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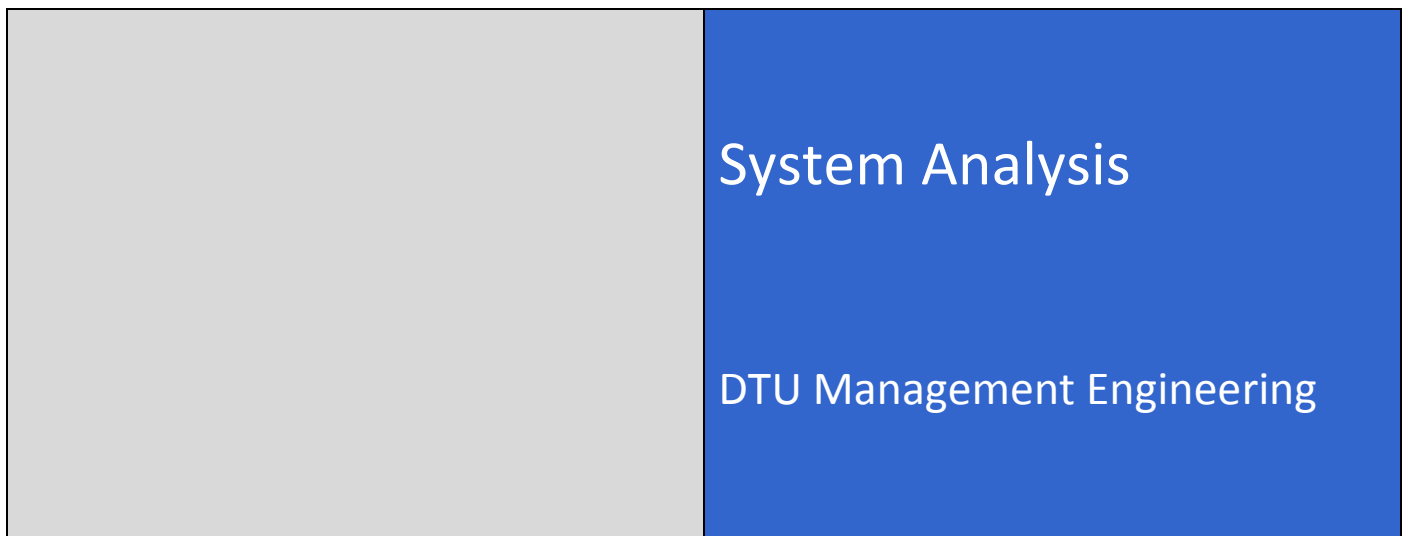
System Analysis

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Evaluation of the impacts of modal shift in the passenger transport sector on the whole Danish energy system

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1. Introduction

The Danish government has set the ambitious environmental goal of becoming independent of fossil fuels by 2050 [1]. Approaching such target for the Danish inland passenger transportation sector requires deep technological and behavioural transformations. The significant challenges faced in moving towards a long-term transport decarbonization include the increase of transport activity, limited availability of alternatives to fossil fuels, limited margins for fuel economy improvement, fuel standards, and diversity in modal perception and preferences. The International Energy Agency (IEA) recommends modal shift as one of the key measures for decarbonizing the energy system in Nordic countries by 2050 [2]. Modal shift consists in the transfer of mobility demand from one mode to another. The dynamics of modal shift in passenger transport result from modal choice changes, corresponding to an evolution in users' preferences. In turn, users' preferences are reshaped due to changes in socioeconomic status, subjective opinion, modal characteristics, infrastructure availability and policy implementation [3].

This study analyses the impact of several levels of modal shift within the Danish inland passenger transportation sector on the whole Danish energy system through the lens of an Energy-Environment-Economic-Engineering (E4) optimisation model (specifically a TIMES/MARKAL model). In particular, the purpose of the study consist in determining the impact of modal shift in the inland passenger transportation sector on the rest of the Danish energy system.

E4 models are tools developed for long-term energy planning and for determining least-cost decarbonization pathways [4, 5, 6]. Initially, E4 models were limited to representing technology changes and were not fully able to evaluate the influence of behavioural variables on the energy system [7]. Recently, researchers have been attempting to integrate transport behavioural features in bottom-up (BU) optimization E4 models. For this class of models, [8] recognize two main approaches to incorporate behaviourally realistic modal shift. One consists in linking the BU E4 model with an external transport model that handles the

behavioural features and determines modal shares [9, 10, 11, 12]. The other approach endogenously assesses modal shift within an energy system model, by enlarging the traditional model structure to include transport-specific variables and transport infrastructure [13, 14, 15, 16].

The approach adopted within this study to determine the influence of modal shift on the whole energy system in Denmark belongs to the first class of those described in [8], as it consists in linking an E4 technology-rich optimization energy system model to a transport model that simulates modal choice. The soft-link developed can address the limitations of E4 models identified in [8], opening a new prospect to better represent the implications of human behaviour on the transport sector, evaluating the influence of modal shift on the future development of the energy system and the contribution of modal shift to the decarbonization of the energy system.

