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METEOROLOGISKA INSTITUTET
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Energy-efficient Methods in Arctic Traffic: State-of-the-Art Report

Version 1.0

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Abstract

This State-of-the-Art document provides background information and context for the the project Energy-efficient Methods in Arctic Traffic (EMAL) funded by the European Regional Development Fund and carried out by the Finnish Meteorological Institute. The background information is an overview of areas relevant to energy efficiency and greenhouse gas emissions related to traffic infrastructure. Areas such as energy supply, distribution and storage, communications, measurement systems and technologies, road and roadside infrastructures as well as built environments overall are considered in this report. This document is a deliverable of the Work Package 2 of the EMAL project.

Tiivistelmä

Tämä kehityksen nykytila -raportti on osa Energiatehokkaat menetelmät arktisessa liikenteessä (EMAL) -projektia. Projektin toteuttaa Ilmatieteen laitos ja rahoittaa Euroopan aluekehitysrahasto. Tämä raportti on taustatietokooste ja kuvaus merkityksellisistä kytköksistä ja aiheista, jotka liittyvät liikenteen ja sitä palvelevan infrastruktuurin energiatehokkuuteen ja kasvihuonekaasujen päästöihin. Raportissa käsiteltävät osa-alueet ovat energian tuotanto, jakelu ja varastointi, tietoliikenne, mittausjärjestelmät ja -teknologiat, tiet ja tienvarsien rakennelmat sekä rakennettu ympäristö laajemmin. Tämä raportti on yksi EMAL-projektin työpaketti 2:n tuotoksista.

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Chapter 1

Introduction

1.1 Background and motivation

This State-of-the-Art document provides background information and context for the the project EMAL funded by the European Regional Development Fund (ERDF) and carried out by FMI. This document is a deliverable of the EMAL Work Package (WP) 2.

The European Union (EU) is aiming for significant reduction in traffic-oriented emissions as part overall goal of decarbonising the society and economy. At the time of submission of the EMAL project proposal (2018-09-26), the greenhouse gas (GHG) emissions reductions target within EU for Finland was 39 % from 1990 levels by 2030 for the sectors not included in the EU Emissions Trading System (ETS)[1]. Since then the increased urgency of action regarding the climate crisis has lead to emissions reductions targets being tightened further both at EU and Finnish national level. The EU target year for carbon neutrality is 2050 and the European Commission (EC) has proposed in October 2020 the 2030 reductions target to be increased from 40 % to 55 % [14]. According to the current Government Programme, Finland will be carbon neutral by 2035. Contributing to that goal, Finland will by 2030 at minimum, halve the emissions from domestic transport compared to the 2005 level.

The observed and modelled increase of average temperatures associated with climate change is larger than the average in high latitudes. Consequently the effects and impacts of the change are expected to be particularly pronounced and rapid in the Arctic regions. This is bound to enhance the interest and urgency of emissions reductions from the Arctic perspective.

The main objective of the EMAL project is to contribute to achieving those emissions reductions goals by identifying and possibly also piloting methods, systems and approaches for reducing the increase and as soon as possible turning the trend to decreasing the GHG emissions from traffic and traffic-related activities by more energy-efficient and low-carbon solutions. Particular focus and framework is arctic conditions and the geographical areas of application are Northern Finland and similar regions in the world.

[1] See description of the ETS at `https://ec.europa.eu/clima/policies/ets_en`. Of the different modes of traffic, only air traffic is ***included*** in the ETS.

The mission of the FMI, FMI's niche as part of the Government of Finland and the resulting research and service competencies and interests are well-suited to address and work on this topic:

> The Finnish Meteorological Institute produces observation and research data on the atmosphere, the near space and the seas, as well as weather, sea, air quality and climate services for the needs of public safety, business life and citizens. The Finnish Meteorological Institute is an administrative branch of the Ministry of Transport and Communications. [5]

As part of the its mission FMI has long experience in traffic-related research and development (R & D) in and for Arctic conditions. This R & D effort has included intelligent traffic themes with particular focus on weather observations and services to road traffic. The EMAL project contributes to creating a connection between the traffic and climate research efforts within the institute.

1.2 Methodology and Scope

This report is primarily a literature survey, hence the methodology and approach is predominantly ***descriptive*** and ***qualitative***. No quantitative analyses have been performed, but quantitative indicators are given to give order-of-magnitude information to for instance permit comparison of GHG emissions reduction potentials between different traffic-related sectors and activities. Application of tools such as life cycle and WTW analyses [***e.g.***, 9] might be appropriate in further more quantitative work. Due to their extensive scope, manufacturing, materials and recycling aspects of vehicles and their structures & systems have been excluded from this report.

The foci and scope of this report are briefly defined below from some perspectives:

Interpretation of *energy efficiency* Energy efficiency is not addressed only in a narrow sense, but more widely in the context of GHG emissions reductions. Reducing GHG emissions may in some cases and contexts lead to ***increased*** primary energy use, albeit energy in different form (such as oil vs. electricity or Hydrogen). From GHG emissions perspective the total Life Cycle Analysis net emissions and emissions reductions are the most relevant, since partial optimisation focusing on some parts of the complete chain may result in increased emissions in other parts of the chain (well to wheels analysis is a wide-scope subset of Life Cycle Analysis – for illustration, *see* Figure 1.1 on the following page).

Modes of transportation The primary focus is on road traffic and transportation; other modes of transportation (such as rail, shipping and air transport) are for the most part outside of the scope, but may be mentioned. However, drones are included due to their role and potential as delivery, logistics, measurement and telecommunications platforms in traffic-specific contexts and applications.

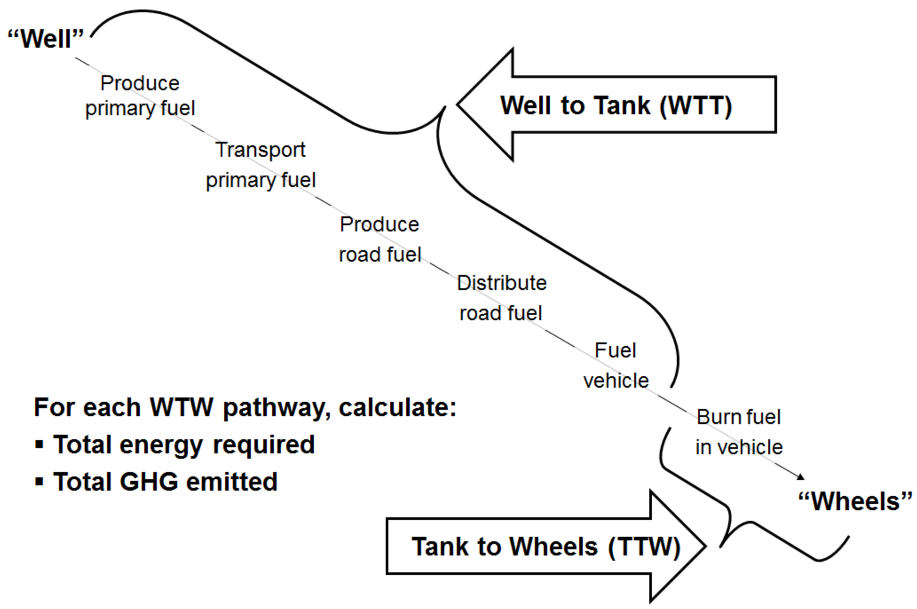

Figure 1.1: Graphic representation of WTW analysis from [9]. ©EU, 2016.

Types of systems and infrastructure In the context of this report ***traffic environment*** covers significantly more than just vehicles – infrastructure closely associated with roads, vehicles and traffic as a collective concept is also included. Notably, telecommunications infrastructure is included, since it plays such a crucial role in intelligent traffic systems – connectivity is a prerequisite for, ***e.g.***, operation of autonomous vehicles (AVs). Information about the environment a driver or an AV can receive through connectivity is also an enabler for navigation and route optimisation. Built environments – ***e.g.***, construction, repair and maintenance – are also relevant to the traffic infrastructure (also in terms of energy efficiency and GHG emissions).

Connections with FMI's current traffic research Since the spectrum of different energy-efficient methods is huge, we are limiting the scope here to the approaches which are compatible with and applicable to FMI's own intelligent traffic infrastructure, services and systems. The Sod5G vehicle winter test track and testing environment in Sodankylä is the main testing and development environment for FMI intelligent traffic services and systems, and therefore also the primary testing and piloting environment for the solutions identified in this report and project. FMI observational infrastructure includes also, ***e.g.***, some Road Weather Stations (RWSs) on public roads, observations systems embedded into both operational and research vehicles as well as the nation-wide weather radar network. The energy efficiencies and GHG emissions of those systems are also within the scope of this report.

1.3 Uncertainties

The actions taken by many states and communities to reduce the spread of the virus causing the COronaVIrus Disease 2019 pandemic have resulted in significant reductions in certain modes and types of transport – perhaps most notably movement of people. At the same time, telecommunications have replaced many traditional modes of transport because of the need for social distancing and for instance, teleworking. Since the long-term development of the pandemic remains highly uncertain at the time of writing, many sectors of transportation may change significantly and in practice permanently, potentially resulting in a very different road traffic system. As an example, social distancing favours private vehicles over public transport, while the climate crisis and energy efficiency favour the reverse.

Overall the COronaVIrus Disease 2019 pandemic, the inreased awareness on the possibilities of other future pandemics as well as the impacts thereof add an increased element of uncertainty in the validity of the conclusions, estimates and predictions presented or drawn in this text.

1.4 Organisation and outline of this report

After this introductory chapter (Chapter 1), Chapter 2 describes the current state of energy supply for the traffic-related systems and infrastructure. Chapter 3 outlines the traffic-related (tele)communications infrastructures, while Chapter 4 covers the relevant measurement and sensor systems. Road and roadside infrastructure (road construction, maintenance and repair) is described in Chapter 5. Chapter 6 provides an overview of built environments using the experiences of the Ii municipality as a representative case. Chapter 7 revisits the energy supply from a future perspective – outlining, what types of changes might occur or be needed to achieve the GHG emissions reductions targets described in Section 1.1. Conclusions are drawn as well as a summary and recommendations are given in Chapter 8.

1.5 Acknowledgements

The authors wish to thank the ERDF for the funding for this work, the project partners and stakeholders for their input to and our FMI colleague Lasse Latva for his constructive comments and feedback on the text and content.

