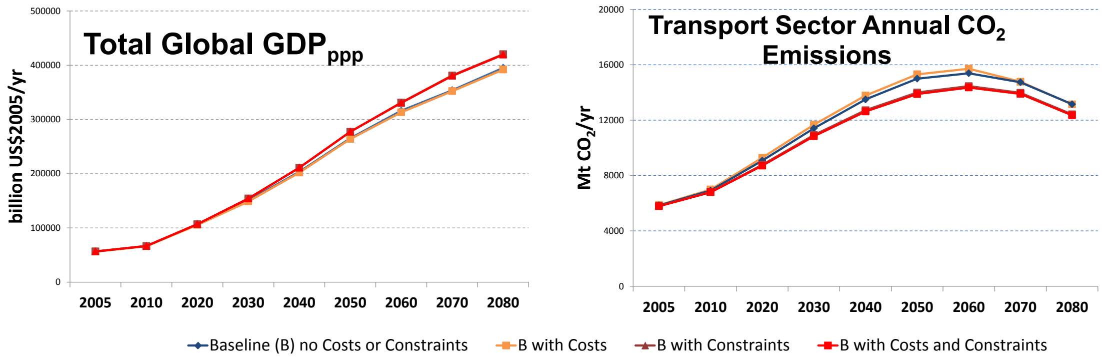


Figure 10 : GDP and CO_2 emissions from the transport Sector in Baseline Scenarios.

The key message in this section is thus that the baseline gets changed with the new approach to modelling infrastructure presented. Investments in infrastructure increase the activity of the construction sector and this slows structural change of the economy towards more productive and less carbon intensive sectors. This results in lowered GDP and higher energy and carbon intensity. Lower GDP lowers demand for oil and oil prices and given that energy is a small part of costs of public transport and air travel use of these two modes increases in response to the cheaper oil.

Carbon budget scenarios with improved modelling of infrastructure.

Introducing a constraint on the emission of carbon across the globe changes activity and carbon emissions in the transport sector. Figure 10 shows that pkm's driven per capita in automobiles falls while they rises for public transport and air travel. This results in a slight overall increase in the number of PKM's driven per capita in 2060 shown in the first panel of Figure 10. This is primarily due to the increase in public transport in the carbon budget scenario. It is interesting to note that even under the carbon emissions constraint that PKM's per capita of air travel increase as compared to a baseline. This is another effect of the price of energy not being a large part of the costs for air travel.

In the implementation of constraining carbon emissions to 550ppm by 2100 the carbon price rises to \$1000 a tonne of CO_2 by 2050. The effects of this cause GDP to decrease relative to a baseline. However when the deployment of infrastructure is restricted in addition to the carbon emission constraint being applied, the GDP loss is less than with the carbon emission constraint only. This suggests that restricting infrastructure lowers the cost of mitigation. This is shown in Figure 11. With the carbon budget fixed i.e. carbon targets are met, the lowered investment in transport infrastructure, and the 'relatively' lowered oil prices that this results in creates more activity in public transport and air travel (similar to as was described in the previous section) and also moves investment to more productive sectors. Thus the key meassage is that there is a double dividened from restricting infrastructure deployment – a lower cost of mitigation i.e. a better economy and less less use of automobiles.

