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Planning for a system wide electrification of the transport sector in Norway

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Summary

In this paper we present preliminary work and results from a newly developed visualization tool for the energy demand of the present and future transport sector in Norway. In this tool the four largest motorized transport modes are included. The transport network is constructed from available data bases, while traffic amounts are retrieved from the Norwegian transport models. The visualisation tool is constructed at a high detail level, allowing users for instance to investigate energy demand of individual road links. One application of this tool is planning charging infrastructure for the future electrical paradigm shift.

Keywords: Energy, charging, demand, market development, mobility system.

1 Introduction

In the recent years electrification has made an impact on the transport sector. Especially the road sector has seen a significant increase of battery electric vehicles (BEVs). Norway is in the forefront of this paradigm shift, with electric vehicles (EVs) having in 2017 a 39.2 % market share for new vehicles in Norway – 20.8 % for BEVs and 18.4 % for plug-in hybrids (PHEVs)[1] [1]. In addition, other transport modes are looking at, and/or relying on, electricity as well. The railroads have long traditions using electricity, and both electric ships and planes are currently making an entrance into their respective markets.

For the transport authorities, as well as power companies and other relevant actors, this puts heavy demand on charging infrastructure. To plan for a system wide electrification, a crucial step is to understand the future need for energy and power within the transport system.

In order to understand the energy demand and consumption for the transport sector in the future, both people's choice of mean of transport and the efficiency of different drivetrains must be considered.

Transport models are used by road authorities all over the world to foresee traffic volumes based on historical data, and for planning of new roads. In the past, only the demand for new roads have been necessary to evaluate. But because of the transition from fossil fuels to more sustainable ones such as electricity, planning

[1] https://elbil.no/english/norwegian-ev-market/

for transportation in the future must now also consider how to expand the infrastructure for new energy carriers.

Emissions and fuel consumption are tested in the WLTP test during type approval, which all cars sold in Europe must pass [4]. Data from the WLTP- and NEDC-test show the historical development in energy consumption for the road transport sector in Europe [5]. New electrical vehicles on the other hand have a higher efficiency rate than vehicles with internal combustion engines (ICE). ICE typical have a thermal efficiency around 20 % [6] and an EV have an efficiency rate about 75 % [7]. This can potentially reduce the energy demand even if the traffic volumes remain on today's levels or do not increases dramatically.

Visualizing data on a map is a good way to make variances in different scenarios more visual and understandable. Energy consumption, air pollutions and future vehicle kilometres are common data to illustrate in maps[2]. As an example, the State Energy Analysis Tool[3] is combining data from electric generation, environmental pollution and zero emission vehicles (ZEV) sales to visualise on a map the energy and climate status aggregated to state level in the US.

In this paper, predictions from transport models are combined with calculation methods for energy consumption by different means of transport. The results are visualized as an energy map for the entire transport system of Norway. The map visualizes both present and future estimated energy demand for vehicular movements, which by physical relations can be further transformed into energy consumption from the power supply, e.g. battery or tank. Because we distinguish between energy demand and consumption, the methodology allows for comparable units in the visualization. This is due to the differentiation of the engine and power supply, where the energy demand is largely independent of the energy carrier, but the energy consumption is dependent on how efficiently the engine converts energy between tank/battery and wheel, propeller, etc.

By combining theoretical models for energy use and speed with transport models for all modes, the total energy demand for both basis and prognosis scenarios is calculated and visualised. This will serve as a basis for future planning of the electrical grid, including charging technologies. The development of this tool is an ongoing project and it will be further developed in the months and years to come.

In the remainder of this paper we present in chapter 2 our calculation methods, the available data bases that are used, and briefly how the visualisation tool technically is constructed. Next, in chapter 3, we show some preliminary results before discussion and conclusions are made in chapter 4.