Chapter 2

Energy supply – current state

2.1 Introduction and terminology

The energy system or supply includes following components:

- generation or actual supply
- distribution
- storage
- conversion between types or modes of energy

The primary terrestrial energy ***supplies*** are derived from basically three primary sources: the Sun, nuclear fission and geothermal. Solar energy can be divided into three subcategories:

1. Stored in fresh or processed biomass
   - oil
   - coal
   - peat
   - natural gas
   - wood and other fresh biomass
2. extracted from solar radiation derived motions and thermal gradients
   - wind
   - waves
   - tides
   - Ocean Thermal Energy Conversion
3. direct solar
   - electric
   - thermal
   - chemical

The fossil fuels oil, coal, natural gas and peat are also solar energy stored first into biomass. This biomass has then been converted by natural processes into solid, liquid or gaseous forms and stored into geological formations over long periods of time.

The Total Energy Supply (TES) distribution by source for Finland for 2019 is shown in Figure 2.1 on the next page.

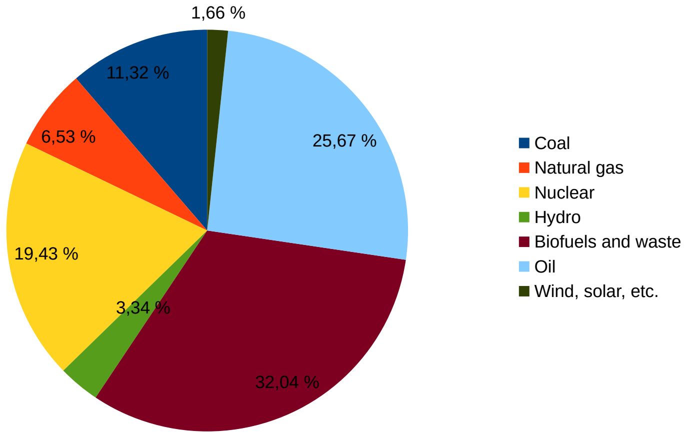

Figure 2.1: TES by source for Finland for 2019 (data source IEA; https://www.iea.org/countries/finland).

Distribution can be implemented via for instance pipelines for liquid or gaseous fuels and hot water in district heating systems; electric power lines, even wirelessly; with transport of containers, tanks and batteries using for instance trucks, trains, ships. The distribution backbones are the electric grid and globally also pipelines for liquids and gases. In Finland transportation by ship, rail and road are more significant, as the natural gas pipelines cover only the southernmost parts of the country.

Storage methods[1] include heat and water reservoirs (potential energy via for instance so-called pumped hydro), batteries, containers and tanks (for liquid and gaseous fuels), compressed air – even flywheels and superconducting magnetic storage. Conversions between chemical, thermal and electric energy can happen in a number of ways, such as

chemical reactions chemical to thermal
fuel cells chemical to electricity
internal combustion engines chemical/thermal to motion and electricity
resistors electric to thermal

2.2 Supplies

2.2.1 Power for stationary equipment and installations

Power is (mostly electricity) drawn from the large-area (national) electrical grid. District heating (grid) may also play a role in keeping buildings and other infrastructure warm, but the feasibility is limited to more densely populated areas or to locations, where waste heat is readily available[2].

[1] https://www.sciencedirect.com/book/9780128129029/power-system-energy-storage-technologies, https://www.sciencedirect.com/book/9780128034408/storing-energy

[2] For instance, in the vicinity of an industrial installation producing waste heat.

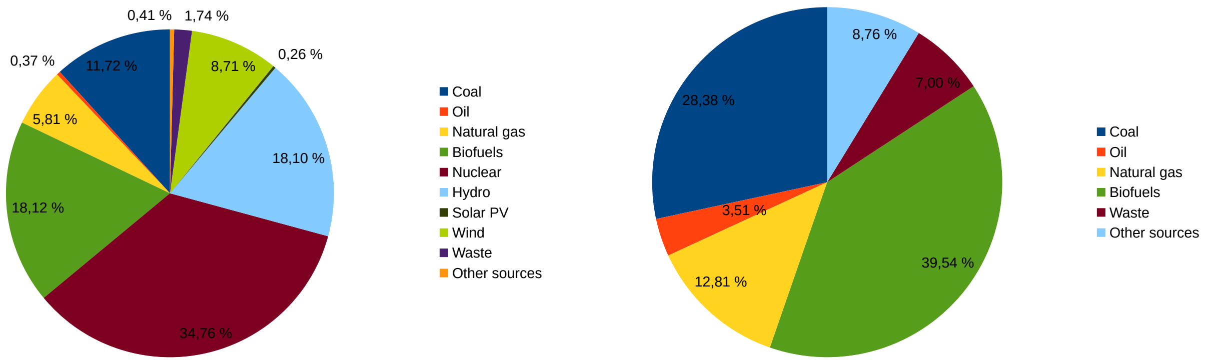

Figure 2.2: Distributions of primary sources for electricity (left) and heat (right) in Finland in 2019 (data source: IEA; ; https://www.iea.org/countries/finland.

The primary sources are often a mixture of the primary sources listed in Section 2.1. The mixture in Finland is illustrated in Figure 2.1 on the preceding page.

Local production means here on-site power supplies, typically either generators burning liquid or gaseous fuels, but also renewables like solar, wind or biomass. For heat production ground- or air-source heat pumps utilising essentially solar energy are fairly common in Finland. Ground source heat pumps (GSHPs) suit Arctic conditions better than air-source heat pumps (ASHPs), since the heat source of a GSHP remains in almost constant temperature throughout the seasonal cycle. Fuel cells are rare even for localised energy supply. Mostly the "base power" is drawn from the grid, while interruptions of grid power availability are covered with backup systems. Such systems may include also energy storage (see Section 2.3 on the next page) such as rechargeable batteries.

2.2.2 Motive power for vehicles

Currently most of the road vehicles in Finland use internal combustion engines, which burn liquid or gaseous fuels[3], primarily extracted from fossil sources. Liquid or gaseous bio- of synfuels[4] are also used in internal combustion engines either stand-alone or as mixtures with fossil fuels. Same assessment applies to aircraft – especially crewed aircraft and larger UAVs – but smaller UAVs use predominantly electric motors. UAVs are described more extensively in Section 4.3.3 on page 28.

The fraction of vehicles powered with electric-only or with electric-combustion engine hybrids remains low overall, but their absolute and relative numbers are increasing rapidly and regionally their numbers may be significantly higher[5]. The primary energy to generate the electricity to charge electric vehicles (EVs) or plug-in hybrid electric vehicles (PHEVs) comes from a variety of sources and the mixture gives an overall figure-of-merit for the emissions originating from the use of electric vehicles (see also Fig. 2.2). For PHEVs the distances and profiles of drives between charging also influence the emissions significantly: on the one hand the electric powertrain and batteries permit savings through recouping of braking energy in

[3] Petrol, diesel, ethanol, natural gas, biogas.
[4] For example ethanol, methanol, biodiesel, biogas.
[5] For example Norway.

more stop-and-go city or suburban traffic, but on the other hand the mass increase caused by the batteries tends to increase fuel consumption and emissions in road driving. The emissions profiles of these vehicles may also depend on how much these vehicles are charged directly from the grid, or whether some local, stand-alone sources such as solar panels are used.

Fuel cells using hydrogen or hydrocarbons have been studied and tested as power supplies for vehicles, but fuel cells are currently not in widespread use. This may change, if Hydrogen becomes a significant medium of energy distribution and storage (*see* Chapter 7 on page 36).

In vehicles powered by internal combustion engines electricity needed by on-board electrical systems is predominantly produced with generators coupled with the engine. Compared with present-day vehicles with lower sensory capabilities and on-board data processing needs, the energy needs of the on-board systems are likely to increase significantly in AVs. In principle some fraction of the energy could be produced for example by covering part of a vehicle's surface with solar cells [30] and storing the produced energy into the vehicle battery.

The energy efficiency and emissions of greenhouse gases of vehicles depend strongly on the type of primary energy used, but also of the power conversion efficiency of the type of engine used: conversion efficiencies of internal combustion engines are at best of the order of 40 %, whereas efficiencies of electric engines are significantly better and can be as high as 98 %[6].

2.3 Distribution and storage

Distribution and storage are presented together in this report, since these two features and aspects of energy supply are closely interconnected already currently. The current state is described in this section, future scenarios in Section 7.2 on page 37.

In the future (and this trend is strong and strenghtening already now) this interconnection between distribution and storage is expected to become even more important and pronounced with both the increased share of renewable and temporally varying energy sources (such as solar and wind) as well as the likely increase in more distributed, local and smaller-scale energy production. The mentioned trends and developments increase pressures towards more intelligent and bidirectional grids and increased storage capacity of both electricity and heat. For instance households and factories or business, which previously have had only a consumer role and have relied entirely on the grid for power supply are increasingly becoming at least intermittent suppliers at various scales to the grids (for instance surplus electricity from rooftop photovoltaic systems or waste heat from cooling systems or industrial processes) or are practicing or participating in load balancing over various time scales.

Liquid and gaseous fuels are a form of energy storage, but electricity storage is currently primarily used in backup systems for interruptions of power availability from the grid. For instance, wireless network base stations need this feature, especially since base stations need to be located also in remote and difficult-to-reach areas. In such areas (and despite of the changes in recent years) the electricity cabling is still often above the ground in Finland, making the grid more vulnerable to weather-induced interruptions (such as storm damage and excessive snow loads).

[6] https://www.fueleconomy.gov/feg/atv-ev.shtml

Technically energy storage could be implemented by producing and storing hydrogen or synthetic hydrocarbons using for example solar or wind power to run electrolysis or chemical synthesis [so-called Power-to-X (P2X)], but such systems are not in widespread use currently.

Energy is distributed primarily via the electricity grid & cabling or by transporting liquid and gaseous fuels to places and vehicles of consumption. It is noteworthy, that the energy transfer capability of pipelines is potentially much greater than the capability of even high-voltage direct current cables. Wireless energy transmission is relatively rare, even over short distances. Smartphones are an example of a system beginning to utilise wireless charging, but this technology holds promise for charged vehicles as well [4].

Chapter 3

Communications

3.1 Justification and overview

Communications services and capabilities have an important supporting role for road traffic already currently, but with the development and eventual adoption of autonomous vehicles (AVs) those services and capabilities are expected to become an integral and indispensable part of – in effect, embedded in – road traffic infrastructures. The requirements of traffic connectivity are also driving many capability requirements – such as bandwidth and latency – of telecommunications infrastructures and systems.