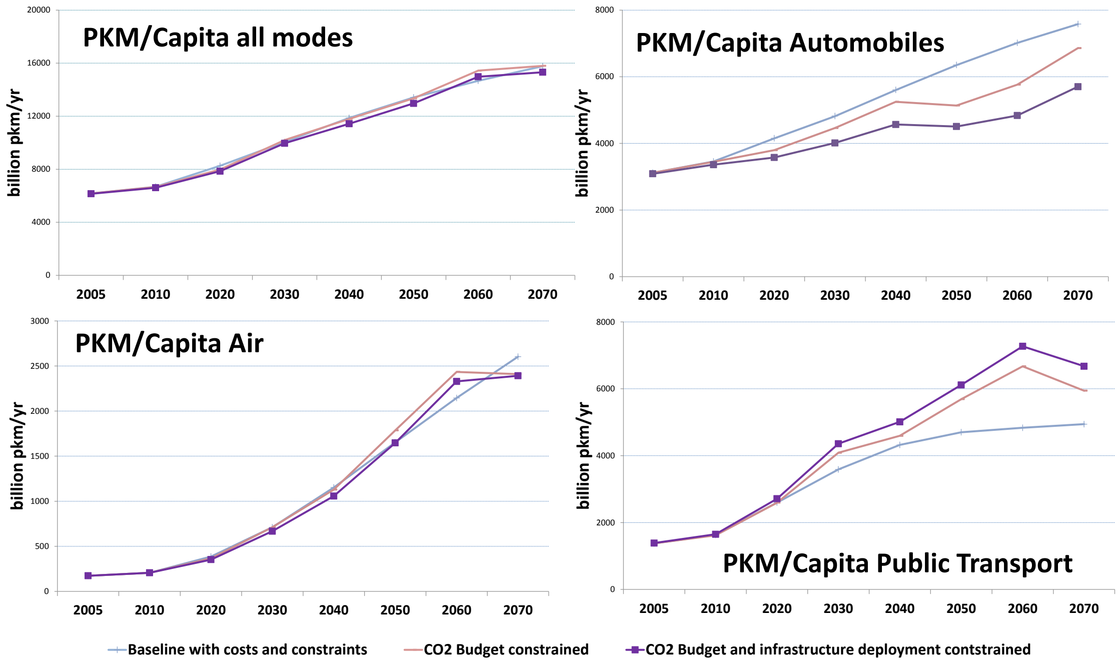


Figure 11 : Passenger Kilometeres (PKM's) under carbon emission constraint.

Exploring model results in detail allows the following analysis to be made concerning wider effects on the energy system of the effects of restricting infrastructure expansion. As GDP and thus income increase over the scenario period the options of travelling on faster modes of transport – automobile or airplane – becomes less attractive due to increased congestion. Because of this householders choose products other than transport services to use their income. This ultimately leads to increased demand in industry and in residential sector. The fall in demand for transport services decreases the prices of oil. As oil is a price leader for other energy carriers this lowers all energy prices. The fall in prices makes natural gas more attractive as an energy carrier in all sectors including electricity production and thus results in a decrease in electricity production from coal and nuclear energy. This also results in further extraction of natural gas resources but less extraction of unconventional oil resources.

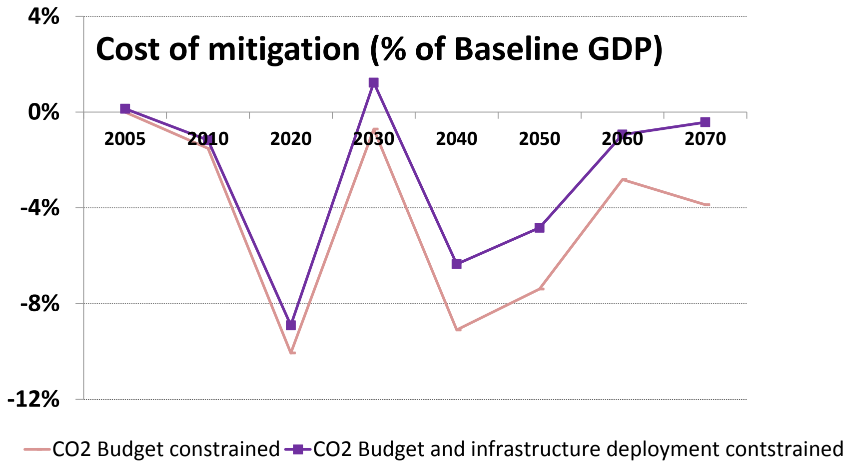


Figure 12 : Change in GDP in constrained carbon emissions scenarios.

