The Use of Energy System Models for Analysing the Transition to Low-Carbon Cities – The Case of Oslo

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Abstract

More than half of the world's population are living in cities today, and by 2050 almost 75% of the population will live in urban areas. Thus, meeting the energy demand in urban areas in a sustainable way is an important challenge for the future. Oslo wants to show how cities can take leadership in the green change and contribute with innovative ideas and solutions for development of sustainable energy systems. A technology-rich optimisation model has been developed in order to analyse how various energy and climate measures can transform Oslo into a low-carbon city. Consequently, the main focus of this work has been to find optimal ways of reducing the CO2 emissions, and secondly, the energy consumption.

Keywords: Urban energy system; energy system model; scenario analysis; renewable energy; CO2 emissions

1. Introduction

In 2014, 54 per cent of the world's population were living in urban areas [1]. Globally, urbanisation is taking place rapidly, especially in less economically developed countries. Sustainable development in urban settlements is therefore a challenge with increasing importance since urbanisation can cause problems such as transport congestion, lack of sufficient housing, and environmental degradation. From an energy and climate perspective, the key features of a sustainable city include among others public transport as a viable alternative to cars, the use of renewable resources instead of fossil fuels, waste is seen as a resource and recycled if possible, and new buildings are energy efficient. Based on this, an energy systems approach is used in this paper in order to link and study the interactions between the abovementioned features.

An energy system is more than a technical system [2], and consist also of markets, institutions, consumer behaviours and other factors affecting the way infrastructures are constructed and operated. Thus, urban energy systems need to be viewed widely to account for the local context. Over the last decade there has been an increased focus on studies of urban energy systems, and in [3] there is an overview of different tools to analyse energy, economic and environmental performances of energy generation systems, buildings and equipment in a community. The survey [3] divides the models into geography models, energy models, evaluation models and clean energy analysis tools, however it does not include the MARKAL/TIMES modelling framework which is the modelling framework used to analyse the transition to a low-carbon energy system in the city of Oslo.

Over the last few years, there has been an increased use of TIMES models also on local scale when analysing pathways to a low-carbon society [4], local infrastructure development [5], and smart city planning [6]. The motivation for developing local TIMES models was in [4-6] to use an optimisation model to analyse cost optimal transition to more sustainable energy carriers and technologies on local level.

As an alternative to bottom-up models like MARKAL/TIMES, an alternative optimisation-based approach [7] was used in a case-study of the city of Newcastle, where Monte Carlo techniques are used to address policy uncertainty.

The analysis of urban energy governance described in [8] compares four European cities by applying an optimisation model to assess the technology pathways to achieve emission reduction targets at minimum cost, including the links between the governance of urban energy systems and the cost of achieving carbon targets. The comparative study does not include the transport sector. In Norway where electricity is mainly produced from hydropower, there is generally little further scope for carbon reduction within the power sector. Thus, policies and measures to decarbonize the transport sector will have a huge impact on Norwegian cities CO2 emissions in the future.

Local energy planning is often focused on analysis and optimisation of individual systems, e.g. heating systems in various buildings, as in [9]. Such analyses are often combined into an overall energy plan for the local community. In general, such an approach can lead to sub-optimal systems because interactions between different systems are ignored. However, some models exist that take into account the overall energy system. EnergyPLAN [10] is a deterministic input/output based model designed for energy system analysis for both national and regional energy planning. The model has been used in several projects in Denmark, e.g. by analysing how to use waste for energy in an optimal way from an energy system perspective [11].

Despite the fact that urban energy systems are of increasing interest to both researchers and policy makers, there is relatively little literature on how to structure assessments of the urban energy system and for recommendation on implementation of effective energy policies. As described in [12], public opposition to efficiency-enhancing policies is a significant barrier when addressing today's environmental challenges. In a more recent work [13], a regional perspective on the interdependence of the energy sector and economic growth has been studied in order to understand the implications of low carbon transitions. The interconnection between socioeconomics, energy, and environmental components for the city of London (UK) is discussed in [14]. Additionally, a techno-economic optimisation model approach [15] was used in order to find an optimal way of covering the energy needs of Athens (Greece).

This paper describes how a technology-rich optimisation model can be used to analyse how various energy and climate policies and measures can transform the city of Oslo into a low-carbon city. The urban energy system model was developed and used to analyse three scenarios: i) a reference scenario (REF) which includes all current policies, used to illustrate the impact of policies analysed in the other scenarios; ii) a 2-degree scenario (2DS), which implies an 85% reduction in CO_2 emissions in Oslo by 2050 (compared with 1990 level). The 2DS is reflecting the contribution from the city of Oslo to the IEA's global 2-degree scenario as described in Nordic Energy Technology Perspectives 2016 [4]. In 2DS the rest of the world pursues the global 2°C Scenario, while the city of Oslo aims for 85% emission reduction, which is a greater emissions reduction than in 2DS, and iii) the climate target scenario (CLI) including the climate targets for Oslo (50% reduction of emissions of greenhouse gasses before 2030, and to use no fossil fuels by 2050). In the scenario analysis the full technological richness provided by the optimisation model was used. In addition to the scenario analysis, the model was used to analyse the impact of 12 individual measures, selected by the representatives from the city of Oslo. This additional analysis was primarily done to study how each individual measure can contribute to reduced emissions and energy demand, but also for obtaining carbon abatement costs.

An advantage with developing and using a TIMES model for a local area, is the possibility to integrate it in a TIMES-model on national or regional scale, which allows for comparison of results on rural vs. urban level, as demonstrated in [4] and [16]. The TIMES-Oslo model used in this work is part of the TIMES-Norway model, thus it can be used to enrich the analysis on national level. As an example, the differences in technology choices between Oslo and the rest of eastern Norway (i.e. spot market area NO1) is more easily identified in two different models than in an aggregated model region. Additionally, analysis results from Oslo can therefore be relevant for other Norwegian cities.

A brief overview of energy system analysis of urban areas is given in chapter 1. Chapter 2 describes the methodology and the TIMES-Oslo model, whereas the scenario assumptions are given in chapter 3. The model results are presented in chapter 4 and discussed in chapter 5. Concluding remarks are given in chapter 6.

1.1 Climate and Energy Strategy for the City of Oslo

The city of Oslo has ambitious climate goals; to halve the emissions of greenhouse gasses before 2030, and to use no fossil fuels by 2050. Oslo has introduced “the green change”; which implies addressing climate change challenges by changing the way energy is produced and used in the city. The green change implies a transition to a renewable and sustainable society, and the main focus is on innovation, implementation of new technologies and using existing systems in new and innovative ways.

The city of Oslo has developed a climate and energy strategy [17], which focuses on urban development through planning of urban areas and public transport junctions, building of new infrastructure for renewable transport fuelling (battery charging, hydrogen and bio fuel), prepare for fossil free transport in freight and in public and private transport, increase the use of public transport, bicycling and walking, contribute to increased utilization of local energy resources, both for heating and electricity, and implementation of energy efficiency measures.

Oslo is a small city in a global context. However, the city wants to focus on how cities can take responsibility for development of sustainable energy systems for the future, and to show how cities can take leadership in the green change and contribute with innovative ideas and solutions. Thus, Oslo has been an active partner in C40 [18], which is a network where cities can collaborate, share knowledge and drive meaningful, measurable and sustainable action on climate change. Additionally, approximately half of the world's urban dwellers reside in relatively small settlements of less than 500 000 inhabitants [1], and in such a context, Oslo is a relevant example of what can be achieved in a medium-sized city.

1.2 Energy System Characteristics

Oslo is the capital of Norway, and is also the most populous city in the country. Oslo constitutes both a county and a municipality, and is the economic and governmental centre of Norway. As of January 2015, the population in the city of Oslo exceeded 647 000 [19], and almost the entire population lives in urban settlements.