2. Methodology

Soft-linking models is becoming a recurring approach to gain additional insights with respect to the type of analysis that one single model framework could provide. In order to reply to the research question of this study, an E4 model has been soft-linked to a transport simulation model. Soft-linking these two models allows to exploit the strengths of both models: the behaviourally realistic and disaggregated representation of individuals' modal choice in the transport model and the technology rich description of the entire Danish energy system in the E4 model. In particular, the transport model simulates modal choice determining modal shares. These are provided in input to the E4 model, which determines for each mode the optimal portfolio of technologies satisfying the exogenous modal demands. The E4 model used in this multi-model framework is TIMES-DK, the TIMES model which represents the entire Danish energy system, from primary energy supply, through energy conversion, until transport, industry, residential and commercial end-use sectors [17]. For the external transport model, the initial idea was to use the Danish Land Transport model (LTM). This is the four-stage transport simulation model of Denmark, which represents all transport activities within, into, and through Denmark [18] [19]. However, the adoption of LTM for this purpose was problematic, due to the likelihood incurring of some issues and due to inconsistencies among modeling framework, among which:

1. The modal shares calculated by LTM may have not been sensitive to fuel prices
2. Different time horizons: LTM simulates only until 2030, because the knowledge of the status of the road infrastructure is a main driver of transport models' simulation and any assumption beyond 2030 is not reliable; instead TIMES-DK is used for exploring scenarios in the long-term, until 2050.
3. Inconsistency between models for CO_2 reduction constraint: in LTM there is no CO_2 emissions constraint, but there is in TIMES-DK.
4. Different aggregation levels: LTM simulates modal choice at household level, thus being much disaggregated demand-side. On the other side, TIMES-DK does not include any form of population

heterogeneity [3]. When data are iterated between the two models or simply when data is provided from LTM to TIMES-DK, this inconsistency might lead to aggregation bias potentially leading to wrong results.

5. It takes about three days to LTM to calculate the solution for a certain scenario. This running time is too long for a modeling framework which needs to be used also for stakeholder involvement.

In order to avoid incurring in the issues highlighted above, an agent-based (AB) model called ABMoS-DK (Agent Based Modal Shift-Denmark) has been developed to be soft-linked to the E4 model. The AB model is capable of simulating travel related decision making for a large number of heterogeneous individuals (represented by agents) with different socio-economic and behavioural characteristics. ABMoS-DK simulates travellers' behaviour towards modal choice in Denmark using datasets from LTM and TU survey [20] to simulate heterogeneity of consumers on individual level. Differently from LTM, ABMoS-DK is sensitive to the variation of fuel prices, which affect the tangible costs of private car and thus may affect the decision of the travel to use car for a certain trip. In order to avoid inconsistencies among the time horizons of the models, in ABMoS-DK the travel demand is extrapolated until 2050 (same end year as for TIMES-DK). Despite ABMoS-DK simulates modal choice at individual level, modal split is aggregated at the level required by TIMES-DK, thus avoiding inconsistencies. The AB model also significantly reduces the amount of time required to run the scenarios. However, similar to LTM, ABMoS-DK is not able to take into account CO_2 emissions. The remaining of this section first describes the AB model, then it provides an overview of the transportation sector in TIMES-DK and finally it explains the framework for soft-linking the AB model and the E4 model.

2.1.   ABMoS-DK

ABMoS-DK (Agent Based Modal Shift-Denmark) is an agent-based model that accounts for travelers' behaviour to simulate modal choice. The BU approach is adopted to describe with high level of detail the characteristics of the consumers (using data from TU survey). ABMoS-DK allows to analyze how alternative transport policies affect modal choice and the resulting modal shift in the Danish inland passenger transportation sector. In ABMoS-DK, a group of travelers with homogeneous characteristics (similar income level, age, car ownership, bike ownership and driver's license) is regarded as an agent that chooses mode of transport to meet its travel demand according to trip characteristics (type of origin and destination, trip length, departure time, waiting time, access/egress time and congestion) and a series of rational behavioural rules. Within ABMoS-DK, agents are independent - the transport mode chosen by a certain agent does not depend on the choice made by other agents. Travelers' heterogeneity is incorporated to take into account that different groups of users have specific preferences affecting modal choice. The modal choice algorithm chooses for each agent and associated trip the mode with the highest utility, which is calculated as a combination of both tangible (ticket price, fuel price, vehicle taxes, etc.) and intangible costs (travel time, level of service, and

reliability). Modal utility also depends on the socio-economic and rational-behavioural characteristics of the households (type of residential area, income level, value of time), to reflect travelers' heterogeneity of decision making.