Embodied Emissions

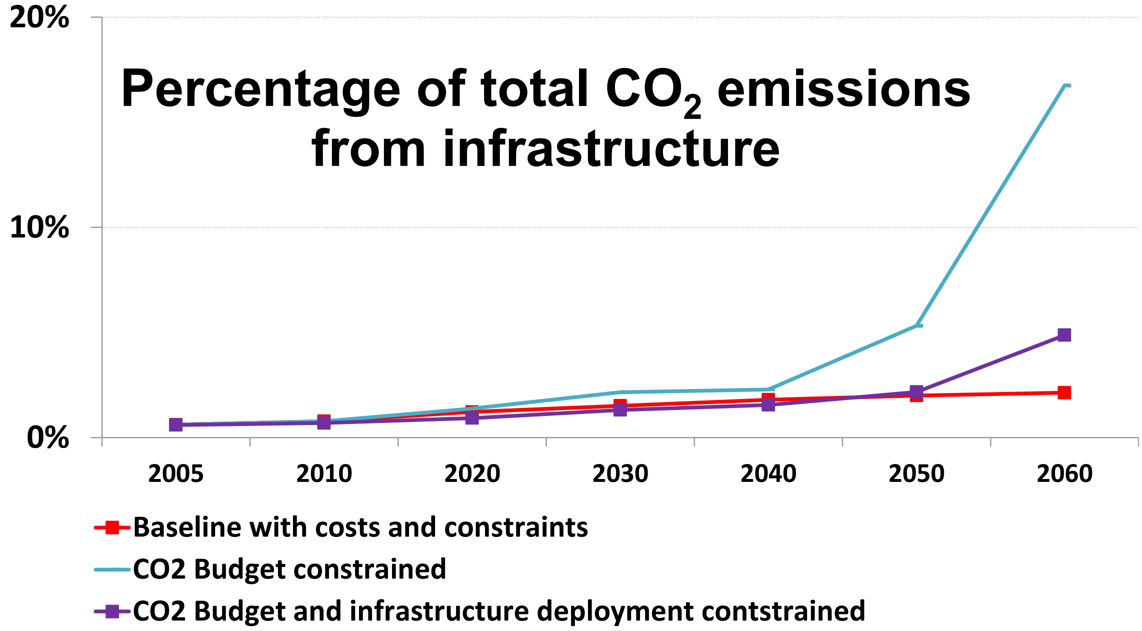


Figure 13 : Proportion of total global CO_2 emissions from infrastructure deployment

Figure 12 shows the proportion of total global CO_2 emissions that result from the deployment of transport infrastructure for three scenarios. The proportion is less than 2% for all four scenarios up to 2050. After this point the proportion increases in the carbon budget constrained emissions scenarios. This is because of large decreases in emissions that occur in other sectors post 2050 while the roll-out of transport infrastructure continues. Somewhat less mitigation occurs in the transport sector in proportion to the other sectors because it is most expensive sector to mitigate carbon emissions from. CO_2 emissions from the production of cement for infrastructure make up over half of the data shown in Figure 12 in the earlier decades but increases to up to 90% of the total by the end of the scenario period as other sectors decarbonize. Figure 12 suggests that in absolute terms that the CO_2 resulting from the deployment of transport infrastructure is not significant in the first half of the century but that an increasingly stringent carbon emission regime will inherently increase its relative importance.

Spending on Infrastructure

Figure 13 breaks down infrastructure spending into that for the three transport modes, for three regions.