Direct CO2 emissions for the city of Oslo have increased slightly from 1.06 Mt in 1991 to 1.23 Mt in 2013. In 2013, the transport sector accounted for almost 60% of the CO2 emissions.

The stationary energy consumption for the city of Oslo was 11.5 TWh in 2009 [20], where electricity is the most important energy carrier with a share of almost 80% of the consumption. Energy consumption per sector is given in Figure 1, where households and services are the two dominant sectors. The energy consumption for the transport sector in the city of Oslo was 2.8 TWh in 2009 [21]. This includes all types of transport modes relevant for the city, including road, rail, and navigation.

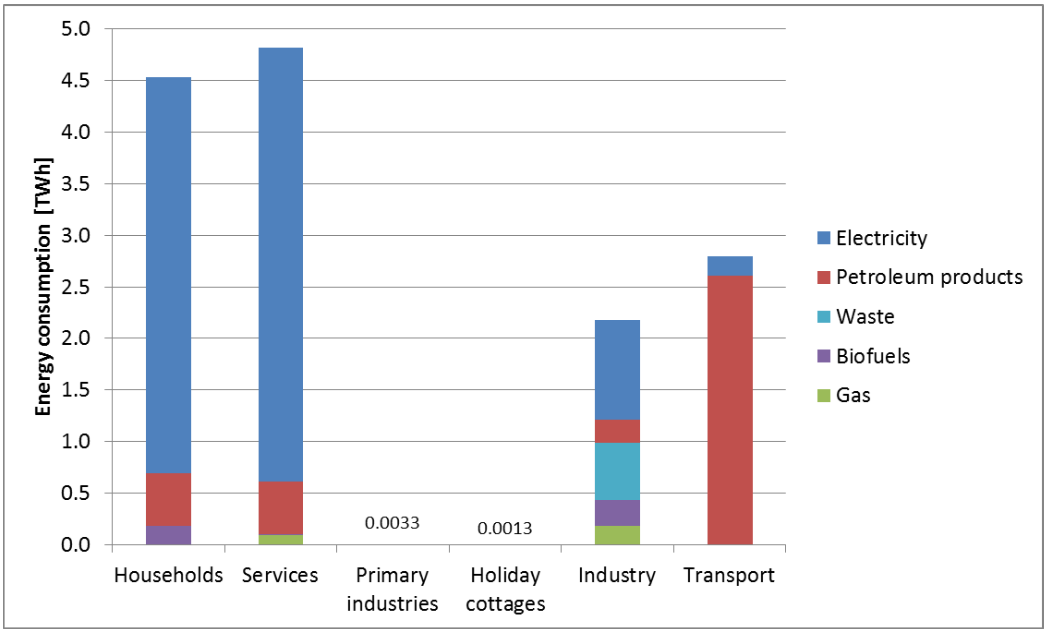

Figure 1: Energy consumption for the city of Oslo in 2009 for various end-use sectors

There is only one small hydropower plant in the city of Oslo. The plant (Hammeren) has an installed capacity of 5 MW and a yearly power production of around 16 GWh. The potential for additional plants within the city boundary are very limited. Electricity is also produced from waste at a combined heat and power (CHP) plant at Klemetsrud, with a maximum annual production of around 160 GWh. Currently, there is also a limited electricity production from solar PV in the city of Oslo, but the potential is much larger, and it is expected that the installed capacity will increase in the coming years due to various local and national support schemes.

Currently, there are 12 district heating plants in the city of Oslo operated by the local energy company (Hafslund Heat). A variety of different boilers (or other heat sources) are installed all over the city, including 30 MW of heat pumps, 240 MW of electric boilers, 450 MW of oil/bio oil boilers, 160 MW of waste boilers, 100 MW of oil/gas boilers, and 56 MW of pellets boilers.

Other local resources available within the city boundary include 4 GWh of straw, 25 GWh of biomass from forestry, biogas (produced from food waste), and bio methane (produced in Bekkelaget sewage treatment plant) for transport purposes.

2. Modelling Framework: TIMES-Oslo

2.1 System Boundaries

As a part of the energy and climate strategy of the city of Oslo, the following five focus areas were identified:

- Urban development, including planning of urban areas and public transport junctions
- Infrastructure, including energy stations for renewable fuels in transport (e.g. battery charging, hydrogen, and biofuels)
- Transport, with focus on green transport fuels and reduced use of private cars

- Buildings, with special focus on prohibiting the use of fuel oil and implementation of energy efficiency measures
- Energy production and distribution, including new infrastructure for central heating and optimal utilisation of local energy resources

TIMES-Oslo is used to analyse the impact of various climate and energy measures on the local energy system in the city of Oslo, and the structure of this new model is illustrated in Figure 2. The base year of the model is 2010, whereas all costs, prices, etc. are given in NOK-2005. Since the Oslo model is based on TIMES-Norway [22-24], it was decided to have the same time resolution in both models (260 time slices per year). Having a time resolution with five time slices per week gives a sufficiently detailed description of the Norwegian hydropower system, while at the same time covering the different demand profiles. The model horizon in TIMES-Oslo is from 2010 to 2050.

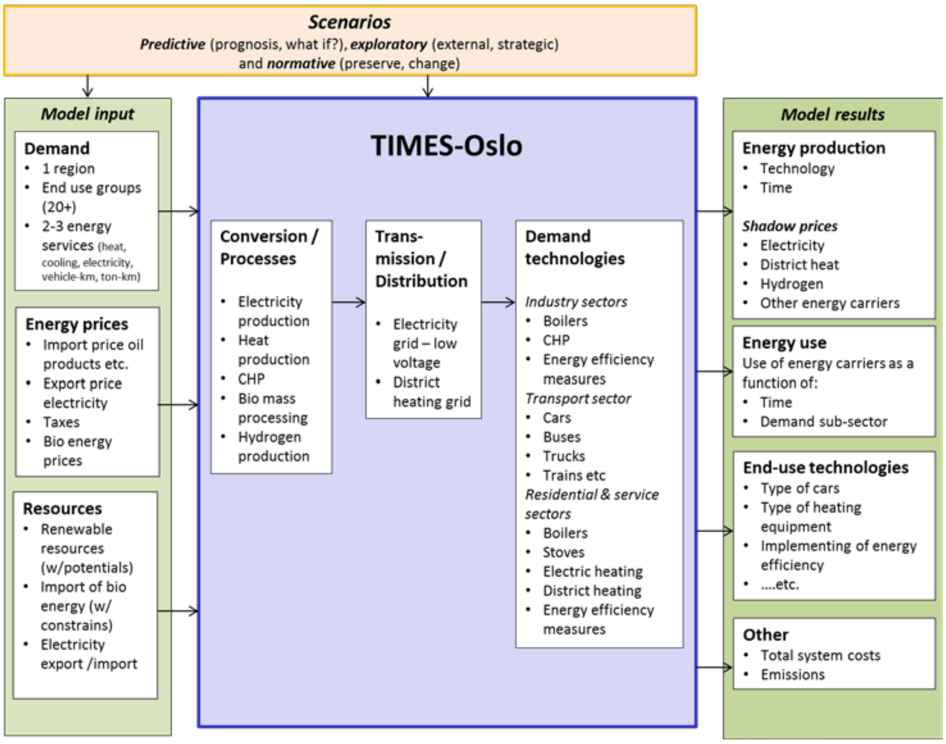

Figure 2: Principal drawing of the TIMES-Oslo model

TIMES (The Integrated Markal Efom System) is a bottom-up, techno-economic model generator for local, national or multi-regional energy systems [25]. It comprises a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon. The model assumes perfect competition and perfect foresight and is demand driven, and the TIMES model aims to supply energy services at minimum global cost by making equipment investments, as well as operating, primary energy supply and energy trade decisions. More information regarding the TIMES modelling tool can be found in [26].