Communications equipment is dependent on energy in at least two major ways: electronics, electro-optics (such as optical fibre systems) and radio systems require electricity to function, but many such systems also require maintenance of a specific temperature range for correct operation. In Arctic conditions that implies mostly heating during the colder seasons, but if a system or subsystem tends to produce a lot of waste heat, with increasing temperatures passive or even active cooling may also be needed during the warmer seasons. With increased use of communications, energy consumption of communications infrastructure will likely increase, but these improved communications and computing capabilities – digitalisation in general – also offer opportunities for improving energy efficiency of other parts of the overall traffic infrastructure and operations. There is hence a trade-off.

When assessing the energy consumption of communications infrastructure (and improvements thereto), it should be kept in mind, that many services and capabilities make use of computing and storage capabilities removed from the end user (either human or machine). On the one hand, processing and storage can take place in the ”cloud” which can reside almost anywhere in the world. On the other hand, low latency requirements in some applications and functionalities mean, that those functions can not take place too far from the end user, resulting in the concept of edge computing. From energy consumption and emissions perspective, the infrastructure and its functionality encompasses more than just the consumption of the equipment in the vehicles or on the roadsides, but the impact is system-wise and geographically potentially much more widespread.

This section describes at the level of some detail the communications infrastructure components relevant for road traffic infrastructures. The description is top-down – starting from larger entities and fixed communications infrastructure, moving progressively towards mobile communications and especially scales and types most relevant to traffic – such as vehicular communications.

Relevant milestones in the evolution of communications systems in the last several decades are included, when deemed necessary to sketch a better picture of the communications system. Future visions and likely directions of evolution are also described to a degree.

3.2 What is a (tele)communications network?

Modern telecommunications networks (often referred just as ***communications networks***) are extremely complex entities and describing them in a comprehensive way is outside the scope of this text.

> A telecommunications network is a group of nodes interconnected by links that are used to exchange messages between the nodes. The links may use a variety of technologies based on the methodologies of circuit switching, message switching, or packet switching, to pass messages and signals. For each message, multiple nodes may cooperate to pass the message from an originating node to the destination node, via multiple network hops [28].

Examples of telecommunications networks include computer networks, the Internet, the Public Switched Telephone Network (PSTN), the global Telex network, the aeronautical Aircraft Communications Addressing and Reporting System (ACARS) network, and the wireless radio networks of cell phone telecommunication providers.

In modern communications networks the links may be implemented with wire or wireless technologies utilising radiofrequency or optical signals for transmission. The high-capacity trunk or backbone connections are typically implemented with optical fibres or satellites[1]. These trunk lines then connect to smaller-scale subnetworks which are – depending on the purpose of the subnetwork – implemented with a mix of optical fibres, copper cabling, directed microwave links and various types of wireless connections (radio or optical) up to end-user terminals. Those terminals can be for example computers, mobile devices (such as phones or tablets), sensors, etc. The users can be both humans and different devices, the end-user terminals can be both stationary and mobile. These networks transmit nowadays predominantly digital data, which can represent almost any type of content.

Communications can be one-to-one (for example voice communications, e-mail, other textual messages), broadcast from one to many (for example radio or TV broadcasts, World Wide Web) or mixtures of both.

Nowadays the most dominant communication systems are cellular networking of access point-served local subscribers with seamless roaming between cells and wireless local area

[1] Satellites are used mostly when a link needs to be established for example across a larger body of water and/or when building a cable connection is prohibitively difficult or expensive – such as in some ***Arctic*** areas, which are characterised by sparse population and long distances – also along roads. Transoceanic links are built using both satellites and cables, .

networking with local subscribers connected to the network with a single (or few local) access points. Software-Defined Networking (SDN) is a new type of network architecture approach, enabling the network to be intelligently and centrally controlled, programmed, using software applications. Cellular networking and wireless local area networking are considered more carefully later on in this chapter (Sections 3.4 on the following page and 3.5 on the next page). SDN is not considered any further, being slightly out of the scope of this report.

3.3 The role of wired networks in traffic infrastructure

The connectivity most closely related to road traffic or individual vehicles is implemented with mobile, i.e., wireless technologies. Cellular networks are an example of the type of networking applicable for traffic infrastructure, but other types of wireless technologies also exist or are under development (see Section 3.7 on page 18). Parts of the overall connectivity is, however, implemented using wired technologies and in many cases a similar connectivity element can be implemented with either a wired or a wireless – depending on current and projected demand for capacity, location (for example the distance from already existing wired network), available other communications infrastructure, cost and in some cases also available energy supplies. The choice between different technologies and solutions is hence a multi-faceted optimisation task. For illustration, see Figure 3.1.

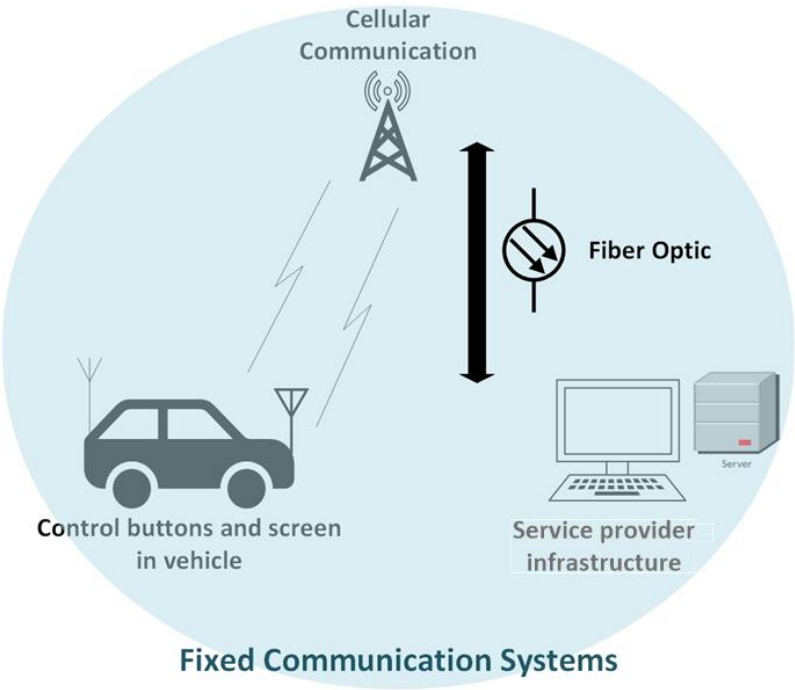

Figure 3.1: A simplified schematic illustrating some components of communications infrastructure for road traffic

A typical example might be a base station of a cellular network (see Section 3.4), which needs to be connected to the larger-scale – even global – communications infrastructure. If a base station needs to relay large volumes of data from and to the trunk network, optical fibre may be the only feasible (but costly) solution, as more construction is needed. If the data transfer requirements are less, a directed-antenna microwave link may be sufficient.

3.4 Cellular networking

One of the basic concepts of cellular networks is the division of a geographic area into smaller cells, which have a base station, which in turn communicates with terminals (typically bidirectionally) within the coverage area provided by the base station. The cells typically have geographical overlap and cells utilising different frequencies, channel access methods and protocols can function in the same area. The base stations relay and route communications both between terminals within the cell as well as to the outside of the cell to the larger trunk network or networks. Mobile phones are perhaps the most prevalent cellular network terminals, but increasingly other types of devices such as sensors and actuators are being connected also to and via cellular networks (so-called Internet of Things (IoT); see Section 3.6).

Cellular mobile communication technologies have evolved from the 1970s through five generations (G) of technologies – analogue to digital, from 0G to 5G (and research on 6G is already underway[2]). Currently 3G and 4G are in wide use[3], the cutting-edge technology being rapidly taken into use (but not yet widely adopted) is the 5G [24]. The cell diameters for the currently used 2G-5G networks vary widely between generations and the frequencies used[4].The interest in high frequences arises from the higher bandwidth of higher frequencies, but there is hence a trade-off between coverage and bandwidth. Different frequencies also have different sensitivities to weather conditions.

3.5 Local Area Networks

Another example of geographically smaller-scale cellular communications technologies are Bluetooth (range of the order of 10 m) and Wi-Fi/WLAN (range of the order of few tens of metres). Wi-Fi is perhaps better known from home, office and public[5] uses and Bluetooth from connecting peripherals with mobile devices and computers. These are also in a sense mobile networking technologies, but geographically on much smaller scales and ranges than the 2G-5G.

Bluetooth, Wi-Fi and similar technologies are, however, relevant also for road traffic related communications, since they can be used either as-is or as starting points for communications within and between vehicles [Vehicle-to-Vehicle (V2V)] as well as between vehicles and stationary infrastructures [Vehicle-to-Infrastructure (V2I)]. These types of communications are described in greater detail in Section 3.7 below.

[2] https://www.oulu.fi/6gflagship/
[3] There are, however, signs of 3G starting to be phased out [29].
[4] For example 5G frequencies fall between 600 MHz and 39 GHz and even higher frequencies may be used in the future. https://en.wikipedia.org/wiki/5G
[5] Many public venues such as restaurants, libraries and similar offer Internet connectivity via Wi-Fi ”hotspots”.

3.6 Internet of Things

Up to fairly recently, the devices connected to the Internet (and in some sense, ”forming” the Internet) have been perceived to be computers of various types, sizes and capabilities, connected via various types of cabling. This picture has been changing both rapidly and very drastically. Some key factors and developments include

- expansion and increased capabilities of wireless communications
- more and more traditionally non-connected and ”non-computer” devices such as vehicles, watches, refrigerators – even toasters – acquiring sensory and computing capabilities
- proliferation of network-connected (so-called ”cloud”) storage and computing

As a consequence, previously unthinkable classes and types of ”things” have become technically and economically feasible candidates for Internet connectivity – hence the term Internet of Things.

This development is changing also dedicated measurement systems (*see* Chapter 4 on page 25). Traditionally they have had dedicated (and often proprietary or non-standard) communications systems for data transfer, but with the Internet technologies (wireless connectivity, hardware, protocols and software), simpler, more capable and significantly less costly options for data transfer have emerged. This is also lowering the threshold of replacing or supplementing traditional measurement infrastructure components with large numbers of relatively simple and cheap sensor systems.