2 Method

The stepwise methodology used to calculate and visualise the energy demand from the entire transport sector is route based, so that the resolution of calculations is detailed in spatial and temporal dimensions. However, this calls for a similarly detailed set of inputs with regards to transport network and vehicle characteristics. For all routes used in the transport models, we start with estimating a speed profile from speed models. The speed profile combined with vehicle parameters forms the basis for the energy calculation, which are based the same principles for all transport modes:

- The energy needed to maintain a specific speed profile is the spatial integral of forces working against the propulsion direction throughout a specific route.
- The energy needed from the power supply is dependent on the engine efficiency.
- The auxiliary load is constant and time dependent.

The calculation results are stored in a data base and visualised in a web browser. Each step is explained in detail in the next sections.

[2]http://airindex.eea.europa.eu/

[3]https://cleanenergyfinanceforum.com/2018/12/04/data-visualization-tools-that-can-guide-energy-and-ev-development

2.1 Speed profile modelling

The speed models can be divided into two types, one for road transport and one for all other modes. The road speed model is more complex due to the operational characteristics. While planes, trains and ships follow a relatively rigid speed profile, road vehicles have large fluctuations due to geometrical, legal and traffic properties. Therefore, the speed profile for non-road vehicles consists of an acceleration phase with a constant acceleration, a cruising phase with a constant speed, and a final deceleration phase with constant deceleration. These values were estimated from AIS data for marine operations, a train operator management database for trains, and by using the FlightAware[4] API for planes.

The road speed model is estimated based on 130 000 logged vehicle trips, which spanned over a total of 245 million GPS points. The functional form of the speed model is:

$$v = C(x_g)e^{U(x_d, x_s, x_f, x_k,)} \tag{1}$$

Here, $C(x_g)$ is defined as reference speed for a specific speed limit (x_g), and $U(\cdot)$ is a linear function of the road variables lane width (x_d), horizontal curvature (x_k) and vertical curvature (x_f as downhill and x_s as uphill). The speed is further adjusted for traffic flow based on volume delay-functions (VDF). For heavy duty vehicles, the speed is restricted upwards to 85 km/h due to speed limiters.

The speed profile from the speed model is further refined by including driver and vehicle characteristics. First, transitions and boundary conditions are taken into consideration by imposing restrictions on acceleration and deceleration values. Then, as a feedback loop with the energy model calculations in the following step, a logical check of the engine´s capability to maintain the speed profile is implemented. The end result is a continuous and smooth speed profile.

2.2 Energy models

With the speed profile as an input, the energy usage is calculated by integrating the power needed at each segment of the road. The power is calculated from well-known mechanics, where the power needed for propulsion is equal to the forces acting on the vehicle. Our approach consists of the following equation for the effect required from wheel-based vehicles and trains:

$$P = v\left\{mg\sin\alpha + mgC_r\cos\alpha + \frac{1}{2}\rho_a v^2 AC_d + m_e a\right\} \tag{2}$$

Here, v is the speed, m is the mass, g is the gravitational constant, α is the slope, C_r is the rolling resistance coefficient, ρ_a is the air density, A is the front area, C_d the drag coefficient, m_e the equivalent mass, and a is the acceleration.

Similarly, the equation for planes is:

$$P = v\left\{m \cdot g \cdot \sin\alpha + m \cdot a + \frac{1}{2}\rho_a v^2 A_w C_{dp} + \frac{1}{2}\rho_a v^2 A_w C_{di}\right\} \tag{3}$$

Here, C_{dp} is the parasitic drag coefficient, A_w is the wing area, and C_{di} is the induced drag coefficient.

The equation for ships is:

$$P = v\left\{m \cdot a + \frac{1}{2}\rho_w S v^2 C_t + \frac{1}{2}\rho_a v^2 AC_d\right\} \tag{4}$$

[4] https://flightaware.com/

Here, ρ_w is the water density, S is the wetted surface, and C_t is the hull resistance.