2.2.   TIMES-DK

TIMES-DK is the first Danish energy system model that includes the complete national energy system [17] [21]. TIMES-DK is able to describe socioeconomic optimal pathways to a low-emissions society in Denmark optimising simultaneously operations and investments of energy technologies across all energy sectors. Covering all sectors in one model speeds up the analysis process, while providing a consistent method of policy analysis across sectors. TIMES-DK is a multi-regional model geographically aggregated into two regions: Denmark East (DKE) and Denmark West (DKW). It is divided into five sectors namely: supply, power and heat, industry, residential and transport. TIMES-DK is calibrated for 2010 (model base year) and has technological and economic projections until 2050. This time horizon is sub-divided into shorter periods of various duration, most commonly 1-5 years. In turn, every year comprises 32 non-sequential time slices, representing seasonal (4 seasons), weekly (working/non-working days) and daily variation [17]. In TIMES-DK, the transportation sector comprehensively describes the Danish mobility service demands, the end-use transport technologies and the technologies producing the transport fuels [17]. Several fuel chains are available to the transport sector, some of which make the transport sector integrated with the rest of the energy system (e.g. bio-fuels, electricity and hydrogen). The transportation sector includes passenger and freight transport, further split into aviation, maritime and inland sub-sectors. The inland passenger sector is represented with a high level of detail and includes eight modes: car, bus, coach, rail (metro, train, light-train), 2-wheelers (motorcycle and moped) and non-motorised modes (bike and walk). The mobility service demands are defined exogenously for each mode, from the base year until the end of the modelling horizon. They are expressed as service demands: passenger-kilometre (pkm). Moreover, the modes have associated more than one demand: for inland transport, the total modal demands are split by class of distance range (extra short/short/medium and long distances for passenger transport). **Figure *1*** describes the structure of the inland passenger transport sector of TIMES-DK.
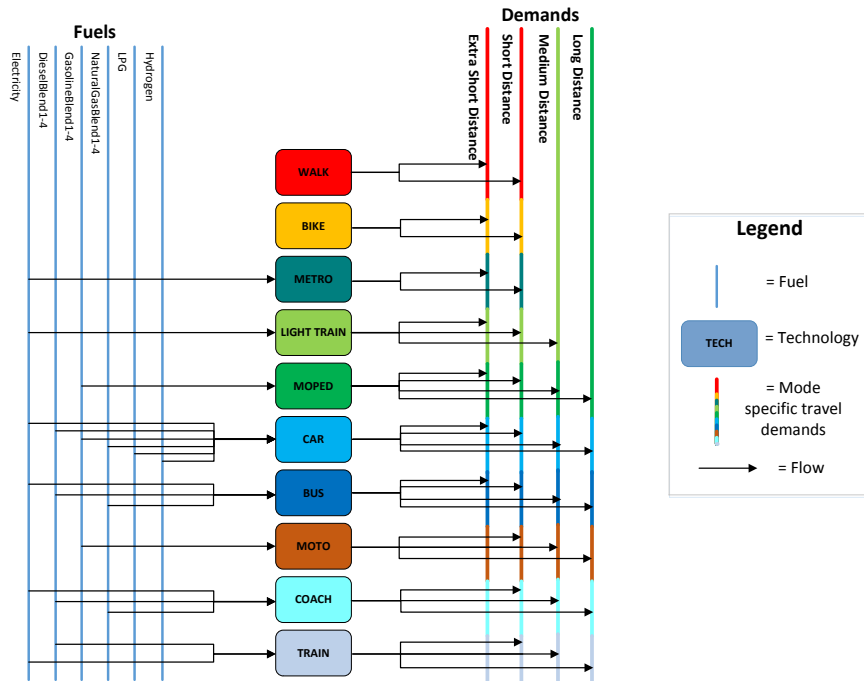
Figure 1: Structure of the inland passenger transport sector in TIMES-DK

The technology database for the transportation sector of TIMES-DK includes existing technologies and technologies that are available for future investments. These technologies compete to meet the projected mobility demands. Competition between transport technologies is exclusively based on costs: TIMES seeks to meet the modal mobility demands with the portfolio of technologies characterized by the lowest levelized costs, while complying with the constraints.