How IoT affects the overall energy consumption & emissions of vehicles and traffic (including communications) infrastructure is not clear. Even if individual sensors may need less energy to operate and communicate, the resulting energy consumption and emissions advantages may be offset and overwhelmed by the increase in proliferation of sensors. There may also be significant indirect effects or trade-offs: the increase in data volumes enabled in part by IoT has the potential of improving the energy efficiency and reduce emissions of many traffic infrastructure elements through advances such as improved weather forecasts, better traffic flow, remote repair and maintenance.

3.7 Vehicular networking

3.7.1 Overview

Vehicular networking means here connectivity, where one or both nodes of the communications transaction are a vehicle and the communication is ***external*** – into or out of the vehicle. Modern cars and other vehicles have also sophisticated ***internal*** communications infrastructure, but those systems are typically closed and the tehcnical solutions may also be manufacturer-specific. Consequently these vehicle-internal communications are not addressed in this text.

Many modern vehicles ***can*** also communicate with the outside utilising for example Internet protocols, but the communications originating from the vehicles' internal, built-in systems are for the most part limited to communications with the manufacturers' systems. Hence the data provided by these systems can – even if technically feasible and potentially useful – rarely be used for other purposes such as monitoring of road or traffic infrastructure state and condition. Consequently, this type of networking is addressed further in this text only superficially and in context with other topics.

There are multiple needs and uses for external vehicular networking – below some examples:

1. A vehicle can act as a source of observations and data on for instance the state of the vehicle itself and of its subsystems. This type of data could be used for remote monitoring of the condition and health of the vehicle, even alerts on service or maintenance needs.
2. A vehicle can act as a sensor platform to record and transmit for instance observations on weather and road as well as traffic conditions such as surface friction, road surface and air temperatures, visibility, accidents, broken pavement and so forth.
3. A vehicle (especially an AV) and its driver can benefit and improve the situational awareness with information from external sources. Traffic situational notifications and warnings, weather and road conditions & warnings, fueling or charging points and availabilities are examples of useful information.

The communications needs are not only between external, fixed infrastructure, but also ***between*** vehicles. Vehicles can transmit for instance road condition or traffic information as well as alerts or warnings directly to other vehicles. This may in many situations be faster and in cases of poor coverage of cellular networks, possibly the only way to expand the sensor coverage from the immediate surroundings of a (possibly autonomous) vehicle. Such V2V communications can also be used to make even less autonomous vehicles or their drivers better aware of the situation around the vehicle and along the route[6].

Research on vehicular networking picked up speed in the early 2000s. The starting point was Wi-Fi (the IEEE 802.11 standard), as an existing and widely used wireless communication system. "Basic" Wi-Fi was soon found to be rather inadequate for vehicular uses. An IEEE 802.11 amendment (IEEE 802.11p) was defined and published in July 2010 to address these concerns. The IEEE 802.11p protocol combined with the IEEE 1609.x protocol adds wireless access to vehicular environments[7]. Both vehicular networking and vehicular autonomy are undergoing rapid evolution and the two are connected. There are several architectures and solutions in development for vehicular networking overall and for the different, specific networking needs. Examples of currently ongoing development and standardisation activities are the new intelligent traffic-oriented amendment IEEE 802.11bd (an improvement over the IEEE 802.11p[8]) and the 3GPP NR V2X [38]. It is not yet clear, whether some networking approaches or technological solutions will become prevalent and in which application areas.

In case of remotely driven vehicles the increase of bidirectional networking needs are fairly obvious: information of the environment and status of the vehicle need to be transmitted to the driver/operator and the driving commands need to be transmitted to the vehicle.

The effect of increased vehicular autonomy on vehicular communications needs may be

[6] A special case of V2V communications is the so-called platooning.
[7] Also known with the acronym Wireless Access in Vehicular Environments (WAVE)
[8] Compared with the IEEE 802.11p, the IEEE 802.11bd reduces the end-to-end latency, increases the throughput and the range (up to twice that of the IEEE 802.11p) and doubles the relative speed between the vehicles (up to 500 $\frac{km}{h}$). Although the IEEE 802.11bd targets the 5.9 GHz frequency, option for the 57 – 71 GHz range (*i.e.*, the millimeter-wave band) is included [38].

unclear – the needs of human-driven and autonomous vehicles may differ and hence place emphasis on different networking architectures and solutions. At higher levels of autonomy, a vehicle needs to be able to collect and process more data in a self-sufficient manner, but the needs for high-accuracy data on roads, road infrastructure such as road signs, road conditions and weather remain or increase compared with the needs of a vehicle with a driver in control (either on-board or remote). For instance wider-area weather forecasts for the planned route can not be generated on-board a vehicle and based on the vehicle's own observations, such forecasts require larger infrastructure. Hence only the products need to be transmitted to the drivers or to the AVs. Some of those data sets need to be updated in almost real time, others less frequently, which lead to different networking and connectivity needs.

From energy efficiency and emissions perspective the advantages and disadvantages of increased vehicular networking are similar as outlined in Section 3.1 on page 14. The net impact may also be very dependent on a specific situation or context.

Below some of the vehicular networking concepts, architectures and tehnologies are described in a compact fashion.

3.7.2 Vehicle-to-Infrastructure (V2I)

The term Vehicle-to-Infrastructure taken literally implies ***unidirectional*** communication from a vehicle to the infrastructure. The communication is, however, ***bidirectional*** and the term hence means communication ***between*** vehicles and infrastructure[9].

V2I communication means a Vehicular ***ad-hoc*** network (VANET) created between moving vehicles and a static infrastructure beside the road – for instance with base stations of a cellular network (see Section 3.4 on page 17) or with other roadside infrastructure elements. The communication architecture is centralized and the roadside infrastructure serves multiple vehicles. In the direction from a vehicle to the infrastructure the communication is of the unicast type, while in the opposite direction the communication type is both broadcast (while delivering general data) and unicast (while responding to the vehicle's requests).

The infrastructure comprises of Roadside Units (RSUs), which are typically equipped with a fixed power supply (connected to the electrical grid) and a sufficiently high-bandwidth connection to the larger communications network. These two resources (power and bandwidth) often do not constitute capacity bottlenecks or constraints, but especially when large sections or the entire system are considered, the energy required, how the energy is produced and the GHG emissions generated by the RSUs may need to be looked into more carefully. In cases of RSUs located in remote or isolated locations (such as may be the case in Arctic areas), both the power supply and sufficiently high-bandwidth links may become constraints.

RSUs can be equipped with multiple and/or directive antennas, providing the downlink channel (from an RSU to vehicles) typically with much higher bandwidth than the uplink channel. In some V2I applications, the uplink channel is meaningless or non-existent, making the service more of a broadcast type. V2I is not, however, a broadcast-only system, since an uplink (existence or at least preparedness for deployment thereof) is an essential element of V2I.

[9] A potentially more descriptive term might be Vehicle-Infrastructure-Vehicle (VIV) communication.

V2I communication is typically used to deliver information from road operators, authorities or traffic-related service providers to vehicles. Roadwork warning is a typical example of a V2I service; a way of implementing such warnings is by deploying vehicular access network transceivers before the roadwork area, informing the vehicles approaching the area about an exceptional situation on the road ahead.

3.7.3 Vehicle-to-Vehicle (V2V)

The V2V communication approach is primarily intended and suited for short-range vehicular communications[10], but longer ranges are possible with multi-hop strategies (see page 21). The general idea is that moving vehicles create a wireless communication network between each other when possible and directly between each other and not using for instance fixed base stations as intermediaries. The communication architecture is hence distributed and of a peer-to-peer type, as individual vehicles are communicating equally. The data exchange between passing vehicles may be uni- or bidirectional depending on the application; the exhange is typically of the unicast type, but also multicast (for example in the case of a platoon of vehicles exchanging traffic information) and broadcast (in the case of accident warnings) transmissions. A pure V2V network does not need any roadside infrastructure, making it fast and relatively reliable for sudden incidents requiring information distribution on the road. However, the reliability and coverage within the vehicle population on the road at any given area and time depends on the networking capabilities of the vehicles in that area and at that time; for instance accident warnings can be received only by vehicles, which are equipped to receive such warnings.

One of the key motivations for V2V communications is the opportunity to enable cooperative vehicle safety applications that can reduce the likelihood of accidents. Such safety applications envisioned for initial deployment include

1. identifying other vehicles in the immediate vicinity,
2. maintaining a dynamic state map of other vehicles (location, speed, heading and acceleration),
3. performing a continuous threat assessment based on this state map,
4. identifying potentially dangerous situations that require driver actions,
5. notifying and warning the driver at the appropriate time and in an approriate manner.

In the future, automated intervention by the vehicles themselves (instead or in support of the driver) is envisioned, but it still needs much work on the validation of the required reliability in communications.

A special case of V2V communications is multi-hop dissemination (including broadcasting) with specific multi-hop protocols. Especially in the case of a traffic accident the vehicle participating in or observing an accident will broadcast a warning message, which is forwarded/rebroadcast by other suitably V2V-equipped vehicles receiving the message during a certain period of time, allowing other drivers or AVs up to kilometers away to make smart driving decisions further away from the actual the scene of the accident.

[10] For instance the range of WAVE is up to 1000 m in a variety of environments (for example urban, sub-urban, rural), with relative velocities of up to 110 $\frac{km}{h}$. For instance the IEEE 802.11bd will improve on both – see Footnote 8 on page 19.

In dense traffic conditions, there is a risk of a broadcast storm problem. Several solutions to the problem exist, most of them derived from the idea of forwarding messages with certain random, weighted or adjusted probability.

The V2V environment is challenging. In V2V the connectivity between the vehicles depends on the traffic situation (the distribution and topology of other vehicles in the vicinity – their distances, relative speeds and networking capabilities). Consequently connectivity may be intermittent. Since in pure V2V there is no roadside infrastructure (but, see also Section 3.7.4), multi-hop forwarding must be enabled to propagate the messages or signals. Due the limitations in connectivity, V2V communications mainly focus on special cases instead of trying to be a general-purpose network solution.

3.7.4 Hybrid/combined solutions and C-V2X

Hybrid solutions combine V2V V2I approaches networking can be seen as plain V2V supplemented with V2I capabilities. V2V is the starting point (with applications defined in Section 3.7.3 on the preceding page), and integrating V2I with the V2V would enable an expanded range of vehicle crash-avoidance safety applications using the same wireless technology. One of the additional features enabled by V2I is intersection collision avoidance, whereby knowing both the dynamic state map of all the vehicles, as well as the intersection geometry, the system could warn a driver (or an AV) about other potentially hazardous intersecting vehicles. From this perspective, hybrid V2V/V2I is often referred to as Vehicle-to-Vehicle/Infrastructure (V2X) communications.