By combining the speed profile with the presented equations and specific parameters for vehicles and vessels, a power profile for each route can be calculated. In Figure 1, an example for this process is illustrated for a passenger vehicle where the speed of the vehicle is estimated using the road based speed model in Equation (1), vehicle characteristic and feedback energy calculations.

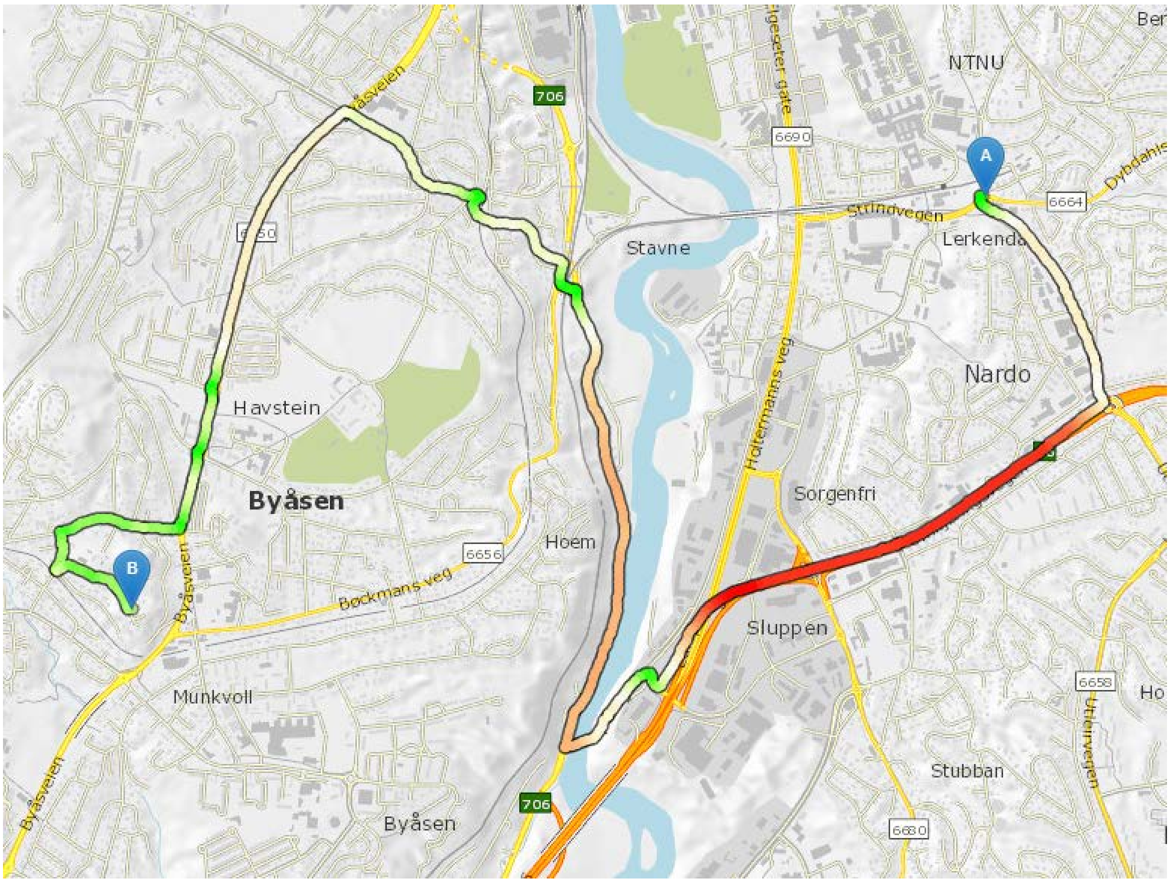

Figure 1: Speed estimation for a road transport route using a passenger vehicle. Red colour shows high speeds (70 km/h), obtained on the highway in this case, while green links shows lower speeds. Typically, steep hills, sharp turns and speed limits will influence the estimated speed for passenger vehicles.