Geographically, the TIMES-Oslo model represents the city of Oslo as a single model region. The reason for choosing such a rigid geographical boundary was to have a modelling framework representing the city of Oslo's jurisdiction area.

Compared to the current version of the TIMES-Norway model [27], TIMES-Oslo represents an extraction of the NO1 pricing area in the Nordic spot market [28]. This means that only a small fraction of the electricity used in Oslo comes from local facilities. The remaining electricity comes through NO1, and is typically produced in either NO1 or other Norwegian regions. Additionally, it is only the transport within the city limits that is included in the Oslo region of the model. All transport activities exiting Oslo is therefore included in the NO1 region, and vice versa.

2.2 Energy End Use Demand

2.2.1 Structure

The demand for various energy services are supplied exogenously to the model. Secondly, the energy system model TIMES-Oslo is used to analyse the consumption of energy carriers and to investigate the substitution effect with technology shifts. In total, there are 43 end use demand categories in the TIMES-Oslo model. Each demand sector is divided into sub-sectors and demand types; electricity, heat, cooling, and passenger/tonne kilometres.

Load profiles are developed for the 43 demand categories (where relevant) described above according to the same procedure as presented in [23]. For the household sector, there is one profile related to the heat demand and one for the electricity specific demand for all kinds of buildings (respectively existing/new and multi-family/single-family). The load profile for the heat demand was calculated according to measured data from a meteorological weather station in Oslo.

2.2.2 Energy Demand Projection

The methodology for energy demand projection is demonstrated in Figure 3. A two-step methodology is used where the demand of energy services is calculated first. This is used as input to the energy system model TIMES-Oslo that calculates the energy consumption. The development in useful energy demand (green box) is calculated as an activity (e.g. m^2) multiplied by an indicator (e.g. kWh/m^2). The development in both the activity and the indicator is based on national studies, adjusted for the projected development in Oslo. Assumptions of economic growth, business development, demographics etc. and development of energy indicators are taken into account, as well as normative measures (e.g. building regulations). The energy demand is divided into four main sectors (with underlying sub-groups); industry, households, service & other, and transport. For the household sector, number of persons per dwelling (ppl/dwelling), area per dwelling (m^2/dwelling), and energy service demand per area (kWh/m^2) are the main energy indicators. Similarly, energy service demand per area or energy service demand per capita (kWh/capita) were used for the primary, tertiary and the construction sector.

As shown at the bottom left of Figure 3, both the development in the activity (A), for instance floor area, and the development of the energy indicators (I) has to be considered. It is essential with knowledge of the general demographic development and the specific sectors analysed since it is necessary to estimate the development of energy indicators and assess the future development in each sub-sector.

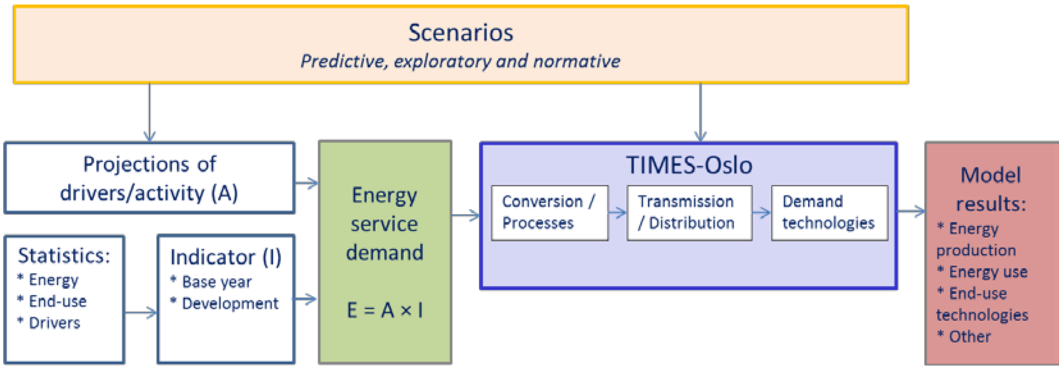

Figure 3: Overview of the energy demand projection methodology

The energy demand is projected to increase by 40% for the city of Oslo from approximately 13 TWh in 2010 to around 18 TWh in 2050. Projections of the future population growth are an important driver for the future energy service demand. Statistics Norway [29] provides population projections for all the Norwegian municipalities at regular intervals, and the energy service demand projection for the city of Oslo is based on this local population projection.

The uncertainty of the forecast can be analysed by using a set of different end-use forecast scenarios, as demonstrated in e.g. [30].

2.3 Modelling of the Transport Sector in TIMES-Oslo

For Oslo, the transport sector is the most important source of CO2 emissions (as shown in Figure 5). Consequently, urban transport systems are therefore one of the core sectors where extensive transformation to a low-carbon system must take place.

In the model, the transport sector is divided into the following transport modes: road, rail, navigation, aviation, and other. Road transport includes passenger transport by cars (divided into short- and long distances) and buses, as well as freight transport. The latter is divided into light duty (LD) trucks and heavy duty (HD) trucks. Navigation includes all domestic sea transport, including different freight ships, fishing vessels, ferries, and passenger ships. Aviation includes all domestic air transport, but is only included in TIMES-Oslo for the model totality, since there is no aviation within the city of Oslo.

Modal shifts between different transport modes (e.g. from car to bus) in the model is handled exogenously. One way of doing this is e.g. to allocate a certain part of the demand for vehicle-km for private cars into other transport modes like public transport, bikes or walks. A conceptual illustration of the transport sector representation in TIMES-Oslo is given in Figure 4. Four types of energy carriers can be used as fuel by the various transport technologies, including biofuels, fossil fuels, electricity, and hydrogen. In order to analyse policies and measures for a low carbon transport sector, it is important to study the interaction between the transport and the stationary energy system. Large scale introduction of zero and low emission fuels, such as biofuel and hydrogen, will utilise energy resources and distribution chains and must be seen in light of alternative use of energy, e.g. for stationary energy supply.

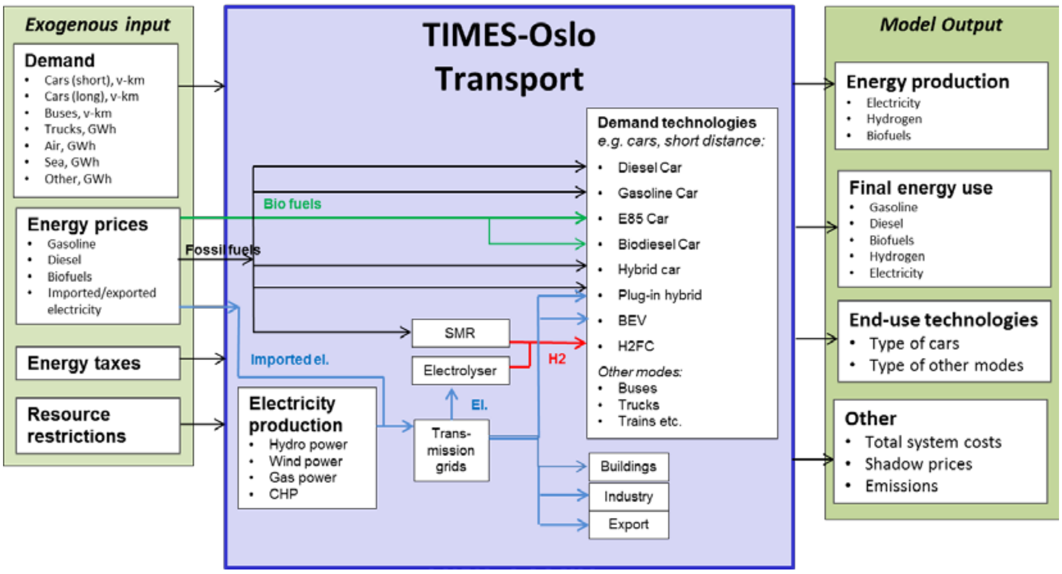

Figure 4: A conceptual illustration of the transport sector representation in TIMES-Oslo

The following passenger car propulsion technologies are included in the TIMES-Oslo model: gasoline, diesel, biodiesel, E85-ethanol, hybrid gasoline, hybrid diesel, plug-in hybrid gasoline, plug-in hybrid diesel, battery electric (BEV), and fuel cell electric vehicle (H2FC). Investment costs and efficiencies of the various technologies are based on information in [31]. The share of biodiesel in the various diesel cars can vary from 5% to 20%.