2.3. Soft-linking

In the modeling framework adopted for this study, the policy measures are run in ABMoS-DK, which determines modal demands for the inland passenger transportation sector in Denmark. These are provided as input to TIMES-DK, which determines the optimal technology investments to meet the exogenous modal demands at the least overall system cost. Moreover, TIMES-DK obtains fuel prices, which are input to ABMoS-DK. This is run again to calculate the new modal shares. Then, a new solution is obtained with TIMES-DK. Data exchange between the two models is iterated until there is convergence between the results (Figure 2).
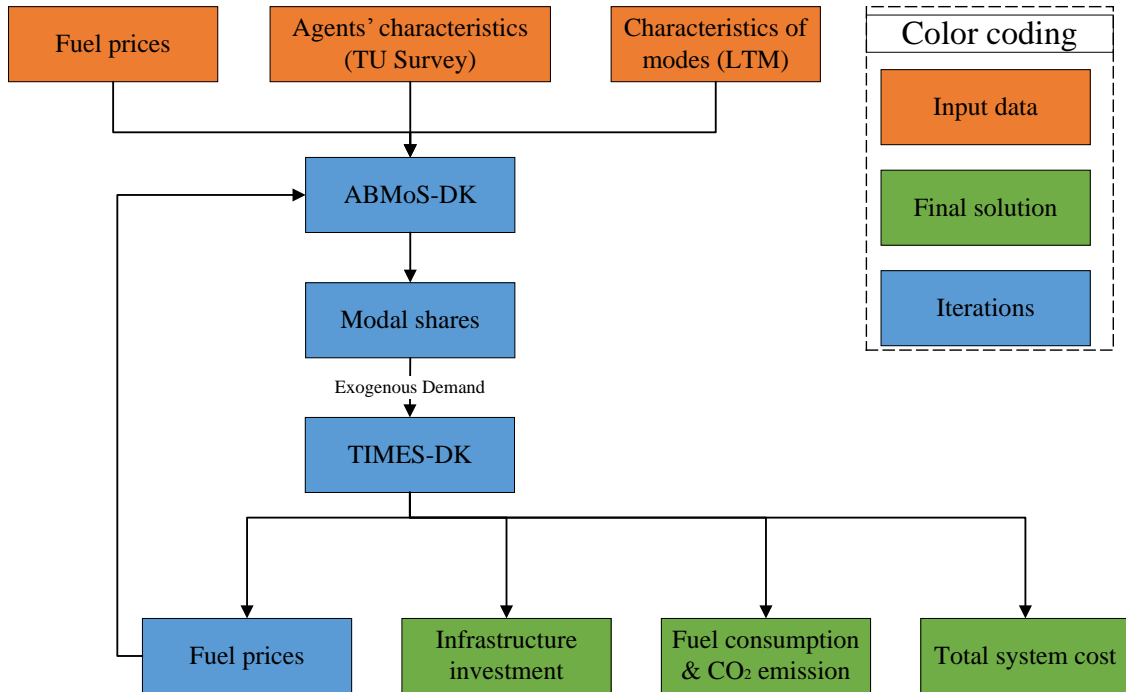
Figure 2: Soft-link between ABMoS-DK and TIMES-DK

TIMES-DK provides in output the investment in transport infrastructures required to accommodate the new mobility demand after modal shift occurs. Moreover, it also determines the total cost of the energy system, fuel consumption and CO_2 emissions from the transport sector and from the entire energy system. In this way, TIMES-DK is used to investigate what is the effect of modal shift on the rest of the energy system.

2.4.   Scenario analysis

ABMoS-DK is capable of simulating behavioural preferences of heterogeneous travellers to understand the effect of policy measures on modal choice, possibly leading towards a shift to more sustainable modes of transport in Denmark. The BU approach allows to disaggregate modal choice at individual level, thus providing the opportunity to analyze modal preferences at the desired level of aggregation. This could help Danish policy makers to formulate effective policies targeting specific consumer groups that could facilitate the achievement of the Danish target to decarbonise the energy system by 2050. Within this study, ABMoS-DK is used to evaluate the effect of three packages of policy measures on modal shift, comparing their results with the business as usual (BAU) scenario. The resulting modal demands are then provided in input to TIMES-DK, to analyse their implication on the whole energy system. The remaining of this section describes the BAU and the three policy scenarios analysed.

2.4.1. Business as Usual (BAU)

The BAU scenario represents a continuation of current conditions based on the assumption of TU survey [20] and LTM [22, 23]. All scenarios include the expansion of Copenhagen Metro, which will become available in 2020. The different assumptions characterizing the alternative scenarios with respect to BAU

scenario are assumed to take place from 2025 onwards. Table 1 shows the parameters for the three cases. The "+" sign indicates increase while the "-" sign indicates decrease with respect to BAU.

2.4.2. Extreme (EXT)

In the extreme scenario, we assume there would be free public transport and very expensive costs for private cars. In particular, we analyse the effect of developing metro systems in Denmark West (DKW) in the urban areas (i.e., Aarhus, Aalborg and Odense). S-Train railways are also assumed to become available in DKW urban and suburban areas. Moreover, public transport becomes available every two hours also during night-time and the frequency of trains and buses is assumed to increase of 10% with respect to BAU. Additionally, free parking for private car users is available for train and S-train, thus eliminating the access and egress time to public transport. All bicycles are electric with free recharging of the battery, thereby extending the maximum trip length to 55 km. We assume doubling the fuel taxes, registration and annual ownership tax for fossil-fueled cars and car parking cost. Moreover, collecting toll on vehicles coming into Copenhagen (50 DKK per trip irrespective of trip length during weekdays from 6 am to 6 pm).

2.4.3. Moderate (MOD)

The moderate scenario analysis the effect of developing metro and S-Train railways, increasing the frequency of public modes, park and ride facilities and free charging for e-bikes as explained in extreme scenario. We assume decrease of public transit fare by 20%, increasing the fuel taxes, registration and annual ownership tax for fossil-fueled cars, car parking cost by 50% with respect to BAU and collecting 30 DKK toll.

2.4.4. Inferior (INF)

In the inferior scenario, we assume the cost of public transit is too high and the cost of private cars is low. In particular, there is no changes in the metro and S-train railways. Increase of public transit fare by 50%, decreasing the fuel taxes, registration and annual ownership tax for fossil-fueled cars and car-parking cost by 50% with respect to BAU.