The calculated energy demand is defined as the energy needed to move the object from A to B. To account for the internal processes, and thus calculate the energy consumption, a representation of the energy efficiency needs to be introduced. The production of useful work is described with simplified drivetrain components, each with their own characteristics and energy losses. For the moment energy efficiencies are assumed to be constant values but will be replaced by variable function by work progresses. The energy conversion process is in reality a complicated one, depending on properties and operating conditions such as engine geometry, speed, pressure, ambient temperature, transmission properties and so on. Additionally, there are power independent processes which also consume energy, such as AC, heating, lighting and other auxiliaries. These are included as time dependent processes and added to the total energy demand.

2.3 Vehicle and vessel characteristic

By describing a vehicle park for all transport modes, both energy demand and consumption is calculated using the same universal physical relations. Additionally, a systematic description of the transport network and traffic flow, we can apply the methodology for the transport sector. The vehicle and vessel park included in the energy map consist of 8 vehicles, 6 ships, 6 trains and 4 planes for commercial traffic, and 16 vehicles, 34 ships, 12 trains and 2 planes for freight transport. Two examples of parameter value sets are shown in Table 1.

Table 1: Example of vehicle parameters

	ICE_{diesel}	Freight train
Weight (kg)	1 510	1 200 000
Acceleration power (kW)	85	3 000
Braking power (kW)	170	3 000
A (m^2)	2.3	14
C_d	0.3	1.8
C_r	0.012	0.0015

2.4 Transport activity estimation

Activity data from transport models are used as a basis to calculate the system wide energy demand from transport. The transport models in Norway and resulting estimations of transport activity falls under the responsibility of the Directorate of Public Roads and the National Transport Plan (NTP) [8]. Nationwide transport models for all modes are developed and maintained, providing estimations of link level traffic data for basis and prognosis years. The methodology for energy calculation is applied on all routes included in the transport models.

For road links in the transport models the geometry is represented in high detail from the National Road Data Base (NVDB[5]), providing all the necessary properties for energy calculations. For the railway there are several data sources that are combined for establishing a 3D representation. An original dataset containing the railway network of Norway is provided from the Norwegian Railway Directorate. Unfortunately, not all parts of this network were assigned with altitude values, therefore a merging with the national height data base API in Norway[6] was performed.

For air traffic we have relied on the API from Avinor[7] and the APIs from FlightAware. In particular, the Avinor API provides information about all flight arrivals and departures between airports in Norway and other airports, both within Norway and internationally. We use FlightAware data to retrieve a flight-corridor with latitude, longitude and altitude data from the flight number of one flight for all possible pairs of airports (both in and out of Norway).

The transport network for marine operations is included in the transport models. Because the energy calculations are relatively independent of the network properties, the level of required detail is quite low.

Technical description of databases

On the technical side all data set described above is added to a PostgreSQL database with the following main tables:

- **Transport modes:** A table formally defining the transport modes in use (currently plane, ship/ferry, train and road vehicles).

[5] https://www.vegvesen.no/fag/teknologi/nasjonal+vegdatabank
[6] hoydekart.no
[7] state-owned limited company that operates most of the civil airports in Norway.

- **Nodes:** A table containing the intersections for road transport, stations for train, docks for ship/ferries and airports for planes (the nodes of the transport network).
- **Links:** A table containing the transport links in the transport networks for all transport modes, starting and ending in nodes in the Nodes table. For vehicles, this corresponds to roads, for trains this is rails, for planes this is the flight corridors and for boats this is the typical routes used.
- **Vehicles:** A table containing technical specifications of the vehicles used in each transport mode.
- **Routes:** A table containing route information (a route consists of sequential links) and the number of travels on each exact route for each vehicle type. The representation that is used is a sequence of nodes from the Nodes table. For all adjacent pair of nodes in these sequences of nodes there must exist a corresponding link in the Links table.
- **Results:** A table containing the resulting energy calculations that are made by running calculations on the links in each route for all routes and the given vehicle. For each defined vehicle the aggregated energy demand is stored at different aggregation levels. Thereby, fast visualization of the links can be done by filtering on transport mode or vehicle type.