The Freight transport demand can be covered by light and heavy duty trucks. In TIMES-Oslo, the technology change options available for this sub-sector include replacing fossil fuel by biodiesel, hydrogen or electricity (light duty only). Bus transport has four alternatives; diesel bus, biodiesel bus, natural gas bus and a fuel cell bus. The share of biodiesel in the diesel bus can vary from 5% to 20%. It is assumed that the biodiesel bus can only use sustainable 2nd generation biodiesel. Transport by train and subway in Oslo has no alternative technology choices, and the only available fuel for this sub-sector is electricity. In addition, it is assumed that all air transport takes place outside the city limits of Oslo.

3. Scenario Assumptions

Unless otherwise noted, the analyses in this paper include all active national measures of today, i.a. the green certificate market (GCM), and present policy measures of Enova, a public enterprise working towards converting energy consumption and generation into becoming more sustainable. The following support schemes are included for renewable heat production [32]:

- District heating grid: 34 NOK/MWh
- District heating plants based on bioenergy or industrial waste: 29 NOK/MWh
- Pellet boilers and geothermal heat pumps installed in multi-family houses or service buildings: 29 NOK/MWh
- Industry sector: 20% reduction in investment costs for bioenergy boilers and heat pumps
- Single family houses: 20% reduction in investment costs for pellet boilers, geothermal heat pumps, and solar collectors

Investments through the GCM are possible from 2012 to 2020, with a cost of certificates until 2035 (see e.g. [27] for more information). The energy taxes are kept constant at the 2014 level until 2050, including value added tax (VAT), nonrecurring tax for new vehicles, fuel tax for road transport, tax on electricity consumption, and various CO2 taxes.

3.1 Energy Prices

The development in energy prices for imported energy carriers are corresponding to the *Current Policy Scenario* of [33]. The prices of electricity import/export, to and from Norway, are given exogenous to the model. The trading prices are based on historical prices until 2014, and thereafter kept at the actual 2014 level throughout the analysis. This means that the various price profiles for each of the 260 time-slices per year are calculated based on the actual 2014 prices. The electricity price for Oslo is determined endogenously in the model. The capacity of the power exchange in the existing grid is included in the TIMES-Oslo model. It is possible to invest in new grid capacity to and from Oslo, as well as internally in the region. Associated costs can be found in [23].

3.2 Scenarios

Three main scenarios were developed in order to analyse the transition towards a low-carbon city. The reference scenario (REF) includes all current national policies. This scenario is used to illustrate the effects of the policies analysed in the other scenarios. In the second scenario (2DS), an 85% reduction trajectory is included for the CO2 emissions. The third scenario (CLI) includes the climate targets for Oslo. In the latter two scenarios, TIMES-Oslo was allowed to use the full technological richness provided by the model. Additionally, 12 measures were developed and analysed in TIMES-Oslo related to the five focus areas described in section 2.1.

To our knowledge, the use of TIMES models for urban analyses is not a common approach. However, in order to avoid sub-optimal systems, we propose to use such a long-term investment model for analysing how the city of Oslo can transform into a renewable and low-carbon society. This is done by taking into account the interactions between different demand sectors within the city.

3.2.1 2-Degree Scenario

A 2-degree scenario (2DS) is carried out with TIMES-Oslo. It corresponds closely to the 2DS presented in [4], where a 85% reduction trajectory is presented. At a global level, it requires an energy system consistent with emission trajectories that would give a high chance of limiting the average global temperature increase to 2 °C. At the Oslo level, we have included overall CO2 emission constraints in 2030 and 2050. For 2030, a 50% reduction from the 1990 level is included, and in 2050 the reduction constraint is 87%.

3.2.2 Oslo Targets

An additional analysis, where the climate targets for Oslo are included, is also carried out with TIMES-Oslo. The targets include to halve the emissions of greenhouse gases before 2030, and to use no fossil fuels by 2050. These two targets are added as restrictions to the model. It is assumed that waste has a carbon content of 11 tons of CO2/GWh in 2050, and these emissions are also restricted.

3.2.3 Climate and energy measures

In this work, 12 individual measures were developed and analysed in TIMES-Oslo with special focus on CO2 emissions and energy consumption. The measures are generally designed for being viable as stand-alone options, but some of the transport measures clearly belong together. The model has been used to get a systematic overview of expected developments in technology and regulatory framework. It was also important to indicate what measures that can contribute in the short, medium and long term. Even though this is not the typical way of using a TIMES-model, the full transparency of the approach makes it a compulsive alternative. Additionally, the perfect competition assumption is not applicable here since the model is heavily constrained in many of its sectors. The measures are briefly described in the table below.

Table 1: Overview of climate and energy measures

Focus area\Sector ->	Transport	Building	Energy sector
Urban development	**T2**: Improved infrastructure for public transport		
Infrastructure	**T3**: Infrastructure for renewable transport fuels **T6**: Transferring freight from road to rail and ship		
Transport	**T1**: No increase in vehicle-km **T4**: Support scheme for renewable fuels **T5**: Procurement of renewable transport services		
Buildings		**B1**: Prohibition of fossil fuels for heating **B3**: Support scheme for passive houses **B4**: Support for energy efficiency measures	**E2**: Energy storage in buildings
Energy production and distribution		**B2**: Providing areas for new energy solutions	**E1**: Renewable energy production from local resources

4. Results

4.1 Reference Scenario

The reference scenario is analysed by keeping the market shares of the different technologies constant within each end-use sector. It is therefore not possible to invest in neither more efficient technologies nor implement energy efficiency measures in this scenario. The only two exceptions are that new buildings can choose any available technology and that each vehicle technology comes with an efficiency improvement.

Figure 5 illustrates the CO2 emissions for the reference scenario. As seen, the total emissions increase from 1.17 Mt in 2010 to 1.46 Mt in 2050. The contribution from the transport sector becomes more dominant in the future. The reason is that the projection of the transportation demand increases more, in relative terms, that the stationary sector. The demand for freight transport on road is increasing the most and it is motivated by the expected economic growth and increased international trade.

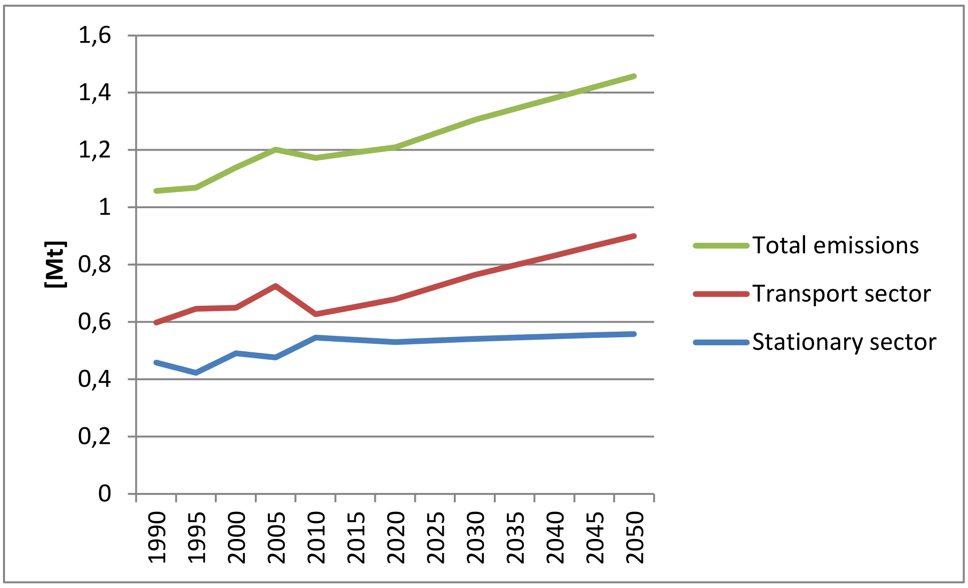

Figure 5: CO2 emissions for the reference scenario (incl. statistics up to 2010)

The total energy consumption for the reference scenario for the city of Oslo increases from 14.2 TWh in 2010 to 19.7 TWh in 2050. Electricity is the dominant energy carrier for all the years, whereas the use of various fossil fuels is highly dominant for the transport sector. The energy consumption per sector in 2050 is given in Figure 6.