Table 1: Parameters for scenario analysis

Parameter	Extreme	Moderate	Inferior
Construction of Metro in DKW Urban	Yes	Yes	No
Construction of S-train in DKW Urban and Suburban	Yes	Yes	No
Increase the frequency of public transit by 10%	Yes	Yes	No
Ticket cost for public transit	-100% (free)	-20%	+50%
Park and Ride facilities	Yes	Yes	No
Free charging for e-bikes	Yes	Yes	No
Fuel tax	+100%	+50%	-50%
Registration and ownership tax	+100%	+50%	-50%
Parking cost	+100%	+50%	-50%
Toll for private cars coming to CPH	50 DKK	30 DKK	0 DKK

2.4.5. Constraints in TIMES-DK

In the multi-model framework adopted for this study, TIMES-DK is run without any environmental target. This is done in order to analyse the effect of modal shift on the whole energy system without accounting any constraint that might influence the results.

3. Results

3.1. Modal shares for inland passenger transport

ABMoS-DK determines the modal shift in the inland transport sector of Denmark resulting from the implementation of the policy packages described in Section 2.4. Figure 3 shows the future modal split (expressed in Billion passenger-kilometer) for the inland modes aggregated on all geographical zones, all income categories and all trips across scenarios. Total mobility demand in 2050 increases of around 31% compared to the base year 2010. In BAU, private car has the highest modal share, because of its availability almost everywhere, often associated with higher travel speed and in some cases, with lower total costs. Train ridership is in the second place due to relatively higher speed, comparative low cost for long trips and ability to accomplish long trips, while busses are more popular for short and medium trips. In the alternative scenarios modal shift start occurring from 2030 onwards.

Figure 3: Modal shift (billion passenger-kilometer)

Figure 3 compares modal shift across the four scenarios evaluated in this study. The results show that under BAU car use is expected to be 76.9 Bpkm in 2050. In the EXT scenario, very high taxes on private cars combined with widespread and free public transit system encourage travelers to shift 53.4 Bpkm away from

private cars (69% w.r.t BAU) in 2050. In this scenario, travel demand shifted away from car is replaced primarily by train. In MOD scenario, car reduces demand to 41.2 Bpkm (46% w.r.t BAU) in 2050, primarily benefitting train (15.8 Bpkm), but also bike (12.9 Bpkm) and S-train (11.3 Bpkm). In particular, in MOD scenario, bike takes over more ridership than other public modes compared to EXT scenario. This might be due to higher ticket prices of public modes in MOD scenario with respect to EXT. In INF scenario, the use of private cars increase to 83.6 Bpkm in 2050, mainly replacing train transport.

3.2. Effect of modal shift on the whole energy system

The four scenarios entail a significant variation in the total system cost (**Figure 4**). The scenarios EXT and MOD are approximately twice and three times higher than BAU respectively and INF is slightly lower than BAU. Such a large difference between the total system cost across scenarios is not due to large differences in the configuration of the energy system (as described further), but it is mainly attributable to the considerable investments in transport infrastructure required to accommodate the new mobility demand after modal shift has occurred.
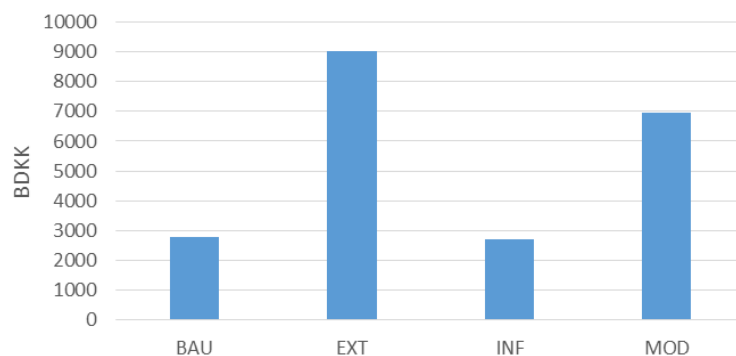

Figure 4: Total system cost in the four scenarios analysed (Billion-DKK)

In EXT and MOD scenarios, existing transport infrastructures are far undersized for accommodating the adjusted mobility demands resulting from the modal shift determined by ABMoS-DK as a consequence of the implementation of the policy measures. For those scenarios, the incapability of the existing infrastructure to cope with the modal shift implies noticeable investment costs to build the extra infrastructure capacity required to accommodate the shifted transport demand (**Figure 5**). In particular, in both EXT and MOD, the main infrastructure investment is needed to expand the capacity of metro in DKE and to build the new metro system in DKW.
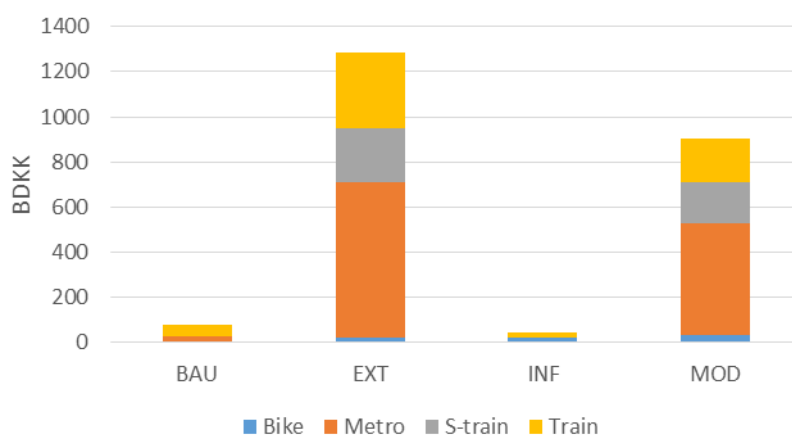
Figure 5: Non-discounted investment cost in transport infrastructure in the four scenarios analysed