3 Results

The energy map is visualized in a web mapping application[8] using Leaflet [9], which makes it easily available in a web-browser. The map shows the energy demand for the road, rail, air and maritime sectors. A heatmap representation of the energy demand is provided for visualization. The visualization is set to become more detailed when zooming in. A secondary approach that is currently being tested is a grid-based visualization, where the total energy use within each cell determines the cell color.

Some of the most prominent features of the tools are:

- **Zoom:** The displayed data is adjusted to the zoom level, with regards to resolution and scale. The scaling adjusts to the maximum and minimum value within the visible area automatically.
- **Choice of mode to be visualized:** As the estimated energy demand is calculated and stored separately for each mode in the database, the user may select modes to be visualized from a checklist. The available options are road, rail, sea and air.
- **Choice of estimated vehicle park composition:** There may be several available vehicle park composition prognoses, which will affect the estimated energy consumption. The user may choose between two different compositions.
- **Export of data:** Data can be exported for a selected area. The default option is to export what is seen on-screen, but it is also possible to extract results for predetermined geographical boundaries, such as administrative regions or municipalities.
- **Choice of energy calculations:** Because of the high level of detail in the energy calculations, each intermediate result is stored in the database. Hence, the user may choose to display the energy demand (powertrain independent), energy consumption (from tank/battery) and energy potential for regeneration.

Figure 2 is a screen dump of the current tool when visualizing road traffic. Added to this figure is the result when zooming in the Oslo area. Additionally, the difference between the heatmap and grid visualization method is displayed in Figure 3.