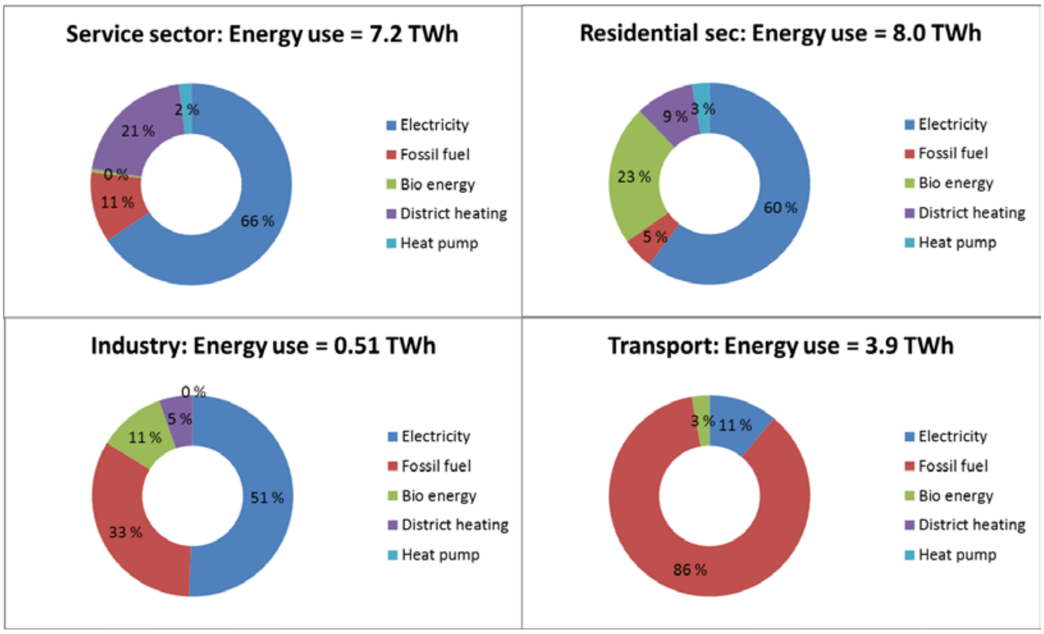

Figure 6: Energy consumption per sector in 2050 in the reference scenario

4.2 Climate and Energy Scenarios

4.2.1 2DS and Oslo Targets

The CO2 emissions for the 2DS and CLI scenarios are given in Figure 10. As seen, both scenarios comply with Oslo's 2030 target, whereas only the CLI scenario satisfies the 2050 target. The contribution from the various end-use sectors varies over the analysing period. However, the transport and the district heating sectors are the main contributors for all years for both scenarios.

As indicated in Figure 9, the final energy consumption for all end use sectors is 0.4% lower for the 2DS in 2050 compared to REF, whereas the energy consumption for the CLI scenario is 1.7% lower. The energy consumption for heating in the household sector is given in Figure 7 for the three main scenarios. For all years, the energy consumption is highest for the CLI scenario and lowest for the REF scenario. This is mainly due to increased use of electricity in the REF scenario; both in electric radiators and in air/air heat pumps. Additionally, 0.4 TWh of fuel oil is used in oil boilers in the REF scenario in 2050. There is no use of fossil fuel for heating for neither of the climate scenarios. Compared to REF, there is a considerable increase in the use of pellet boilers for both 2DS and CLI, and especially for the latter scenario. For 2DS, decreased use of electric radiators and oil boilers is compensated by increased use of district heating (1.6 TWh in 2050). District heating is mainly based on waste incineration (which entails greenhouse gas emission).

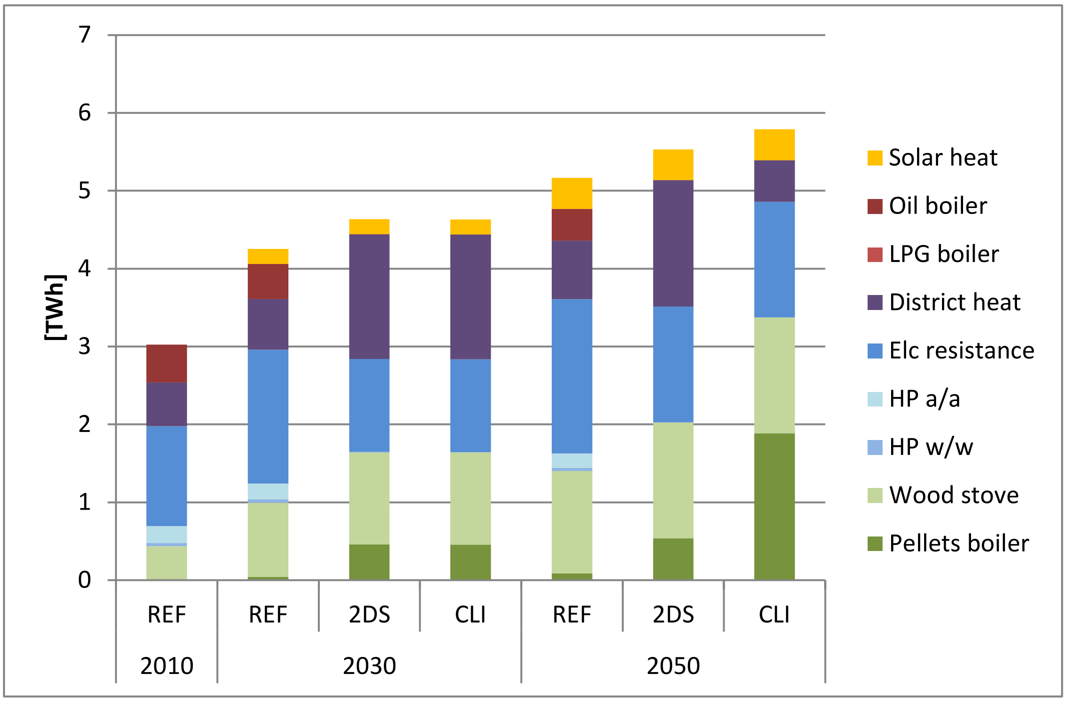

Figure 7: Household energy consumption for heating

Table 2 compares the technology choices for the three main scenarios for the transport sector, whereas Figure 8 gives an aggregated view of the use of different energy carriers. As seen, the energy consumption is reduced by roughly 41% for the climate scenarios compared to REF. This is due to the use of more efficient technologies like e.g. electric cars. Consequently, the electricity consumption is considerably higher for both 2DS and CLI compared to REF. In the reference scenario, there is considerable use of fossil fuels for all transport modes. As the transport sector is the most important source of CO2 emissions in Oslo, this sector undergoes significant changes in both 2DS and CLI. The results show considerable efficiency improvements through electrification of passenger transport. This includes both the use of electric vehicles (2DS and CLI) and plug-in hybrid vehicles (only 2DS). For the CLI scenario, long distance travels by car is covered mostly by the use of biodiesel vehicles whereas hybrid vehicles using electricity and gasoline is used in 2DS. Other differences between 2DS and CLI include additional use of biodiesel for other transport modes (e.g. construction machines, cranes, etc) in CLI instead of the use of regular diesel, as well as use of hydrogen in sea transport in the CLI scenario. For freight purposes, a combination of electric (light duty) and biodiesel (heavy duty) vehicles is used in both climate scenarios.