The modal shift determined by ABMoS-DK not only affects the requirement of extra infrastructure capacity, but it also entails a significant variation of fuel consumption from the inland transportation sector. Overall, modal shift away from car enabled by the policy measures tested in EXT and MOD encourages the electrification of the sector and, as a consequence of the better fuel economy of electric motors compared to internal combustion engines (ICE) combined with the substitution of cars with more fuel efficient (or fuel-free) modes, the reduction of fuel consumption in the transportation sector. **Figure 6** clearly shows that in EXT scenario, modal shift away from car to non-motorized modes and to more fuel efficient modes dramatically reduces the total fuel consumption and accelerates the electrification of the transportation sector. A similar pattern, but with lower fuel savings than in EXT is also visible for MOD. On the other hand, in INF scenario, fuel consumption from inland transport is similar in pattern and absolute numbers to BAU.
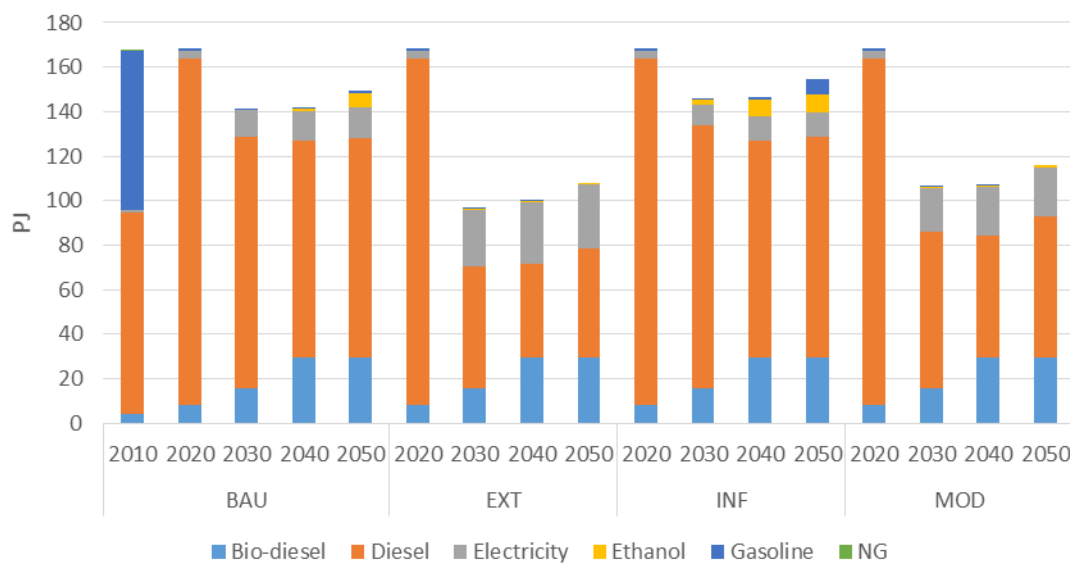

Figure 6: Fuel consumption from inland transport sector in the four scenarios under analysis

Considering the substantial electrification of the transportation sector that characterizes EXT and MOD scenarios (+15 PJ and +9 PJ of electricity respectively), it is interesting to analyse how the future power generation changes across scenarios with respect to the BAU scenario. The power generation throughout the modeling time horizon divided by source is provided in **Figure 7**, which shows that after 2030 power generation is characterized by a substantial increase, mainly produced from coal. Besides coal, on-shore wind generation increases more than five-fold along the modeling time horizon and the power generated from waste doubles along the same time span. On the other hand, all the other sources decrease their use in 2050 compared to 2010.
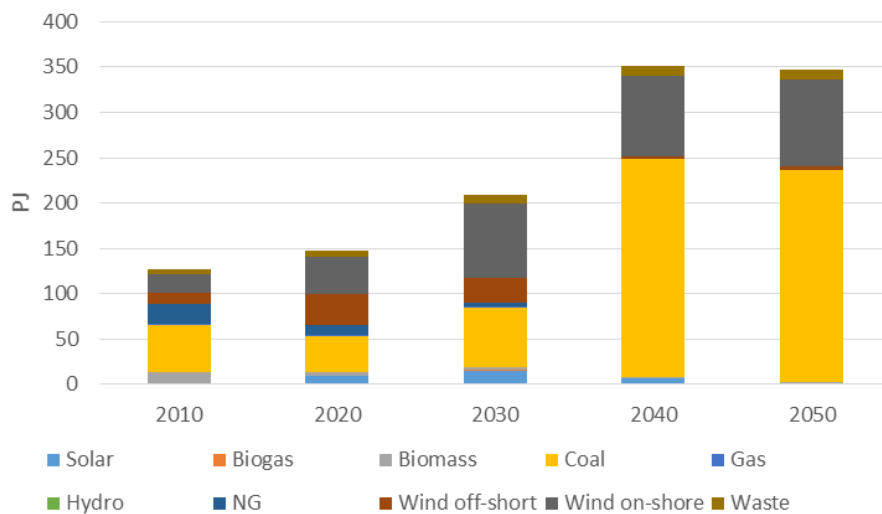