[8] http://mobilitet.sintef.no/energikart/

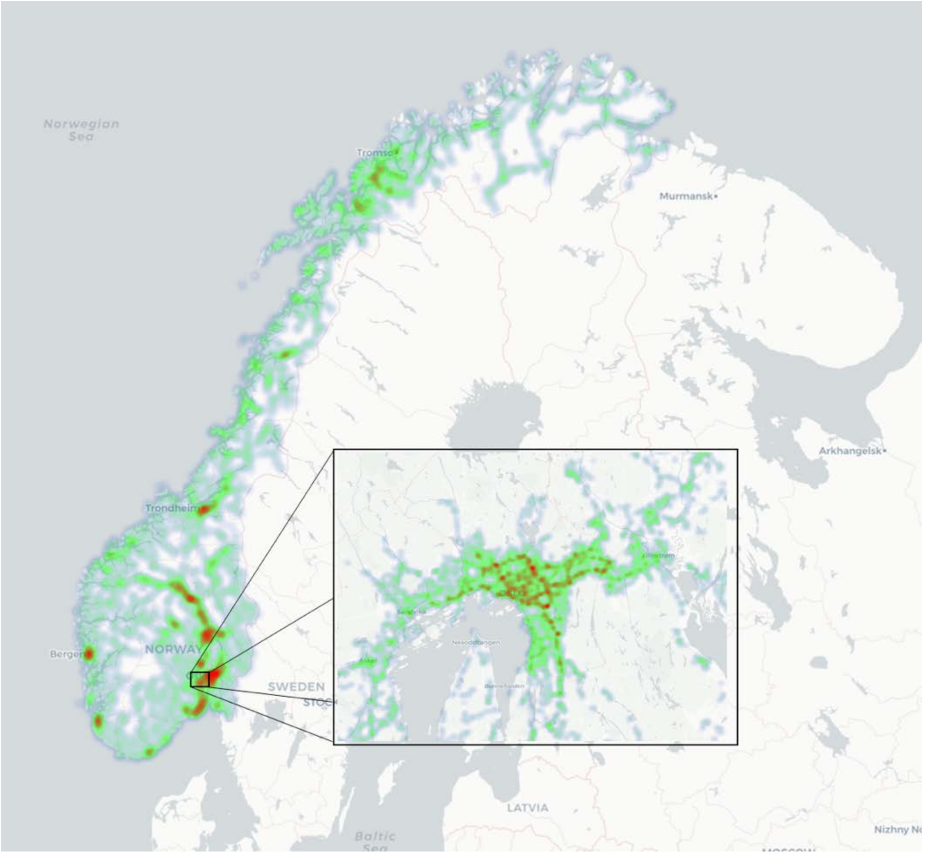

Figure 2: Visualization tool, with an added zoom layer to show effect. The red areas are the most energy intensive.

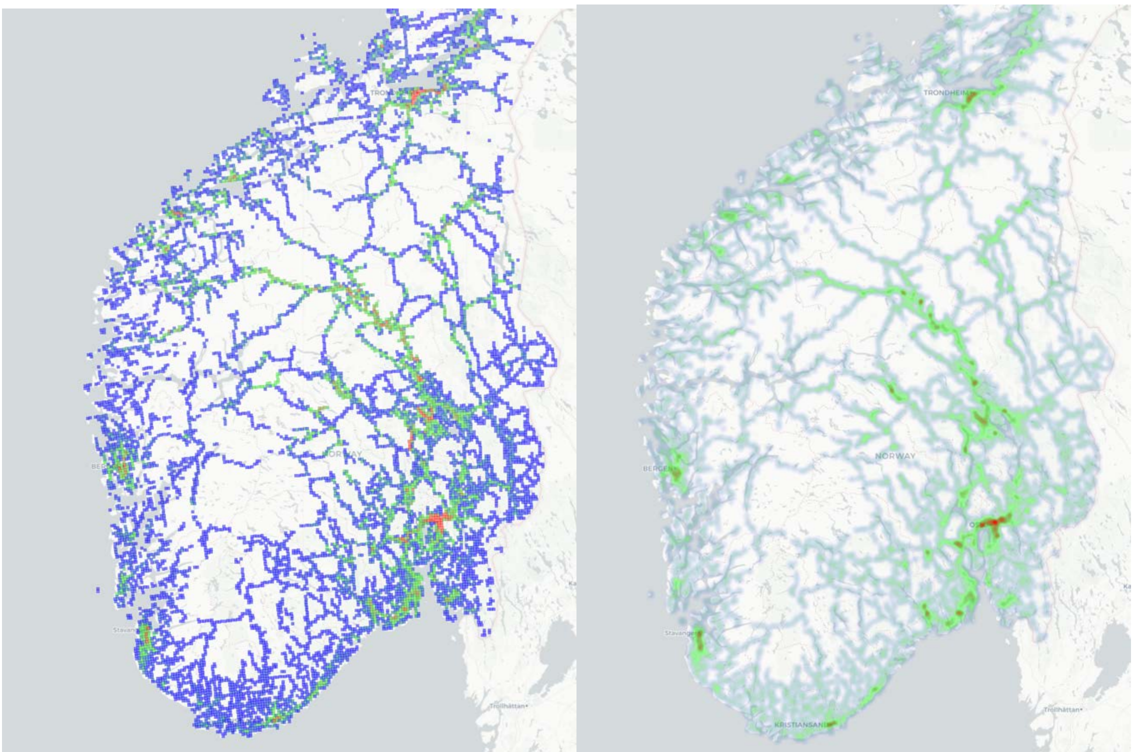

Figure 3:A side-by-side comparison of the grid (left) and heatmap (right) visualisation options. The red areas are the most energy intensive.

Currently, only energy calculations for road and rail traffic is included, see Figure 4. Including calculations for air and water is currently under development, but the transport networks and traffic numbers are available for both modes and can also be visualised in our tool.