In this section the combined or hybrid V2V/V2I is considered as its own special case of communications. A similar kind of approach has been presented in. As mentioned in Section 3.7.2 on page 20, the RSUs, (the fixed infrastructure of V2I) usually have fixed power and can employ directive antennas especially tailored for RSUs, often making the downlink signal from a RSU to the vehicle dominant compared to the uplink provided by the vehicle. Furthermore, a RSU tends to communicate with many vehicles, while a vehicle tries to optimise its use of communication resources by minimising intervention with other vehicles. Finally, as a RSU usually has a fixed network connection, it can be seen also as an access point of the wireless network in a special kind of vehicular wireless network.

As stated above, the combined V2V/V2I communications access network consists of vehicles and RSUs, with relatively different objectives. Vehicles are communicating with each other in a V2V manner whenever in the vicinity of each other, basically exchanging their traffic observations or forwarding/broadcasting either multi-hop messages or wide-area data received earlier from an RSU. However, when entering the coverage area of an RSU, vehicles not only exchange data with the RSU, but may also exchange data with services located in the fixed internet, through an access link provided by the RSU. As the interaction time with an RSU is very limited, such service hot-spot communication procedures must be pre-configured into the vehicle user profile, to be initiated automatically when the vehicle is close enough to an RSU. The vehicle should therefore initiate different operational procedures for interactions with other vehicles and with RSUs. The RSU procedures are basically similar, regardless of whether the network architecture is V2I or combined V2V/V2I.

The concepts of V2V and V2I networking or VANET are based on local area networking, exploiting typically an IEEE 802.11p based access network. Theoretically, an element of such a network can achieve up to a 1 km communication range. Due to such a short range it is not realistic that such a Local Area Network (LAN) system can be cost-effectively deployed to achieve complete coverage throughout the road network.

Cellular networks (*see* Section 3.4 on page 17) provide good geographical coverage and high data capacity. However, Wireless Local Area Network (WLAN) -based solutions are faster and offer lower latencies. A solution to the coverage/response time problem is to bind a VANET and cellular networking into a hybrid vehicular networking system. From the continuous connectivity perspective, the handing over of the connection from one protocol to another plays a crucial role [7]. A straightforward approach in a hybrid vehicular networking architecture is to always prioritise VANET networking whenever available, and when arriving into the range of another vehicular networking unit, with the price of breaking up the ongoing cellular network data transfer.

Cellular-based Vehicle-to-everything (C-V2X) communication is used for information transfer amid different traffic entities with ***network assistance*** to decrease traffic fatalities as well as improving traffic efficiency. C-V2X technology increases road safety by helping drivers avoid road accidents and dangerous scenarios by permitting vehicles to exchange information between each other, pedestrians and road-side infrastructure. In vehicles, V2X sends data to drivers in the form of warning messages.

C-V2X is being developed and it has started taking the limelight from already matured and well-established technologies but with less conjunction towards 5G. The C-V2X is an evolving and scalable technology well-suited for connected and autonomous vehicles. C-V2X permits the users to communicate by using the available cellular infrastructure (including the 5G network). C-V2X must meet stringent Quality-of-Service requirements for communication [***i.e.***, ultra-low latency and ultra-high reliability (99.999 %)].

Two mature sets of standards for V2X communication exist, namely the Cooperative Intelligent Transport Systems (C-ITS) standards from the European Telecommunications Standards Institute (ETSI) and the European Committee for Standardization (CEN) in Europe as well as the Dedicated Short-Range Communications (DSRC) in the United States. Nowadays DSRC co-exists with wideband WLAN systems, rendering DSRC unreliable and therefore practically useless for emergency services. These functionalities can potentially be realized with IEEE 802.11p/ITS-G5 based systems; such realization requires, however, a substantial extensions to the existing set of standards. IEEE 802.11bd is tackling with these issues by introducing more capacity with less latency (*see* also page 19). The 5G cellular system offer great enhancements in functionality and performance, including a new radio technology. So-called C-V2X is an approach combining cellular networking (in 5G/LTE network) with V2X-kind local vehicle-to-vehicle type communication.

C-V2X has been piloted and initial deployments have taken place in China. Field tests in the USA have demonstrated good reliability, performance and range as well as an ability to withstand large communications loads. "Plug-tests" are also planned by ETSI and 5G Automotive Association (5GAA) in Europe to determine interoperability for multiple vendors, while several corridor programs (5G Concordia and Carmen projects) are being scheduled to investigate the technological aspects on the road [6].

The C-V2X technology will be prominent in AVs to assist in the vehicle's situational awareness (traffic, weather, etc.) as well as in evaluating risks and making decisions based on this information.

Chapter 4

Measurement and sensor systems

4.1 Overview

This section handles with and describes the different measurement and sensor systems used to monitor the road and its relevant environment – such as the weather, road surface conditions (such as damage or whether the road surface is wet or covered with snow or ice), traffic sign status, etc.

Individual measurement and sensor systems can be stationary (fixed; Section 4.2) or mobile (Section 4.3 on the following page); measurement and sensor systems can operate on the ground, embedded or attached to it. Such systems can also be airborne (Section 4.3.3 on page 28).

These systems need energy to operate – both in terms of their core functionality, but often also to keep the equipment in the right temperature range for correct and accurate operation (heating, cooling or both). These systems also need maintenance, repair and replacement; those activities have also an energy consumption aspect to them.

4.2 Fixed/stationary measurement systems

Road Weather Stations (RWSs) are sets of measurement instruments installed typically to a pole at the side of the road. In Finland there are over 350 RWSs that are maintained by FinTraffic. FMI has a couple of stations for research purposes as well. Most of the stations have instruments for measuring surface temperature, air temperature, humidity, precipitation, wind speed and road condition. Surface temperature measurements are typically made with asphalt embedded Vaisala DRS511 [32], but at some stations surface temperature is measured with the optical Vaisala DST111 [34]. At some stations there can be several sensors installed at different lanes. Many stations include also Vaisala DSC111 [33], that measures optically road condition (for example dry, wet, icy...) and friction.

Typical power consumption for an RWS is of the order of 18 W, but when the weather is cold and sensor heating is required the power consumption can rise considerably. As an example, at −10 °C the power consumption can be over 100 W [19]. One easy way to increase the energy efficiency of an RWS would be to install solar panels to the station. It could also be possible to store energy to rechargeable batteries for later use. One way to cut power consumption could be to decrease the measurement frequency in uninteresting weather situations, like when surface temperature is not likely to drop below 0 °C. However, it should be studied whether keeping the sensors in constant temperature consumes more energy than letting the sensors cool and then heat them up again. In addition, it should be considered that although frequent measurements would not be required in the road maintenance perspective, RWS measurements are used also in other ways, for example for research purposes. The measurements should be made at least every hour to ensure enough data for these purposes.

In an energy efficient RWS the instruments should be also made durable and so that one does not need to replace entire instrument when the sensor breaks. The design of many Vaisala instruments has been improving with increasing degree of modularity. Energy efficiency of the RWS could be also increased by reducing the amount of necessary maintenance and sensor cleaning visits.

4.3 Mobile measurement systems

Mobile measurement systems can be dedicated systems, which provide their own mobility, but mobility can also be achieved by using systems already built-in to vehicles or attaching measurement and sensor systems to mobile platforms [such as different types of vehicles either moving on the ground or in the air (*see* Fig. 4.1 as well as Sections 4.3.1 on the next page, 4.3.2 on the following page and 4.3.3 on page 28)].

Figure 4.1: A Teconer RCM411 sensor system [27] attached to a car (image source https://www.teconer.fi/en/surface-condition-friction-measurements/#RCM411).

4.3.1 Vehicle types

Factors influencing features of mobile measurement systems – such as size and weight, sensor sophistication and number of sensor types available per vehicle as well as availability of sensor data – include size, type of use and ownership of vehicles.

Larger-size vehicles such as trucks, buses and agricultural or forestry vehicles can reasonably accommodate considerably larger and more complex sensor packages than cars [26]. Cars and vans are more limited in this respect, the sensor data from these groups of vehicles are more likely coming from built-in sensors such as cameras, anti-lock braking systems (ABSs) and anti-skid systems.

Type of use may influence availability and coverage of data: some types of vehicles [such as buses operating scheduled traffic services, trucks or vans on fixed routes (for example ore transports [26] or postal distribution vehicles) or private vehicles used for regular commuting between home and workplace] provide regular coverage of specific stretches of the road network, while other vehicle groups (such as taxis, vans used for "last-mile" package deliveries and private cars used for non-commute purposes) provide potentially better statistical coverage of the road network both temporally and spatially.

Some special types of vehicles can provide well-targeted information about road conditions and even specific types of road conditions. An example of such a class of vehicles is snow plows. Even tailored sensor packages are available for attachment to snow plows [35]. Other similar groups of vehicles might be agricultural and forestry vehicles.

Ownership influences features such as data availability as well as contractual aspects: a commercial vehicle ***fleet*** (trucks, buses, vans, taxis) more often has single owner or point-of-contact per a larger number of vehicles, while in case of private vehicles each individual vehicle typically has a separate owner. Vehicle fleets hence may offer a faster and lower administrative overhead to access a larger set of vehicles. Privacy issues related to for example location information may also be more pronounced when dealing with private vehicles.

4.3.2 Parameters observed

A large set of meteorological and road condition parameters can be observed utilising built-in or attached systems (Table 4.1 on the following page).

An example of a vehicle-mounted sensor system used in FMI is the Teconer RCM411 Road Condition Monitor (Fig. 4.1). The system measures the state of the surface[1], the surface water layer thickness and optionally the surface temperature. Coefficient of friction is derived from these measurements [27]. Similar and even more versatile systems are available from other vendors as well (for instance the Vaisala MD30 [35]).

[1] dry/moist/wet/slushy/snowy/icy

Table 4.1: Some parameters observable with systems built into or attached to vehicles.

Parameter	Comments
Air temperature	***in situ*** or remotely sensed
Air humidity	***in situ*** or remotely sensed
Air pressure	***in situ***
Dew point	***in situ*** or remotely sensed
Surface temperature	remotely sensed
State of the surface	dry/moist/wet/slushy/snowy/icy; remotely sensed, imaging
Surface friction	Derived/computed from other measurements; ABS or anti-skid systems
Visibility or optical thickness	imaging, LIDAR
Road surface damage	imaging, LIDAR
Obstacles on the road	imaging, LIDAR
Precipitation types	water, snow, slush
Precipitation rate	windshield imaging, wipers

4.3.3 Unmanned Aerial Vehicles

Multiple terms are used to refer to UAVs or systems related to them. Perhaps the most common in general use is ***drone***. UAV and drone are almost synonyms and refer typically to the airborne craft only. A UAV is defined as

> a powered, aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or nonlethal payload [31].