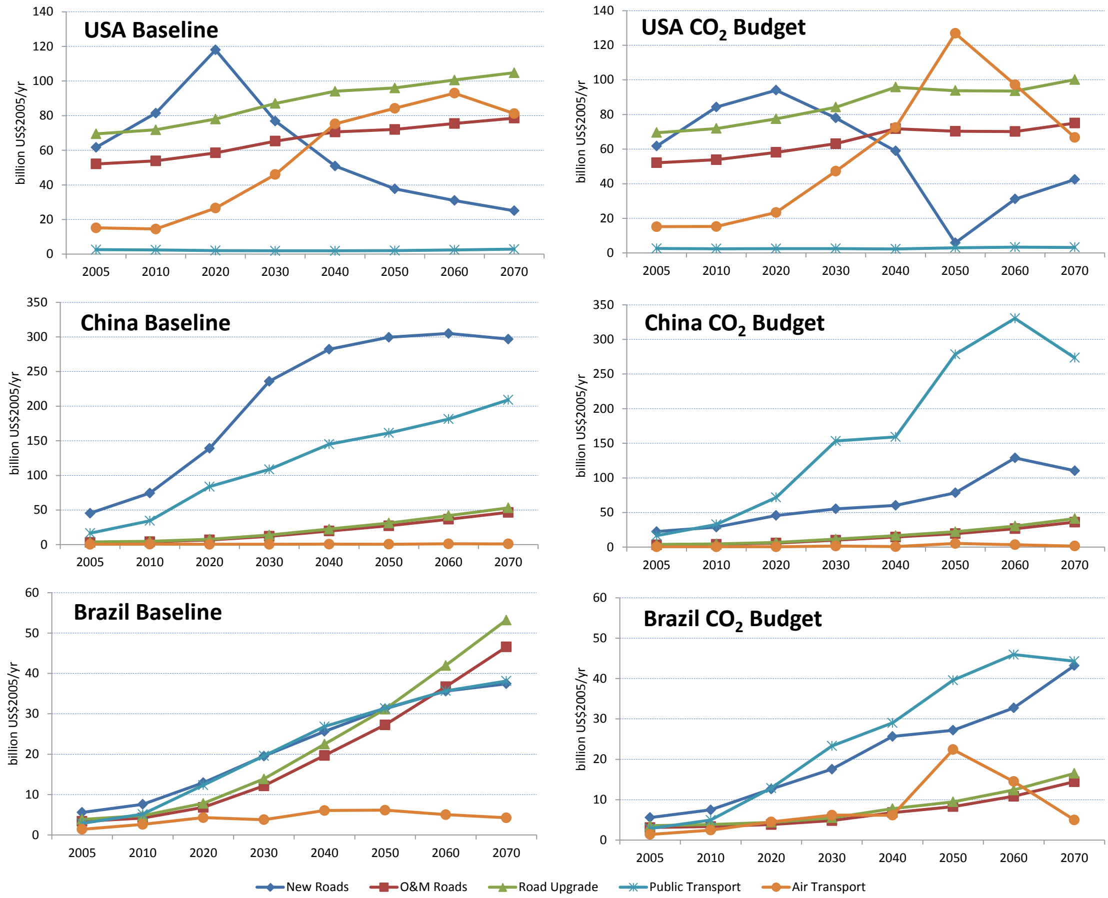


Figure 14 : Infrastructure spending in three global regions.

It can be observed that for an OECD country, the USA, that spending for maintenance and upgrade of road infrastructure is significant, while that for public transport is minimal. In a carbon constrained scenario, spending on air infrastructure expands significantly as air travel replaces road travel as income increases. In two non-OECD countries, Brazil and China, large increases in automobile and public transport can be observed in the baseline scenario. In the CO_2 budget scenario spending on infrastructure for public transport increases while that for automobiles are reduced. The large differences in levels of spending on public transport and aviation between the USA and the two other countries is due to a combination of their respective calibration year data and the growth dynamics that follow. For example in the USA in 2001 1500 pkm per capita were flown whereas in China it was 5 pkm per capita. Although similar growth rates in aviation are modelled for both countries subsequent to 2001, the USA grows to 10000 pkm per capita by 2070 whereas China grows to 500 pkm per capita.

Discussion on modelling results

The above modelling development suggests that including costs for and constraints on the deployment of transport infrastructure has an impact of baseline values of key indicators. It also suggests that restricting infrastructure expansion results in mode shift away from automobile transport and a lowered cost for mitigation. It has also been shown that embodied emissions in transport infrastructure are not significant but costs for maintenance of transport infrastructure are.

A closer examination of model results has revealed that of the three restrictions placed on transport deployment (the construction capacity in the region, the density of the existing road network and the maximum percentage of GDP that can go to infrastructure) that it was the first constraint that resulted in most of the difference between the baseline scenarios with and without constraints. The third constraint was met on some occasions while the second constraint on road density was never met. The data used for the first constraint was taken from Dulac (2013). The author used existing data for production capacities but also added a buffer to allow for increased productivity in each region. It could be argued that for the purposes of this work that the empirical data should have been used and that this should have been allowed to increase to reflect increasing efficiencies and technology developments in the sector. This is something that may be considered under further work.

No feedback exists in the model between increased deployment of infrastructure and productivity . As it stands the model treats investment in concrete as being a less productive activity than investment in other sectors. This results in the model showing lowered GDP resulting from infrastructure deployment. This can be justified in response to the discussion presented in the introduction of this report on whether deployment of infrastructure results in increased GDP. The conclusions given were that there can be a positive relationship with GDP on some occasions but this is not guaranteed because there are other non-economic reasons for infrastructure deployment and also a lack of empirical evidence to support a linear relationship with GDP. On the other hand it could be suggested that there should be some coupling to reflect the role of big projects such as the US Interstate highway. This is also something that could be considered under further work.