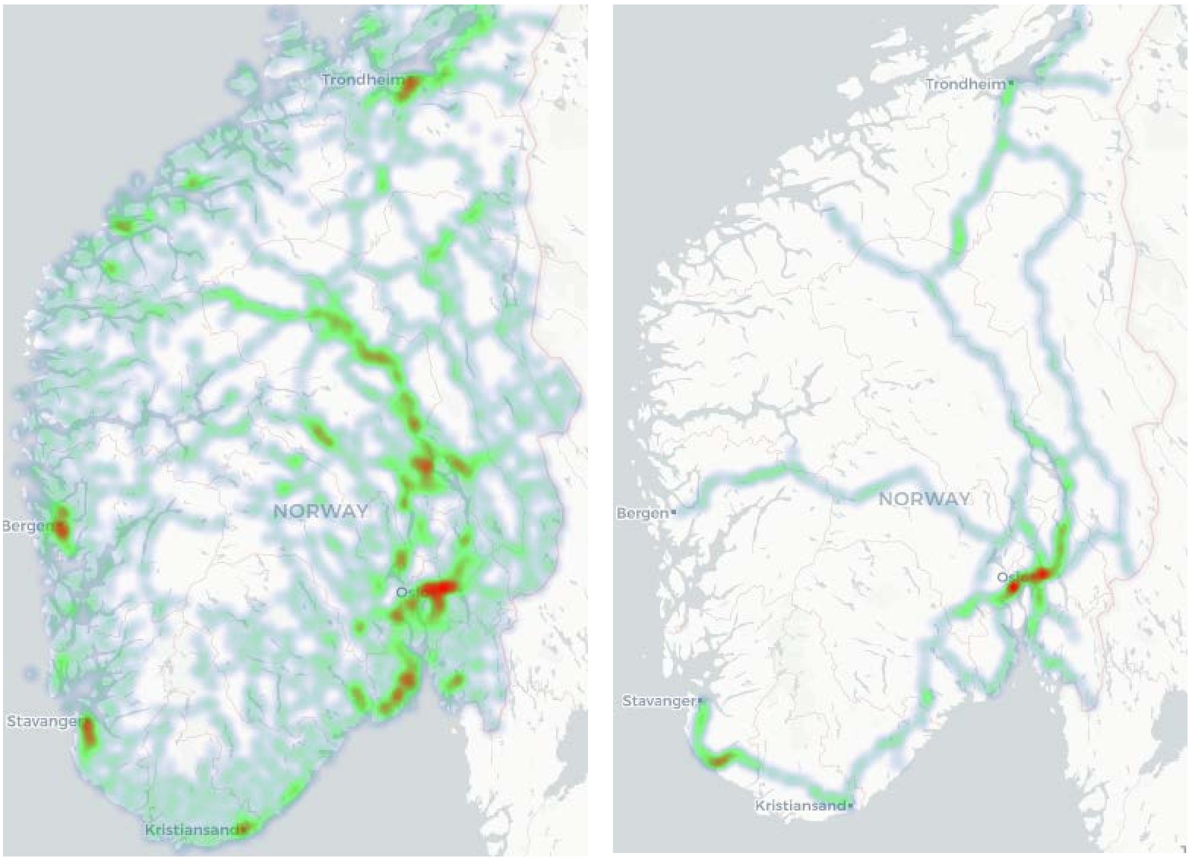

Figure 4: Output from the tool for road (left) and rail (right) traffic. The red areas are the most energy intensive.