In this document the term Unmanned Aerial Vehicle (UAV) is primarily used for the actual aircraft. The terms Remotely Piloted Aircraft System (RPAS) and Unmanned Aerial System (UAS) refer more to the entire system (including ground systems and communications). In this document the term UAS is used in this context.

Fig. 4.2 on the next page shows an FMI UAV in flight.

Sensor platforms

UAVs can act as sensor platforms for meteorological and other environmental measurements. As such UASs are a potentially very valuable supplement (and in some wontexts, replacement) to existing infrastructure. Although the UAVs have a limited range, they are filling the gap between space and on-ground observations, are less costly to acquire and operate, more flexible and have potentially smaller environmental impact than manned flight observations.

UAVs can perform both ***in situ*** and remotely sensed observations. Remotely sensed data can be, for example, imaging at optical and other wavelengths (even hyperspectral imaging) or data obtained via LIDAR (Fig. 4.3). In situ measurements can have otherwise difficult to

Figure 4.2: An FMI DJI Matrice 600 Pro UAV [1] in flight on 30 Oct 2019 in Sodankylä. The payload is a Rikola hyperspectral camera. Photo: A. Rimali/FMI.

obtain sampling characteristics by having UAVs fly with suitable flight profiles and patterns. For example, the Atmospheric Boundary Layer (ABL) can be sampled by having an UAV ascend or descend near-vertically. Another example might be an UAVs to fly along a road to carry out atmospheric sensing at a relevant altitude, while simultaneously imaging or scanning the road for for example surface conditions (wetness, ice) or possible pavement repair needs.

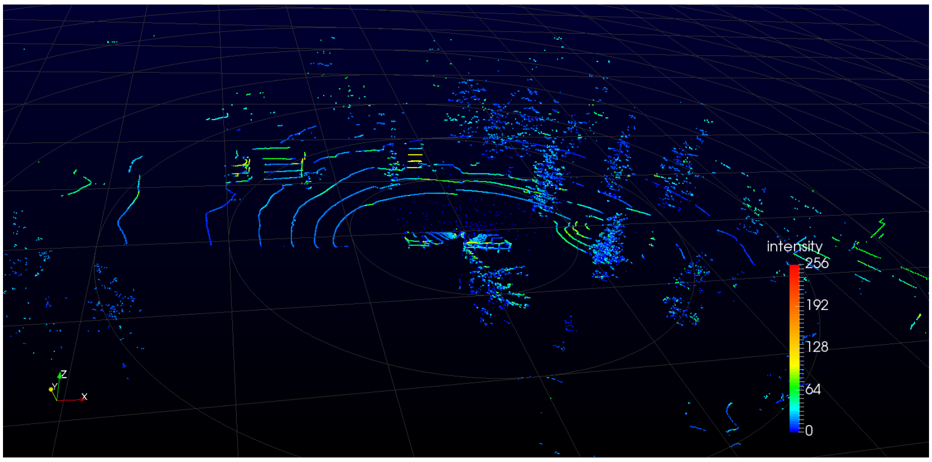

Figure 4.3: An example of visualised data collected by a UAV-mounted LIDAR. The sensitivity of this LIDAR is likely poor on purpose to detect better fixed objects and structures instead of precipitation (rain or snow).

UAVs, weather and energy

UAVs can improve weather forecasts, but UAVs also need perhaps more accurate and more specialised forecasts for safe and optimised operations. Availability and use of such forecasts can have an impact on route and energy use & optimisation of UAVs.

UAV-supported wireless communications platforms

A communications-related type of UAV use or application is use as platforms for network base stations. This application may be needed perhaps most typically in emergency situations – either unavailable fixed base stations can be temporarily replaced with this method or network coverage can be temporarily extended to areas not covered by fixed installations. Other uses include also situations, where extra capacity through additional base stations is needed for short term.

UAV piloting *vs.* autonomy

Currently UAVs are mostly piloted by humans via remote control. After lift-off UAVs can be set to autopilot type or preprogrammed flight modes during flight. In the future this will change further, as drones become more autonomous, not unlike AVs on the roads. Autonomous UAVs face partly similar, partly different requirements for capabilities in sensing their environments and for reaction time (and onboard processing) needs.

UAV autonomy has the potential of improving repeatability and reliability of observations – partly since maintaining a flight profile similar to earlier flights is more challenging when an UAV is piloted manually or semi-manually. Increased autonomy in landing and lift-off improves also UAVs ability to utilise charging or refueling equipment without human control or active supervision, thus permitting automation of longer sequences and series of UAV observation flights.

Energy supplies and systems

Figure 4.4 on the following page provides an overview and comparison of drone energy sources [3].

From energy efficiency perspective UAVs lose to electric and diesel surface vehicles in cities [11], but have the benefit of being able to use routes not possible for surface vehicles. UAVs can be powered with electricity, which can be produced from renewable sources, thus reducing GHG emissions. From the perspective of Life Cycle Analysis (LCA) UAVs can perform better in dense urban or rural areas [22]. The reduction of environmental impact in rural areas is by up to a factor of 16 compared with urban areas [17]. With the possible future improvements of battery technologies, the environmental impact of UAVs will be reduced even further. The longer flight times from battery improvements will increase the usability of UASs to more scenarios and areas.

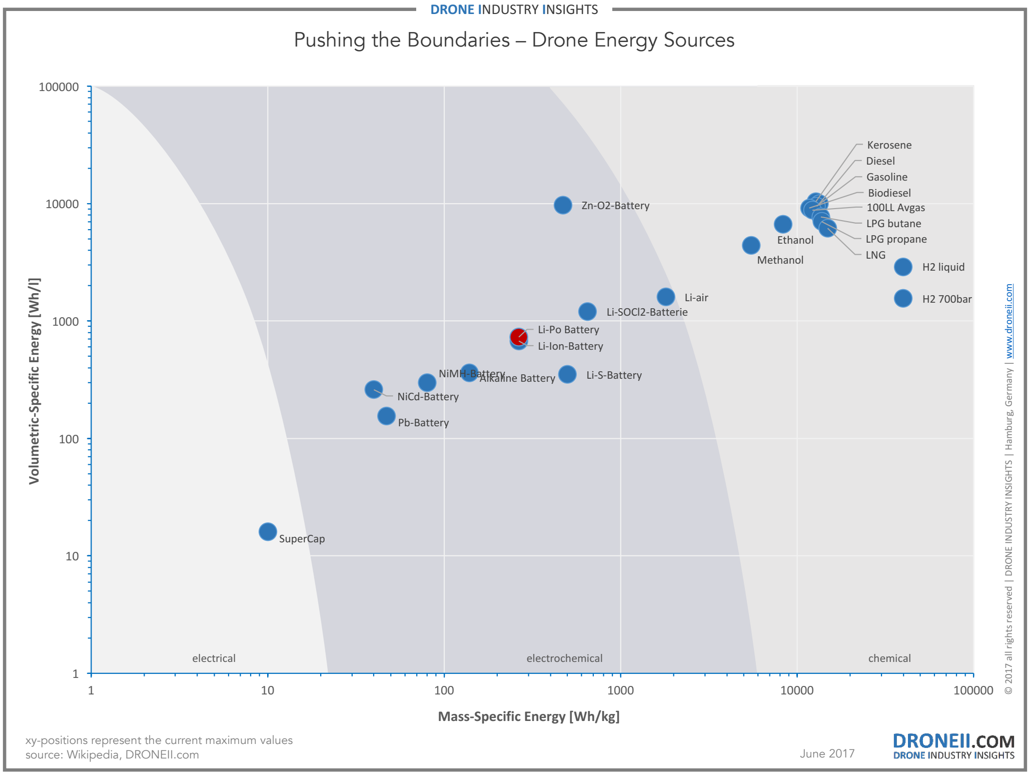

Figure 4.4: Comparison of drone energy sources [3].

Increased UAV autonomy increases the need for onboard processing and very likely will also increase the power consumption of onboard systems. Thus there is a trade-off between autonomy and range, the outcome of the trade-off depending on the relative energy requirements of onboard processing ***vs.*** communications for remote piloting.

FMI status and outlook

Currently UAVs are being increasingly used within FMI for a variety of purposes. In Lapland UAVs are used for intelligent traffic scenarios, documenting areas, vegetation indexes, vegetation fluorescence, wind speed, air sampling and snow research.

The number of areas of application where drones will be used will likely increase. This is because of ease, flexibility, lower cost and lower GHG emissions of use when compared to use of crewed aircraft for similar observations – such as provision of ground truth for satellite observations.

Chapter 5

Road and roadside infrastructure

Other traffic infrastructure components that have energy aspects (consumption, supply, storage, efficiency) are the elements of road and roadside infrastructure. These include here the road itself and adjacent light transport[1] paths, tunnels and bridges as well as components or groups such as traffic signs, road markings, under-the surface piping, etc. This set of elements has some overlap with the components of fixed communications or measurement systems (*see* 4.2 on page 25) such as base stations of cellular networks, V2I Roadside Units and RWSs. These types of systems are mentioned in this section only when there is clear overlap or synergy. Some overlap exists also with the built environments – addressed in Chapter 6.

5.1 Road markings and traffic signs

Currently road markings, traffic signs and traffic lights are for the most part visual[2] aids or sources of information for traffic participants[3]. Many of these markings and signs are unchanging and their energy aspects are limited to manufacture, repair and maintenance. Traffic lights, changing speed limit signs and information display boards are both dynamic & changing and require energy (electricity) to operate. Some of these infrastructure elements also provide attachment, communications and power supply opportunities for RWSs and other sensor systems.