In modelling embodied emissions, a constant value for process carbon emissions from a unit of added value in the construction sector is applied. As shown above embodied emissions were found to be not significant i.e. less than 2% of total before 2050. This approach to modelling process emissions does not take into account efficiency improvements in cement production, or the possibility of the installation of carbon capture facilities in the sector. If such developments were taken into consideration process emissions may have been found to be even lower.

Further work an transport, could be to add charging stations for electric vehicles. However an obvious extension of the work is to add non-transport related infrastructure such as the expanded electricity grid needed for the mass deployment of intermittent renewables. A basis for such work would be the ‘rules of thumb’ for grid expansion outlined in Section 3.2. In addition generic costs of infrastructure deployment used in four of the IAMs involved in the ADVANCE project has been assembled which can also form the basis for the costs to be included in for e.g. grid deployment. A section of these costs are given in Table 4. The idea behind the data is to present and compare the costs of deployment of energy distribution and transport Infrastructure in the REMIND, IMAGE, WITCH and IMACLIM IAMs. The other IAM models involved in the task currently do not include such costs. A contrast in the data presented is that IMAGE and WITCH present costs measured as a proportion of installed capacity while REMINDs costs are per MWh used. The IMAGE model differentiates between costs for power infrastructure within region and across regions. For the IMACLIM model, which does not as yet include costs for grid expansion, data for transport infrastructure costs (not shown) are available although not including costs for refueling stations. For the latter the IMAGE model includes a cost that must be added to each vehicle cost to account for the level of refueling infrastructure in existence. One straightforward use of the data in the table is for other models to use to include costs for energy and transport infrastructure in their models.

Table 4 : Generic chart of infrastructure costs for distribution infrastructure

			Distribution Infrastructure				
			stationary end consumer:			to vehicles:	
			Electricity	Natural Gas	Gasoline/Diesel	Electricity	Hydrogen
REMIND	Unit		$/MWh	$/GJ	$/GJ	$/MWh	$/GJ
	Value		25	2.4	2.5	25	4.6
	to compare: average SE price 2020		60	6	15?	60	10?
	Lifetime of Infrastructure		45	45	45	45	45
	Discount rate		5%	5%	5%	5%	5%
	Approx. Share of total costs:	Investment	60%	36%	37%	60%	55%
		O&M	30%	12%	63%	30%	45%
		Energy loss	10%	52%	0%	10%	0%
	scaling behaviour:		linear with demand				
	explicit modeling of stocks and lifetimes?		yes				
IMAGE/ TIMER	Unit		$2005/MWe installed electric capacity			**$/vehicle**	$2005/GJ
	Value		1,092,500			1000	between 5 and 15
	to compare: average SE price 2020						
	Lifetime of Infrastructure		60			10	30
	Discount rate		10%			4%	10%
	Approx.	Investment	100%			100%	100%

	Share of total costs:	O&M	0%		0%
		Energy loss	Not measured as a cost component, but total T&D losses drop from 19.8% in 1970 to 11.8% in 2100 (Western Europe)		Not measured as a cost component. Truck transport leakage rate: 2%. Pipeline leakage rate 0.1%.
	scaling behaviour:		linear with installed capacity (not linear with demand)		Non linear due to different scales
	explicit modeling of stocks and lifetimes?		yes	no	yes
WITCH	Unit		$2005/MWe installed electric capacity	WITCH models the electric infrastructure only	
	Value		400000		
	to compare: average SE price 2020				
	Lifetime of Infrastructure		60		
	Discount rate		3.8%		
	Approx. Share of total costs:	Investment	100%		
		O&M	0%		
		Energy loss	0%		
	scaling behaviour:		Linear with capacity + exponential contribution related to VRE penetration		
	explicit modeling of stocks and lifetimes?		Yes		

4. Conclusion

This task has involved exploring the extent to which physical network infrastructure has been modelled to date in integrated assessment models, and then the development of the IMACLIM-R and REMIND models to better incorporate such. The overview has shown limited incorporation of transport infrastructure in IAMs. The work carried out for the task on transport and electricity grid infrastructure provides methodologies that other teams can implement in their own models. These are the key contributions the task makes. In both cases a way of including the costs of infrastructure deployment is involved. The application of the methodology in the IMACLIM-R model has shown how baseline scenarios can be improved and also the macroeconomic and mitigation effects of having an infrastructure lever included in models.

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