Table 2: Technology choices for the transport sector (LD = light duty and HD = heavy duty)

	2010		2030			2050	
	REF	REF	2DS	CLI	REF	2DS	CLI
Biodiesel (car + blend)	17.9	17.9	0.0	0.0	20.3	0.0	108.1
Electricity (car + hybrid)	0.7	2.6	473.8	473.8	2.9	499.7	475.1
Diesel car	340.7	340.1	0.0	0.0	385.8	0.0	0.0
Gasoline (car + hybrid)	857.8	859.9	18.6	18.6	972.9	19.9	2.8
LD + HD trucks (biodiesel blend)	39.3	49.3	17.3	17.3	82.8	0.0	0.0
LD + HD trucks (diesel)	746.4	937.5	328.9	328.9	1574.0	0.0	0.0
LD trucks (electric)	0.0	10.9	312.8	312.8	0.0	450.3	450.3
HD trucks (biodiesel)	0.0	0.0	0.0	0.0	0.0	397.5	397.5
Other transport (biodiesel)	0.0	0.0	0.0	0.0	0.0	0.0	227.4
Other transport (diesel)	285.7	286.5	286.6	286.6	288.0	288.0	3.7
Public transport (elc)	223.4	271.3	324.1	324.1	432.0	432.0	432.0
Public transport (diesel)	139.7	142.7	151.5	151.5	173.5	0.0	0.0
Public transport (biodiesel)	7.4	7.5	8.0	8.0	9.1	182.6	182.6
Sea transport (fossil fuels)	6.0	6.6	7.5	7.5	9.0	9.0	0.0
Sea transport (hydrogen)	0.0	0.0	0.0	0.0	0.0	0.0	9.0

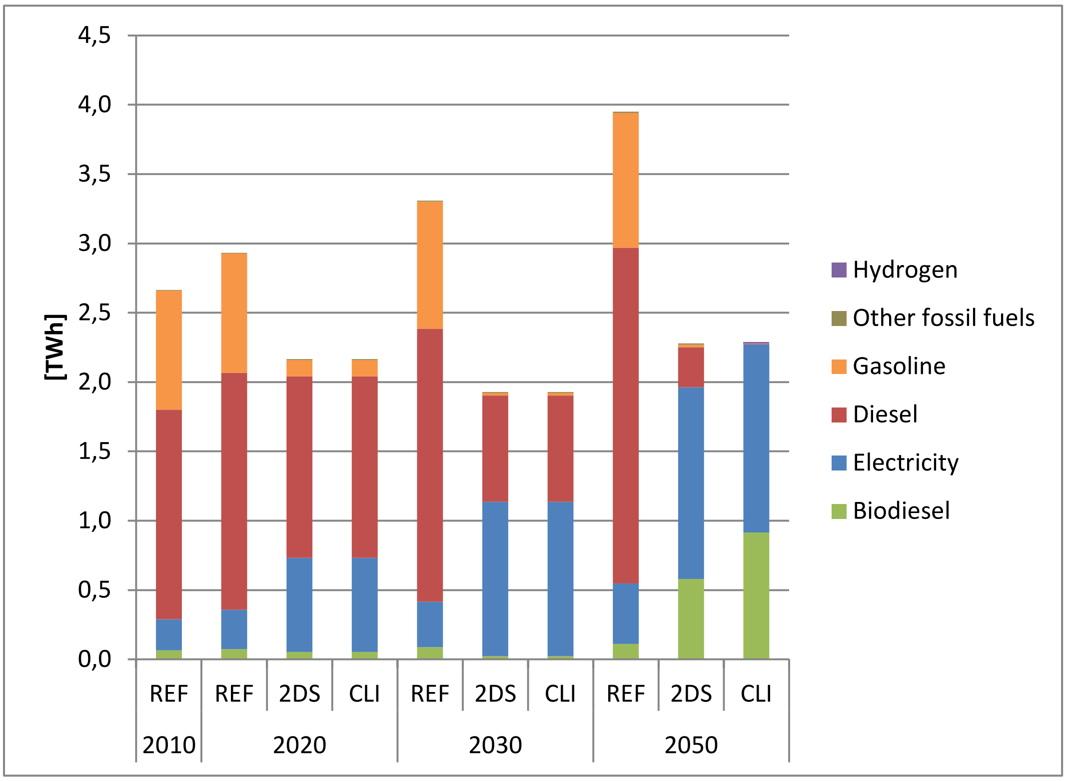

Figure 8: Use of energy carriers for the transport sector

4.2.2 Focus Areas

The CO_2 emissions for all the analysed measures and scenarios are sorted and presented in Figure 9. Besides the two climate scenarios, B1 (Prohibition of use of fossil fuels for heating) results in the lowest emissions with a reduction of 0.49 Mt in 2050 compared to the reference scenario. For multi-family houses, this come as a result of more use of wood pellet boilers and district heating, whereas for single-family houses, the results show an increased use of wood pellet boilers, woodstoves, and electric radiators. In 2050, only 7% of the CO_2 emissions for B1 come from the stationary sector. This is related to heat production from the combustion of waste in district heating facilities, as well as the use of liquefied petroleum gas (LPG) within the construction industry. As shown in Figure 9, the total energy consumption is also a bit lower in B1. This is due to an increased use of more efficient technologies and energy carriers.

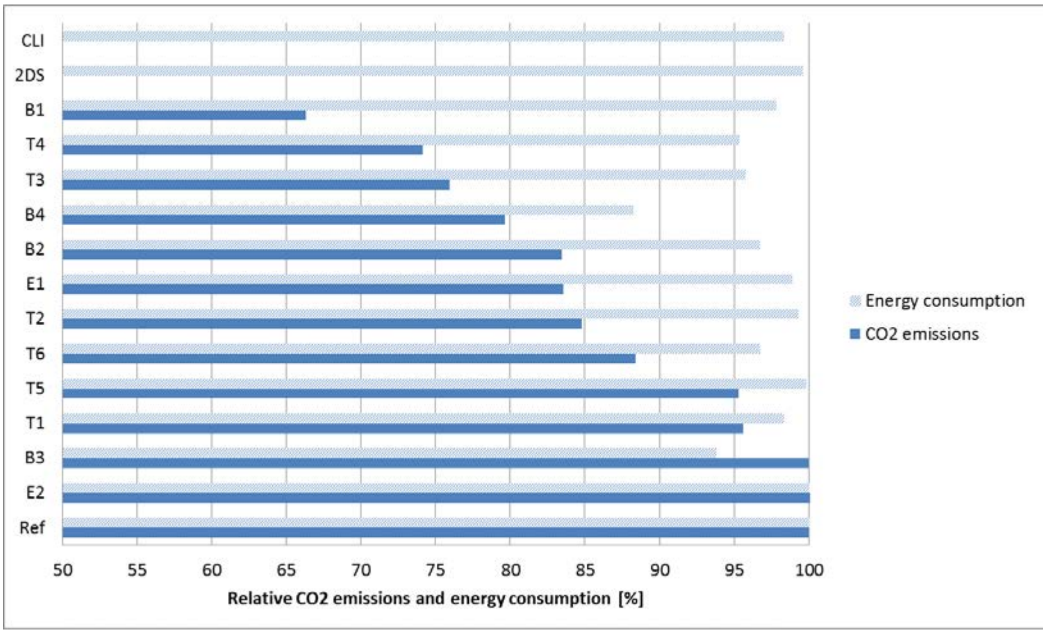

Figure 9: CO2 emissions and energy consumption for each analysed measure compared to the reference scenario for 2050

Measure T4 (Support schemes for implementation of renewable transport fuels) comes second when considering CO2 emission reductions for the individual measures. In 2050, a reduction of 0.38 Mt of CO2 is experienced when compared to the reference scenario. As a consequence, the contribution from the transport sector is slightly lower than the contribution from the stationary sector for all years after 2020. In 2050, the energy consumption related to transport for T4 reaches 3.0 TWh, where various fossil fuels contribute to 61% of the consumption, electricity 26%, biofuels 7%, and hydrogen 6%. For the transport sector, a decrease of 0.9 TWh (22.8%) is achieved for T4 compared to the reference scenario.