In comparison with traditional markings & signs, the increased connectedness of vehicles as well as the introduction of autonomous vehicles (AVs) into traffic changes and expands the requirements of the characteristics and capabilities of the markings & signs. The AVs are required to be able to detect and interpret also traditional visual-only information designed for humans. However, the capabilities of humans in interpreting unclear, varying or partially obscured[4] traffic signs are superior to those of current computing systems, hence there is push towards modifying traffic signs and markings to be readable by AVs' image recognition systems

[1] for example pedestrian and bicycle traffic.
[2] In some cases also auditory – for example traffic lights indicating right-to-walk or not with audio signals.
[3] Human drivers, bicyclists, pedestrians.
[4] Examples of factors causing such obscuration are snow or dirt coverage on the signs and precipitation (rain, hail, snow) reducing visibility.

with better reliability and consistency. The needs of the AVs also push towards adding to the markings and signs self-cleaning (dirt, snow) and beacon-type capabilities; in the latter case for instance traffic signs broadcast their meaning and messages to the AVs using V2I type communication methods and protocols. Such capabilities and modes of operation require power and networking capabilities from these "intelligent" markings and signs.

Speed limit signs can already now be variable, the changes being in most cases controlled remotely. Instead of remote control, speed limit signs or groups of them may have autonomy based on independent sensory capability on for example visibility. The variability, sensory capability and connectivity all require some level of power supply.

5.2 Construction, maintenance and repair

The construction sector accounts for approximately one quarter of global carbon dioxide (CO_2) emissions. Close to net zero greenhouse gas (GHG) emission road construction by 2045 appears to be possible, but to achieve that goal multiple breakthroughs need to be achieved and several measures all need to be adopted in the road construction processes and in the supply chain. Karlsson *et al.* [10] have included in their estimates the following supply chain activities:

1. steel production and use
2. cement/concrete production and use
3. asphalt production and paving
4. heavy transport
5. construction process

Their study case is construction of a new road in middle Sweden; the proximity to Arctic region lends relevance to the results and their applicability to Arctic circumstances as well.

Maintenance and repair of roads and their associated infrastructure consumes energy and the need for heavy vehicles for transport and repairs results in CO_2 emissions from fossil fuels. Several (if not all) of the activities included by Karlsson *et al.* apply to road maintenance and repair as well. From FMI perspective interesting specific approaches may be use of UAVs as well as remotely operated or autonomous vehicles to support monitoring, maintenance and repair activities of infrastructures related to roads.

5.3 Use of roadsides and road infrastructure for energy production

From energy supply perspective the roadsides and road structures offer some potential for local and renewable energy production in form of for instance Solar Thermal Energy (STE), solar electricity [23] or piezoelectric energy harvesting from passing vehicles [*e.g.*, 37]. Although the Arctic seasonal patterns are challenging, the long distances and sparse populations also pose challenges for grid-dependent energy supply.

Chapter 6

Built environments

Community development is not directly interacting with intelligent traffic, but for example several different "smart cities" research initiatives are aiming to combine community development and intelligent traffic into a single entity. Therefore, it is essential to consider community development also in this report, as a source of potential energy efficient methodologies to be imported into the traffic environment. Energy efficiency methods have been applied in community development for some time already, and it can be seen as a pioneer environment for energy efficient methods and low-carbon solutions.

The practical methods and experiences evaluated here are mainly gathered from the city of Ii. More information on the local solutions described below is available from the technology centre Micropolis Ltd. in Ii[1].

The city of Ii is committed in aiming at zero-waste, energy self-sufficient and non-carbon economy. Strategy is to develop the public sector and simultaneously create a platform for private sector including inhabitants to be able to follow the same road. The strategy is defined in the Energy Intelligent Ii Roadmap 2050 that was created together with participation of the politicians, citizens and civil servants of the city. Micropolis coordinates the main activities in this field. Ii is located approximately 150 km South of the Arctic circle, experiencing long winter periods and relatively harsh conditions. Therefore, the practical experiences gained in Ii can be applied to Arctic conditions as well.

6.1 Energy consumption

Heating of public buildings has been converted to use renewables during the last years. Fossil fuels have been replaced by wood chips and ground or air-source -heat pumps. Solar collectors and panels were installed on the roof of the Micropolis building in 2015. Rest of the public buildings are connected to the district heating network where primary energy is bioenergy.

Currently all electricity in Ii is generated with renewable sources: wind power, small- and large-scale hydro- as well as solar power. In 2017 eleven more solar power plants were installed on the roofs of public buildings with combined average power of 190 kW. As renewable energy

[1] https://www.micropolis.fi/en/

production tends to cause problems in energy control, Ii is studying renewable energy storage starting from solar energy. The expected schedule for pilot case is estimated around 2022.

6.2 Smart energy systems

Since 2012 all new public buildings have been equipped with LED technology and smart control systems. In 2016 the Micropolis building got an intelligent lightning system – LED lights with motion detectors and Bluetooth connection between each led light. Lights go on as you walk along and turn off behind you. Technology is developed by the VTT Technical Research Centre of Finland. First pilots were built in VTT Oulu and in Micropolis.

New central kitchen built in 2016 is exceptionally energy efficient. The kitchen is equipped with a GSHP instead of district heating. Heat from cold compressors of the refrigeration equipment is also used for heating. The heat pump is used also for cooling.

Open source measuring systems of electricity, heat and water consumption will be developed and installed in the first twenty public buildings in 2016 aiming to extend to all the buildings. In consequence there is no need to visit every building for energy consumption readouts anymore. As data is received in real time and deviations in consumption causes alarms, problems such as water leaks are revealed without delays. Just one failure exposing will probably pay back the entire investment. Next step is to combine the energy consumption data to billing systems.

6.3 Smart community technology

Ii has done a long-term development in the field of renewable energy production. As energy self-sufficiency is now achieved, Ii has created a platform for the development and piloting of new generation cleantech technologies. These technologies include strongly the development of smart energy systems.

Work has been started as the smart LED lighting was installed in technology centre Micropolis. In 2016 Ii invested in smart street lightning. Smart energy systems will be developed in co-operation with entrepreneurs. Ambition is to conceptualize a control system for smart hybrid energy production. System should manage and optimize the economic efficiency by means of energy production and consumption. Concept will include renewable energy storage. Smart energy systems as well as the use of solar energy as primary energy source in wintertime is new not only in the national but also in Nordic context and more broadly.

There are several smart solutions existing for property maintenance. Problem is, they mainly cover one entity such as heating, ventilation, lighting or electricity consumption. This causes troubles when separate control systems operate against each other. There are examples where smart energy systems actually raise maintenance costs. A smart control system for energy efficiency and management is required. Control system minimizes the energy consumption and optimizes the energy production by the means of economic efficiency. Control system prioritizes also the own energy production of the building with respect to bought energy.

Chapter 7

Energy supply – a future scenario

7.1 Supplies

Primary energy supply is at a fairly rapid pace moving towards large reductions in GHG emissions. In many countries (including Finland) burning of coal and peat for even in cogeneration is being phased out and replaced with a variety of primary energy sources such as natural gas[1], biomass, wind and solar.

Finland has currently four nuclear reactors in operation in two power stations providing approximately 30 % of electricity supply [16]. The electricity outputs of all these four reactors have been increased significantly during their lifetimes and further so-called ***uprates*** are planned. After several delays a ***new*** reactor[2] is currently expected to start production in early 2022 and another new reactor is under preparation[3]. There is also interest in Small Modular Reactors (SMRs) for district heating or for cogeneration, but there are no concrete plans yet.

For use in district and individual building heating use of waste heat sources and heat pumps are projected to increase significantly. An emerging trend is the conversion from district heating to ground source heat pumps – of even large apartment buildings. For the heating needs of traffic infrastructure buildings and equipment enclosures the use of heat pumps may be an increasingly feasible and cost-effective option.

Wind power generation is increasing in Finland and is getting cheaper. According to the planned projects list of the Finnish Wind Power Association (FWPA) currently 212 wind power projects with a total capacity of 18 000 MW are in planning [36]. Of these 7 % (1300 MW) are under construction and nearly 40 % (6600 MW) have construction permits or land use plans. Although not all the projects are likely to be completed, the increasing trend is clear. Some noteworthy

[1] Primarily methane (CH_4) and also a fossil fuel, but due to its higher hydrogen content causing less GHG emissions than coal, oil and peat. Since CH_4 itself is a strong, but short-lived GHG, leakage in extraction, transport and use is a source of emissions as is ***flaring*** during production [15].

[2] The Olkiluoto 3 with nominal electricity output of 1600 MW.

[3] Hanhikivi 1, nominal electricity output of 1200 MW; however, this project has not received its construction licence yet.

trends in this industry are:

- increasing turbine tower heights (which increases production in for instance forested regions),
- Power Purchase Agreements (PPAs) [18] – long-term electricity purchase agreements where typically, a large electricity user or a number of smaller electricity users purchase a certain amount of electricity from the electricity producer under the contract for example, for 10-20 years, and
- as a baseline the new wind power projects are market-based – they no longer need state subsidies.

In situations (such as remote locations), where traditional power supplies are not feasible or they are prohibitively expensive, energy harvesting [2, 12] may become a useful local production option. Solar and wind energies are forms of energy harvesting, but there are several other possibilities. An example of energy harvesting in vehicles is solar cells on surfaces of cars and thin-film solar cells on or embedded into car windows [30].

7.2 Distribution and storage

In addition to the needs to reduce GHG emissions in primary energy production and trends to achieve that, the distribution, storage and consumption components of the energy system are expected to undergo changes on multiple scales. Electrification of the system is already underway both in traffic and in other sectors and affects the electric grid as well as development and use of technologies for electricity storage such as batteries. Electrification appears to be a feasible path for some sectors of traffic, such as automobiles and some parts of logistics chains.

Electrification offers interesting storage approaches, such as two-way use of electric vehicle batteries: if the use and ownership patterns of electric vehicles (EVs) remain similar as today, many EVs tend to be used only a relatively small fraction of the time. The battery of a stationary EV could be used as storage capacity for the electric grid or to balance local electricity production such as home photovoltaic panels. However, possible expansion of AVs probably implies increase of vehicles' time in traffic and hence reduces their time as stationary

Due to for instance energy density limitations, electrification is technologically more challenging for some modes of traffic such as heavy road, marine and air transport. Also in construction, forestry and agricultural machinery problems similar to heavy road transport arise. A trend supplemental and in some areas possibly alternative to electrification of traffic is the emergence of Power-to-X; in other words, energy distribution, storage and use (see also Section 7.3) utilising chemicals such as Hydrogen, hydrocarbons (e.g., CH_4) or ammonia (NH_3) synthesised from CO_2, water and Nitrogen with low- or non-GHG-emissions primary energy sources. P2X also offers a possibility of balancing the unpredictability of some renewable primary energy sources such as wind and solar. Another advantage of the P2X is the possibility to use existing infrastructures for distribution, storage and use[4]; in some forms of P2X the fuel is the same from the system's and end-users perspectives, although the process by which the fuel has been produced has changed significantly. Such synthetic fuels can be mixed with fossil

[4] Especially, when the "X" is a gaseous or liquid hydrocarbon.

and biofuels resulting in a more gradual transition as well as multiple pathways of utilising for instance solar energy. A disadvantage is the loss of primary energy due to inefficiencies of the synthesis processes, which may differ depending on the end products as well as the processes and pathways chosen.