Figure 7: Power generation by source over the time horizon in BAU scenario

Figure 8 shows the difference between power generations per source in the three alternative scenarios with respect to BAU. The analysis reveals that in EXT and MOD the power generation in 2050 increases with respect to BAU (of 4% and 2% respectively), while in INF the power generation slightly decreases (-1%). In all scenarios, such variation almost entirely attributable to the variation in fuel consumption in the transportation sector. Moreover, without any environmental constraint, the extra (or missing) power demand is fulfilled almost completely by coal generation plants.
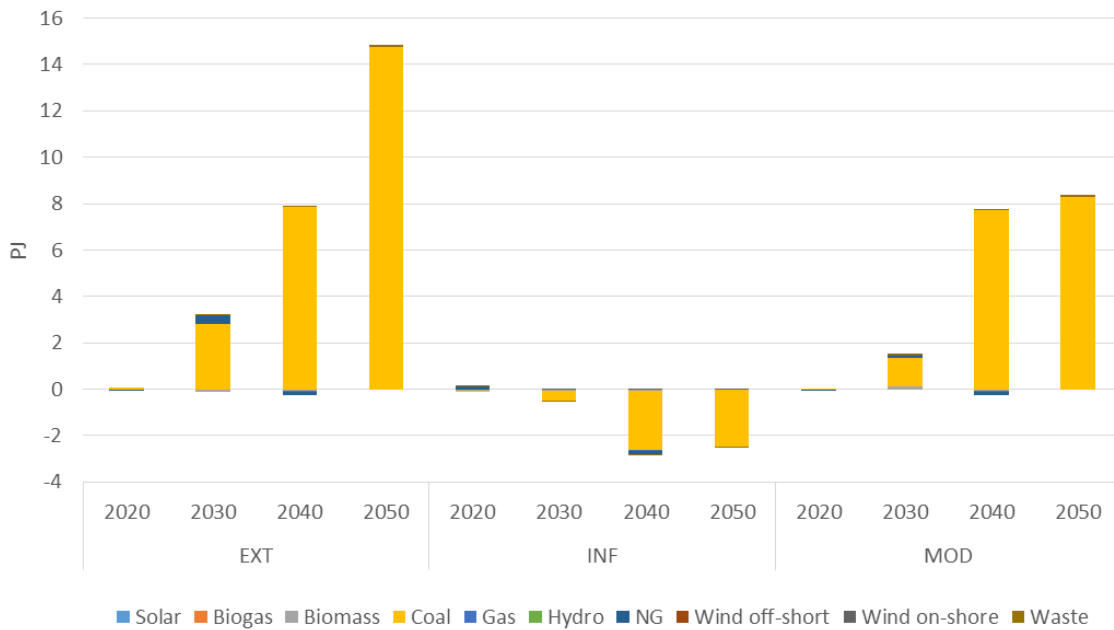
Figure 8: Difference in power generation by source with respect to BAU across the alternative scenarios

Due to the very small variation in power generation across scenarios, the effect of modal shift on average annual power prices is limited, ranging within ±1.4% for all scenarios and years. Moreover, since the extra (or missing) power demand is produced by a combined heat and power (CHP) plant, the variation in power generation necessary to cover the power demand resulting from modal shift also slightly affects the district heating (DH) prices. The average annual centralized DH prices vary in a range of ±2.9%, while decentralized DH prices vary in a range of ±2.2%.

Concerning CO_2 emissions, in the BAU scenario the emissions from the residential, industrial and inland transportation sector decrease in 2050 compared to the base year, while those from aviation and navigation transportation sector and in particular from power sector significantly increase (**Figure 9**). The rise in CO_2 emissions from the power sector is due to the combination of the electrification of the whole energy system, demonstrated by the rise in power generation, and of the increased power generation from coal shown in **Figure 7**.
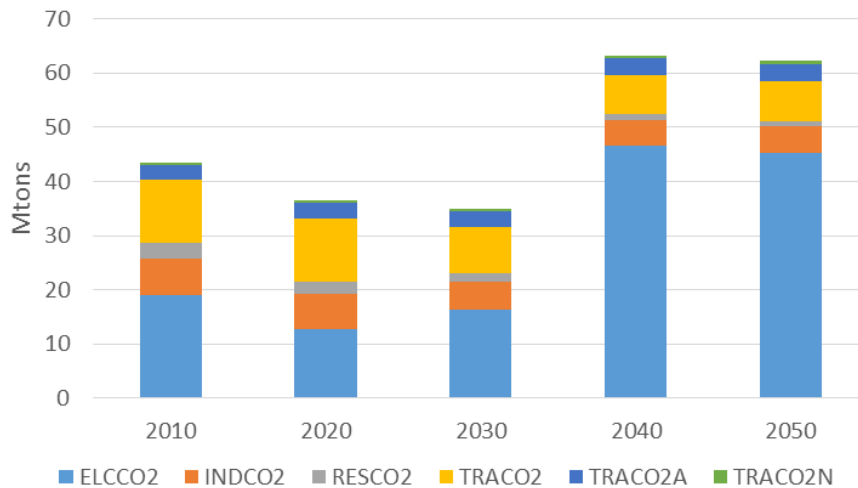
Figure 9: Trend of annual CO_2 emissions from the whole energy system in BAU scenario