For measure T3 (Establish infrastructure for renewable transport fuels), a reduction of 0.35 Mt CO2 is achieved in 2050. For all the years between 2015 and

2050, the contribution from the transport sector is lower than the contribution from the stationary sector. Compared to the reference scenario, a reduction in the energy consumption of 0.9 TWh (22.8%) is achieved in 2050 for the transport sector. The reduction is related to increased use of electric vehicles for short distance travels, as well as the use of plug-in hybrids for long distance travels. These vehicle types have a better efficiency than the alternatives based entirely on fossil fuels.

B4 (Financial support for energy efficiency measures) has the lowest energy consumption in 2050. For households, a reduction of 1.4 TWh (17.6%) in 2050 is achieved. Additionally, a reduction in the use of fossil fuels and electricity is also experienced for all years between 2020 and 2050 for this sector. This is compensated by increased use of bioenergy (mostly wood) and district heating. Numerous energy efficiency measures are also implemented. Most of these are applied in order to reduce the heating demand, but there are also some measures that are introduced in order to reduce the electricity consumption. For the service sector, a reduction of the energy use of 0.9 TWh (12.4%) is achieved in 2050 compared to the reference scenario. This is due to a combination of fuel switch, i.e. from fossil fuels to electricity and biofuels, and implementation of several energy efficiency measures. In total, approximately 25% of the theoretical energy efficiency potential is implemented in B4.

The two measures with less effect on the CO2 emissions are E2 (Energy storage in buildings) and B3 (Support schemes for passive houses). For E2, the total load is the same as in the reference scenario, but it is moved within a week due to the use of various energy storage processes. The CO2 emissions remain unchanged since the same energy carriers are used as in the reference case. However, due to the flexibility of the energy storage processes, the investments in new production capacity are reduced. For B3, only new buildings are affected by this measure. Since this is only a small part of the total building sector, and additionally, use only renewable energy sources, the CO2 emissions remain unchanged. The total energy consumption is reduced by roughly 7% in 2050 since the heating demand is significantly lower for the buildings satisfying the passive house standard.

4.2.3 Combination of Measures

The city of Oslo has ambitious climate targets; to halve the emissions of greenhouse gasses before 2030, and to use no fossil fuels by 2050. As shown in section 4.2.2, the single measure with the highest CO2 reduction is to prohibit the use of fossil fuels for heating purposes, resulting in a reduction of 33 % (0.49 Mt) in 2050 compared with the reference scenario. However, by combining independent measures, an even larger reduction in the overall CO2 emissions can be obtained. As shown in Figure 10, a combination of the two measures with lowest CO2 emissions (B1 and T4) gives a reduction of 0.79 Mt (60%) in 2030 and 0.88 Mt (60%) in 2050 compared to the reference scenario. As seen, the emissions increase slightly after 2020, which is due to the increase in freight transport beyond this year. For 2030, the overall target for the city of Oslo is reached, whereas the emissions in 2050 are too high compared to the target.

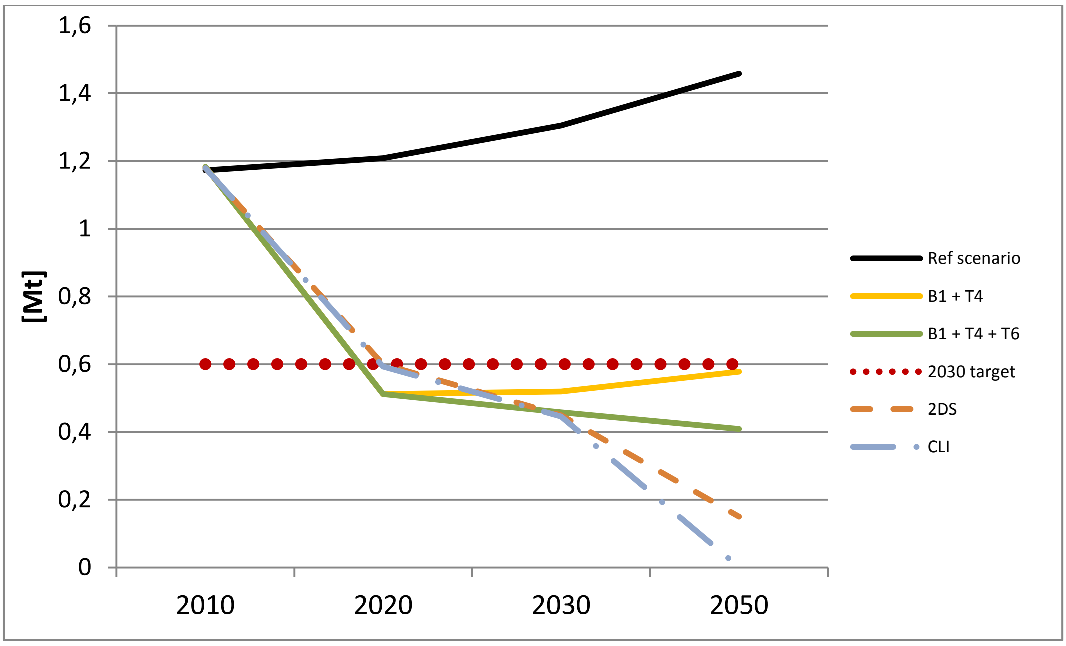

Figure 10: Summary of CO2 emissions for various scenarios and measures

Measure T6, transferring of freight transport from road to rail and ship, is independent of both B1 and T4, and can therefore be combined into a portfolio of measures in order to reach the 2030 and 2050 targets. As shown in Figure 10, such a combination will clearly satisfy the 2030 target for the city of Oslo. However, there is still some way to go in order to reach the 2050 target.

5. Discussion

For the two climate scenarios (2DS and CLI), we observed a high utilisation of new fuels and technologies. Generally, urban areas are more energy efficient and have more technology options available to mitigate climate change. The results showed that biofuels are required in the medium and long term to decarbonise heavy duty vehicles for freight transport. Additionally, electric vehicles contribute massively to personal transport. In urban areas the driving distances are typically shorter, and charging infrastructure is therefore more easily constructed due to urban compactness. The average abatement cost for the 2DS analysis is just above 2300 NOK per ton CO2 removed. In addition to all costs related to the energy system (e.g. investment and operational costs), the calculated abatement cost includes costs related to disposal of oil boilers and tanks, as well as costs for retrofitting existing buildings for obtaining better energy performance standards. The average abatement cost for the CLI analysis is 2370 NOK per ton CO2 removed. This is slightly higher than for the 2DS analysis, where the increased costs among other are related to the use of advanced construction machineries and hydrogen technologies within sea transport.