3.1 Use cases

The main purpose of the energy map is to provide a foundation for the future electrification of the transport sector. A system wide calculation of the energy demand from transport will support this by providing spatiotemporal data for future electric vehicles and vessels. For the energy demand calculations, several use cases can be identified: For accounting and educational purposes, the **total energy consumption** may be of special interest. For specific problems and road authorities, challenging **hot spots** in the transport network can be of interest. This will usually be situations where the traffic volume is especially high, steep inclines and high velocity links. As transport models are used as a representation for the transport activity, **prognosis situations** for the energy use is available. This will be relevant for a comprehensive study of future infrastructure projects and the derived energy use from the resulting transport. In line with this, the visualization of the energy use from the transport demand will act as a **quality control** of the transport models. Finally, due to the relatively constant relationship between fuel consumption and **CO_2-emission,** the energy map will provide a visualization of estimated direct GHG-emissions from the transport sector.

The need for estimating charging infrastructure, both static and dynamic, based on a combination of power demand and traffic variation curves represents another interesting group of use possible cases. This provides a basis for determining the placement of **charging stations,** especially if already available charging stations are included in the interface. Similarly, the design value for the power needed for the transport sector is important in **electric road feasibility studies.** This coincides with aspects regarding availability of power and components from the **grip perspective.**

4 Discussion and concluding remarks

The presented energy map will provide important information to both authorities and private actors. It will provide a basis for planning road-based charging stations as well as charging infrastructure for other transport modes like the maritime sector. It will also serve as an important input to the power industry for preparing the power grid network for future electric mobility. For freight terminals, this will act as a tool towards planning for sufficient power capacity. In a case where alternative fuel types are being introduced, it will be possible to study the demand for those, such as hydrogen. However, as electricity quickly is becoming the new major fuel type in Norway, focus needs to be given to electric vehicles and their infrastructure.

The amount of input data to the energy map is relatively large. As each input introduce some inaccuracy, the accumulated inaccuracy is of importance. Regarding the energy models, each parameter comes with a given inaccuracy, which may be quantified through experiments. Through this, an interval for the margin of error may be introduced. This is however not a part of the scope of the current work within the energy map and will be object for further research.

The greatest uncertainty in the input data is probably the activity data. As the traffic volumes account for a large share of the aggregated energy use, any variation in these numbers will greatly impact the end result. The validity of the traffic volumes estimated by transport models may be debated. Although the basis situation is calibrated to available traffic data, the future scenarios are increasingly inaccurate the further ahead in time they are estimated for. Now, more than ever before, the future traffic situation is hard to define, due to the possible introduction of disruptive technologies and services such as autonomous vehicles and MaaS[9]. However, there are currently few or none relevant alternatives to traditional transport models available.

A further development of the energy map will include improved energy models, especially regarding the engine efficiency representations. Currently, more detailed relationships between engine efficiency and the engine load are being estimated for various engine types. Additionally, the energy map will be coupled to equivalent models for the power grid, enabling a coherent planning of future charging infrastructure.

Acknowledgments

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[9] Mobility as a Service

Authors

Odd A. Hjelkrem has worked with simulating and modelling traffic for years, both in his masters and doctorate degrees, and in multiple research projects at SINTEF. A regular theme in Hjelkrem's work has been analysing traffic data in order to understand road user behaviour. A premise for this work has been knowledge about and experience with programming, databases and GIS tools for processing large data sets from both stationary and mobile units.

Petter Arnesen have a PhD in statistics, and an M.Sc. in industrial mathematics. His has knowledge and experience within the field of data analysis, primarily with classical and modern statistics. The last years he has primarily worked with data related to mobility, traffic and within the transport sector in general. He has experience with several programming languages and broad knowledge about the digital tools and methodologies that is necessary to meet today's demand for data analysis within the transport research and operational field.

Hampus Karlsson has a Master of Science in Urban Planning from NTNU with focus on bike planning and sustainable urban development. He started working at SINTEF in 2018 where he is involved in different projects, for example Mobility Zero Emission Energy System with focus on the maritime sector. He also works on bike related projects like calculate health effects and energy consumption connected to cycling. Together with writing his master thesis he worked with for the Norwegian Public Road Administration investigating who gain health benefits from cycling.

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