Use of Hydrogen in P2X differs from use of for instance hydrocarbons, since production, distribution and storage of Hydrogen are different and in many ways more challenging due to cryogenic temperatures required for liquid Hydrogen[5], easy leakage due to small size of the H_2 molecule and the flammability of Hydrogen when mixed with air. Hydrogen could also be transported in form of NH_3[6] and NH_3 can also be used as-is as fuel, for instance in ships and in aircraft [20]. Hydrogen would be ultimately produced with electrolysers. As mentioned also in Section 2.3 on page 12, pipelines (for instance using Hydrogen) are more cost-efficient and offer larger transfer capacity than electricity cables in transferring of energy over long distances – such as from areas of large amount of available solar energy to areas of consumption. In traffic it would also be much more efficient to convert Hydrogen to electricity and vehicle motive energy with fuel cells and not with internal combustion engines. A possible future scenario for traffic is that electrification turns out to be a transition phase to Hydrogen. Hydrogen also has multiple uses in chemical processes and not just as fuel, meaning that the overall industrial demand would be larger.

When the traffic infrastructure (including communications) is viewed holistically and not the different systems as separate, for instance co-locating systems more into clusters would allow to better utilise and share local and renewable energy production, electricity and heat storage[7]. If long-term (even seasonal) heat storage through for instance Borehole Thermal Energy Storage (BTES) [13] or new storage materials [8] becomes feasible and cost-effective, use with co-located systems would be more sensible, since heat losses are reduced with increased storage size. Co-location would also offer energy efficiency and savings potential in maintenance[8] and repair – both through coordination of visits to the equipment locations to reduce fuel/energy consumption and to design maintenance and repair to be carried out remotely.

7.3 Consumption

Climate change and more frequent elevated temperatures may in time increase the need for cooling in the summertime conditions even in the Arctic regions. Storage of waste heat for use in the winter is conceptually most sensible, but may be technically difficult or does not make sense economically, even if higher wintertime temperatures may reduce the heating needs. One approach is to take also cooling needs into account in design and construction of infrastructure and use passive cooling when feasible. If active cooling is needed, energy needs may increase, although higher wintertime temperatures may compensate.

[5] The low average and winter temperatures in Arctic regions may be an advantage in liquid Hydrogen storage.
[6] With H extracted from NH_3 for use in fuel cells or other processes.
[7] For instance by scaling batteries and heat storage facilities to serve all co-located systems.
[8] Including supply of consumables and spare parts.

Chapter 8

Summary and conclusions

This State-of-the-Art (SotA) report provides and overview of a variety of areas and factors related to energy efficiency and greenhouse gas emissions of traffic and traffic infrastructure relevant in general and in particular for the Arctic environments and geographical areas. This collection of information, context and ideas is intended to act as a source and reference for FMI smart traffic and infrastructure R & D and assist in taking the efficiency and emissions aspects into account in an as comprehensive way as feasible, when new research and operational concepts & activities (including construction) are devised, planned and designed.

Some of these topics can be pilot-tested in and at areas around the FMI Sodankylä facilities (including the test track [21, 25]), capitalising on the existing infrastructure, personnel and other capabilities already existing and available there.

Glossary

3GPP 3rd Generation Partnership Project. 20

5GAA 5G Automotive Association. 24

ABL Atmospheric Boundary Layer. 29

ABS anti-lock braking system. 26, 28

ACARS Aircraft Communications Addressing and Reporting System. 15

ASHP air-source heat pump. 11

AV autonomous vehicle. 7, 12, 14, 19, 20, 22–24, 30, 32, 33, 39

broadcast storm Accumulation of broadcast and multicast traffic on a computer network rendering the the network unable to transport normal traffic. 22

BTES Borehole Thermal Energy Storage. 40

CEN European Committee for Standardization. 24

CH_4 methane. 38, 39

C-ITS Cooperative Intelligent Transport Systems. 24

CO_2 carbon dioxide. 33, 39

cogeneration Generation of electricity and useful heat (such as for district heating) at the same time for instance in a power station. https://en.wikipedia.org/wiki/Cogeneration. 38

Covid-19 Covid-19 is an infectious disease caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). https://en.wikipedia.org/wiki/Coronavirus_disease_2019. 8

C-V2X Cellular-based Vehicle-to-everything. 2, 22–24

drone See UAV.. 28

DSRC Dedicated Short-Range Communications. 24

EC European Commission. 5

edge computing A distributed computing paradigm that brings computation and data storage closer to the location where it is needed, to improve response times and save bandwidth (https://en.wikipedia.org/wiki/Edge_computing). 14

EMAL Energy-efficient Methods in Arctic Traffic (in Finnish *Energiatehokkaat menetelmät arktisessa liikenteessä*). 1, 2, 5–8, 10–13, 15–24, 26–31, 33, 34, 36, 37, 39–41, 44–46, 48–50

energy harvesting https://en.wikipedia.org/wiki/Energy_harvesting. 39

ERDF European Regional Development Fund. 1, 5

ETS Emissions Trading System. 5

ETSI European Telecommunications Standards Institute. 24, 45

EU European Union. 5

EV electric vehicle. 12, 39

FinTraffic Provides and develops traffic control and management services in all traffic forms as well as ensures safe and smooth traffic in a responsible manner in Finland. (https://www.fintraffic.fi/en). 25

FMI Finnish Meteorological Institute. 1, 3, 5–7, 25, 27–29, 31, 33, 42

FWPA Finnish Wind Power Association. 38

GHG greenhouse gas. 1, 5–8, 21, 30, 31, 33, 38, 39, 42

GSHP ground source heat pump. 11, 36, 39

IEA International Energy Agency. 3, 10, 11

IEEE 802.11 A Local Area Network protocol for implementing a Wireless Local Area Network. https://en.wikipedia.org/wiki/IEEE_802.11. 19

IEEE 802.11bd An approved amendment to the IEEE 802.11 standard to add Wireless Access in Vehicular Environments (WAVE), a vehicular communication system.. 20, 21, 24

IEEE 802.11p An approved amendment to the IEEE 802.11 standard to add Wireless Access in Vehicular Environments (WAVE), a vehicular communication system.. 19, 20, 23, 24, 45

Ii A municipality of Finland. https://www.ii.fi/en. 35, 36, 45

in situ A Latin phrase that translates literally to "on site" or "in position". It can mean "locally", "on site", "on the premises", or "in place" to describe where an event takes place and is used in many different contexts. https://en.wikipedia.org/wiki/In_situ. 28

IoT Internet of Things. 1, 16, 18

ITS-G5 An ETSI standard for vehicular communication based on the IEEE 802.11p. 24

LAN Local Area Network. 1, 17, 23, 44

LCA Life Cycle Analysis. 30, 45

LED Light-emitting diode. 36

LIDAR Laser Imaging, Detection, and Ranging. 3, 28–30

Life Cycle Analysis Life Cycle Analysis (LCA) is a method used to evaluate the environmental impact of a product through its life cycle encompassing extraction and processing of the raw materials, manufacturing, distribution, use, recycling, and final disposal. 6

LTE Long-Term Evolution. 24

Micropolis A development company boosting green growth in the north of Finland. Located in the municipality of Ii. `https://www.greenpolis.fi/en/`. 35, 36

NH_3 ammonia. 39, 40

NR New Radio. 20

OTEC Ocean Thermal Energy Conversion. 9

P2X Power-to-X. 13, 39, 40

peer-to-peer A distributed network or application architecture, where nodes are equals (peers) without centralised hub or control. `https://en.wikipedia.org/wiki/Peer-to-peer`. 21

PHEV plug-in hybrid electric vehicle. 12

platoon In ***platoon***ing a single vehicle with a driver shepherds other vehicles driving in very close proximity – grouped or clustered. The motivation is to increase vehicle density and hence the capacity of the roads, while keeping a human in control, yet reducing the total workload required from human drivers.. 19, 21

Power-to-X A number of electricity conversion, energy storage, and reconversion pathways that use surplus electric power, typically during periods where fluctuating renewable energy generation exceeds load. The X in the terminology can refer to one of the following: power-to-ammonia, power-to-chemicals, power-to-fuel, power-to-gas, power-to-heat, power-to-hydrogen, power-to-liquid, power-to-methane, power-to-mobility, power to food, power-to-power, and power-to-syngas. 13, 39, 45

PPA Power Purchase Agreement. 39

PSTN Public Switched Telephone Network. 15

R & D research and development. 6, 42

RPAS Remotely Piloted Aircraft System. 28

RSU Roadside Unit. 21–23, 32

RWS Road Weather Station. 7, 25, 26, 32

SDN Software-Defined Networking. 16

SMR Small Modular Reactor. 38

Sod5G FMI Winter testing track with 5G, vehicular networking and dense road weather measurements and services. https://sod5g.fmi.fi/. 7

SotA State-of-the-Art. 1, 2, 5–8, 10–13, 15–24, 26–31, 33, 34, 36, 37, 39–42, 44–46, 48–50

STE Solar Thermal Energy. 33

TES Total Energy Supply. 3, 10

UAS Unmanned Aerial System. 28, 30

UAV Unmanned Aerial Vehicle. 2, 3, 11, 28–31, 33, 43

V2I Vehicle-to-Infrastructure. 1, 18, 20–23, 32, 33

V2V Vehicle-to-Vehicle. 2, 18, 19, 21–23

V2X Vehicle-to-Vehicle/Infrastructure. 20, 22–24

VANET Vehicular ***ad-hoc*** network. 20, 23

WAVE Wireless Access in Vehicular Environments. 19, 21, 44

Wi-Fi Family of wireless network protocols, based on the IEEE 802.11 family of standards, which are commonly used for local area networking of devices and Internet access. See also WLAN. https://en.wikipedia.org/wiki/Wi-Fi. 17–19

WLAN Wireless Local Area Network. 17, 23, 24, 44, 46

WP Work Package. 1, 5

WTW well to wheels. 3, 6, 7

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