As expected, modal shift is found to affect CO_2 emissions from the energy system, as visible in **Figure *10***. Scenarios EXT and MOD are characterized by an overall reduction of CO_2 emissions in 2050 with respect to BAU. In particular, emissions from the inland transportation sector reduce due to modal shift and to the consequent electrification, and migrate to the power sector. Despite modal shift occurs from private car to more efficient modes of transport and thus reduces the total energy demand (see **Figure *6***), the fact that the additional power demand is fulfilled generating almost entirely by coal entails that, overall, the CO_2 emissions reduction from the whole energy system in EXT and MOD is limited. Also INF scenario entails a migration of CO_2 emissions from the transportation to the power sector, despite the absolute difference in emissions is negligible.
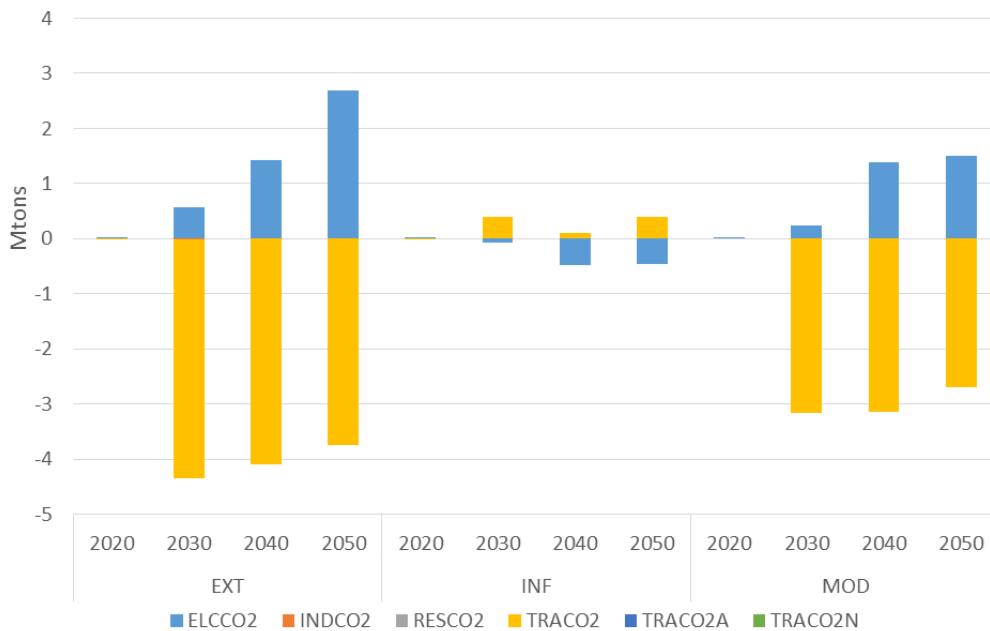

Figure 10: Difference in CO_2 emissions from the whole energy system with respect to BAU across the alternative scenarios

4. Discussion and conclusion

The scenario analyses carried out within this study have proved that implementing policy measures in the transportation sector alone for encouraging modal shift does not automatically entail a substantial cut in CO_2 emissions. Modal shift delivers limited environmental benefits if not coupled with ambitious decarbonisation targets in the rest of the energy system, particularly in the upstream sectors. This is demonstrated by the EXT and MOD scenarios evaluated in this study, where fossil fuels consumption within the transportation sector are replaced by carbon-intense electricity, leading to almost negligible CO_2 emissions reduction. Given this finding, sectorial models allowing to analyse only the decarbonisation strategy for one sector at the time have limited benefits for long-term energy planning. On the other hand, integrated energy system models such as TIMES allow to determine decarbonisation pathways with a holistic view, considering cross-sectorial dynamics and synergies among the different sectors that constitute the energy system. Moreover, the analysis of the effect of modal shift on the whole energy system has not observed any change in the end-use sectors other than transport and a limited effect of upstream sector, consisting of small variations in the average annual power and DH prices.The recommendation is to combine policies promoting modal shift away from car to non-motorized or more efficient modes of transport with efforts to reduce the carbon intensity of the power grid, thus avoiding that oil products are substituted by electricity generated with carbon-intense sources, e.g. coal.

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