Based on the model results, the abatement cost for measure B1 is 922 NOK per ton CO2 removed. This is considerably higher than indicated in [34], where the abatement cost is calculated to be lower than 500 NOK per ton CO2 removed from the household or service sector. This includes around 50% of the emissions from the stationary sector in Oslo, and these can be removed by conversion from the use of oil boilers to either electric boilers, various types of heat pumps or district heating. One of the reasons for the relatively high abatement cost for B1 is that measures within the district heating sector is more expensive than 500 NOK per ton CO2 removed, e.g. increased recycling of plastic waste. 5% of the stationary emissions in the city of Oslo come from the food industry, and these emissions can be removed by converting from fossil fuels to e.g. biofuels. Besides increased recycling of plastic waste, the feasibility of all the actions above can be characterised as relatively easy to implement.

Based on the model results, the abatement cost for measure T4 is 448 NOK per ton CO2 removed. This figure is also dependent on the future costs of fast charging stations for electric vehicles. In the current work, a cost of 750 kNOK per fast charging station is assumed, which is the average cost found in [35]. The abatement cost for T4 is line with [34], where the introduction of electric (or hydrogen) vehicles for personal vehicles comes with an abatement cost of below 500 NOK per ton CO2 removed. Depending on the ambition level (i.e. number of vehicles), the feasibility of this action can be characterised as either easy or medium.

T3, T4, T5 and B1 are the most effective measures for reaching Oslo’s long term climate targets. All of these measures are therefore implemented in the solution for both 2DS and CLI. B4 is also an effective measure, since it is profitable from both a socioeconomic and private economic point of view. Generally, not all of the energy efficiency measures in B4 will be implemented. This could be due to discrepancy between the socioeconomic and private economic benefits of implementing the measures, various forms of market failure, or different behaviour aspects. B3 is an efficient measure for reducing the future energy demand, but has limited effects on the CO2 emissions. E1, E2 and B2 are not effective measures for reaching the climate targets, and are therefore not chosen in neither the 2DS nor the CLI scenario.

In addition to the positive impact on CO2 emissions and energy demand, these measures have a positive impact on local air pollution, as reduced use of fossil fuels in stationary and transport sector also will reduce other emissions, such as particulate and NOx, and thus improve air quality. The measures might also have other positive impact on city level, not calculated in this analysis, as establishment of new infrastructure for transport and deep retrofitting of buildings will demand not only new technologies and solutions, but will also generate new job opportunities. The most important measures in terms of mobility, is the improvement of infrastructure for public transport, as well as the restriction on private vehicle use. These measures imply a change from the use of private cars to public transport options, and are dependent on a huge effort to build new public transport options.

Based on the model results, the abatement cost for measure T6 is 1750 NOK per ton CO2 removed. The abatement cost for transferring of freight transport from road to rail and ship is mainly dependent on the availability of necessary infrastructure. Even though Oslo already has access to great facilities for both maritime transport and rail services, considerable investments are still needed in order to implement this measure. The feasibility of T6 can be characterised as either medium or hard depending on the level of ambition.

For the transport sector, a significant amount (0.35 Mt) of CO2 is still being emitted for the combined portfolio of B1, T4, and T6, and almost 0.55 Mt if measure T6 is removed. The majority is related to emissions from road freight from light and heavy duty trucks fuelled by gasoline or diesel. Navigation and other mobile combustion do also contribute to the emissions in 2050. In order to reduce or eliminate the dependence of fossil fuels in road freight, deployment of alternative technologies like e.g. gasoline and diesel hybrids, ethanol, compressed natural gas (CNG) or hydrogen fuel cell is needed. The latter is the only of these alternatives that have the potential to totally eliminate the fossil fuels dependence. Another alternative is biofuels produced in a sustainable matter, not just for freight transport, but for the entire transport sector. As discussed for the 2 degree scenario (2DS), a combination of using hybrid and bio-fuel vehicles contributed to a significant reduction in the CO2 emissions for freight transport. Furthermore, by introducing traffic management schemes, emissions from the transport sector can be even more reduced. This could include park and ride schemes, cycle lanes, congestion charging schemes, car-pooling, and low emissions zones.

The results are based on a linear least cost model assuming perfect competition and perfect foresight. Future technologies not invented are not included in the model. Another shortcoming of this model approach is that the human behaviour aspect is hard to incorporate properly. This is particularly relevant when considering implementation of energy efficiency measures where the public's willingness to implement such measures is not taken into account. In addition, infrastructure costs for non-energy items (e.g. tunnels or roads) are not included in the model. This is a clear weakness, since such costs must be added after the analysis. Another shortcoming of the model approach is the lack of emissions beside CO2. In an urban area, the local air quality is clearly of high importance. Despite these limitations, the TIMES-Oslo model is still a powerful tool for analysing alternative pathways to a low-carbon city.

6. Conclusion

The city of Oslo has ambitious climate targets for the next 35 years, including a 50 per cent reduction of greenhouse gas emissions before 2030, and to use no fossil fuels by 2050. In order to meet these targets, there is a need for new infrastructure, transport solutions and more energy efficient buildings that do not depend on fossil fuels. Oslo has a shared responsibility with other Norwegian cities by leading by example, and it is important that the results from Oslo are transferable to other cities, both nationally and internationally.

One of the key findings from this work is that the majority of the emissions from the stationary sector can be removed at a low abatement cost (below 500 NOK/ton CO2), where most of these actions are relatively easy to implement. Analyses with the TIMES-Oslo model show that none of the individually analysed measures were able to reach the goals in 2030 and 2050 respectively. However, by combining independent measures, the target in 2030 is achievable. This indicates that it is necessary to invest in a portfolio of technology choices in order to satisfy the targets, and not one single measure in one energy sector.

Transport in the Oslo region must undergo huge changes if the target for 2050 shall be met. The increase in transport demand must therefore be covered by either public transport, bikes or by walking. Additionally, the public transport in Oslo must be based on renewable energy sources by 2020 and a bicycle strategy must be implemented by 2025 in order to see 15% of the daily travels by bike. Additionally, renewable fuels must be used for all transport modes by 2050 in order to reach the overall target. Another finding from the analysis is that strong support schemes for hydrogen infrastructure are needed for decarbonising the entire transport sector. This action comes with a medium feasibility, and with an abatement cost approaching 1500 NOK/ton CO2.

As demonstrated in this paper, bottom-up optimisation models like TIMES are well suited for analysing how urban areas can develop sustainable energy systems for the future. TIMES-Oslo was used in two different “modes” in this work. The first approach consisted of using the full technological richness provided by TIMES-Oslo, and analysing what a 2-degree scenario (2DS) and the Oslo Targets (CLI) would imply for the city of Oslo. The results from the analysis provided the most cost-efficient way of reaching such different climate targets, where the dynamics between the sectors are taken into account. However, for the latter approach, it is harder to identify both the underlying measures and the relevant policy instruments required to obtain the solution.

The second approach consisted of running several measures, one at a time, in order to investigate each measure’s impact on especially the CO2 emissions and the energy consumption. One advantage with such an approach is full transparency of the model results for each individual case. Additionally, it is easier for the decision makers to come up with relevant policy instruments in order to implement different measures. However, one disadvantage with this approach is the possibility of obtaining non-optimal solutions when combining individual measures into a portfolio. Consequently, there is a risk that sub-optimal systems can arise because interactions between different systems are ignored. Additionally, so-called command-and-control measures as described in this paper, can typically lead to reduced production of goods in order to reduce carbon emissions. Such a loss in output or activity translates into a deadweight loss in welfare.

Finally, the two approaches were compared to study the effectiveness of the different measures in reaching Oslo's long term climate targets. Six of the measures (T3, T4, T5, B1, B3 and B4) were found in the cost optimal solution of both the climate scenarios, clearly implying their effectiveness. Three of the measures (E1, E2 and B2) were not found in any of the cost optimal solutions, and are therefore not seen as effective for reaching the CO2 targets. However, these measures could provide other positive aspects, like e.g. reduced demand for grid investments, as well as increased security of supply. Additionally, the three remaining measures (T1, T2 and T6) contributed to reduced emissions, but were not included in the overall optimisation since modal shifts between different transport modes must be handled exogenously.

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