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SOCIO-ECONOMIC BENEFITS OF THE EPS STERNA CONSTELLATION AT HIGH LATITUDES

REPORT OF TASK 3 OF THE EPS STERNA CONSTELLATION IMPACT STUDY

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Name of project

Socio-Economic Assessment of AWS Constellation at high latitudes

Commissioned by EUMETSAT

Title

Socio-economic Benefits of the EPS Sterna constellation at high latitudes

Abstract

This report presents a combined meteorological and economic study commissioned by EUMETSAT as part of the planning trajectory for the EPS-Sterna polar-orbiting satellite constellation. The focus of the study is on the foreseeable effects of EPS Sterna on meteorological forecasts and the resulting socioeconomic benefits, particularly regarding application at high latitudes, with emphasis on the Nordic countries. The study has an explorative character, hence the quantified estimates of benefits only indicate orders of magnitude for selected sectors. A more comprehensive assessment of expected benefits would necessitate a larger study.

The report focuses on sectors for which significant benefits were expected, being civil aviation in Nordic countries (excluding Iceland) and wind turbine-based electricity production in the Nordpool area. For civil aviation, increased precision in forecasting winterly precipitation enhances preparedness on airports, thereby reducing weather-related delays. The potential annual benefit for the aviation sector in the Nordic countries is estimated at approximately €5 million, with an additional €1 million in avoided travel time loss. The upscaled effect for aviation in Europe is estimated at around €15 million per year. In wind power production, timely identification of probable formation of ice and snow on turbine blades benefits the Nordic power market through smoother operations and cost savings. The expected annual benefits for society are approximately €15 million, growing to €27 million when considering growth in electricity use. Applying a satellite constellation lifetime of 12 years (2029–2040), the estimated cumulative benefits range from €240 million (using base year levels without expansion) to €495 million (using maximum values per sector). No discounting of benefits nor costs has been applied.

Other sectors with potential benefits include construction, tourism, urban operational management, and more. A coarse assessment for the Finnish building sector suggests expected annual benefits of about €1 million. The study notes that EPS Sterna's forecast improvements may lead to the development of new smart services, influencing property management and generating economic effects. Realizing the benefit potential of EPS Sterna data requires dedicated weather service development and improved data integration with non-meteorological data. The report recommends establishing a repository of cost-benefit analysis (CBA) data and results to facilitate future evaluations of satellite constellations.

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List of Abbreviations

abbreviation	full name	description / comment
APRON	-	the area of an airport where aircraft are parked, unloaded or loaded, refueled, boarded, or maintained (Wikipedia)
ATFM	Air Traffic Flow Management	
AWS	Arctic Weather Satellite	
BCA	Benefit-Cost Analysis	same as CBA, BCA is preferred term in North-America
BCR	Benefit-Cost Ratio	
CBA	Cost-Benefit Analysis	
EO	Earth Observation	
EPS	EUMETSAT Polar System	
ESA	European Space Agency	
ICAO	International Commercial Aviation Organization	
LVP	Low Visibility Procedures	operational regime on an airport when limited visibility demands extra caution, e.g. keeping longer distances and time intervals
MWh	Megawatt hour	= 1000 kWh
NWP	Numerical Weather Prediction	
OSSE	Observing System Simulation Experiment(s)	Testing impacts on forecast quality by withholding and adding data sources
RMSE	Rooted Mean Square Error	
TWh	Terawatt hour	= 1000 000 MWh
VSL	Value of Statistical Life	Aggregate willingness to pay of a society to save one (hypothetical) life due to increased safety
WCS	Weather & Climate Services	
WSCA	Weather Service Chain Analysis	Value chain based approach aimed at understanding the decay of the (potential) information impact reminiscent of survival processes
WTP	Willingness-to-Pay	The amount of money (‘price’) survey participants state as being prepared to pay for a service or facility that improves conditions in some respect; the complementing concept is Willingness-to-Accept, which refers to the amount of money a citizen would receive in order to accept the current (non-optimal) situation.

Executive Summary

As part of the planning trajectory for the EPS-Sterna polar orbiting satellite constellation EUMETSAT commissioned a combined meteorological and economic study on the foreseeable effects of EPS Sterna for meteorological forecasts and the consequent socioeconomic benefits at high latitudes. This report discusses the socioeconomic benefits that could be engendered by EPS Sterna with a focus on applications at high latitudes, notably the Nordic countries.

Even though also numerical indications of benefits are provided the study should be regarded as explorative, hence results indicate orders of magnitude of benefits for selected sectors. A comprehensive and more pertinent assessment of the expected value of benefits would require a larger study.

Generally, weather services practically always generate far more benefits than what the generation of these services costs. However, if the valuation concerns non-trivial investments for an *incremental* component of observation in an already well-developed system, it is not a priori certain that benefits clearly exceed the costs. EPS Sterna can be regarded as such a case.

Based on internal project team discussions and consultations with operational meteorologists it was decided to focus on sectors, of which significant benefits could be expected, while allowing a data availability that enables assessment of responsiveness to better weather information and the cost consequences thereof. Eventually this meant that quantitative assessments have been carried out for civil aviation in Nordic countries (except Iceland) and for wind turbine-based electricity production in the Nordpool area.

For civil aviation increased precision on the onset and ending of winterly precipitation (snow, sleet, icy rain, frost) reduces mismatches in sufficient preparedness for such conditions and thereby can reduce weather related delay volumes considerably. For the Nordic countries as a whole, based on the delay data of the major airports it was estimated that the annual (potential) benefit for the aviation sector has an expected value of approx. 5 million € per year. On top of that comes approx. 1 million €. avoided travel time loss for travellers. Furthermore, this figure can be expanded for several reasons, such as underestimation of the improvement in forecast accuracy (no feedback with global model included), inclusion of smaller airports in Northern Europe and airports in the rest of Europe. Also ‘en route’ benefits may still be achievable as well. Therefore, the upscaled effect for aviation in Europe is estimated at approximately 15 million € per year.

For wind power production the timely risk identification of ice and snow getting attached to the turbine blades makes the Nordic power market (Nordpool) running smoother, incurring less cost to wind power producers and to some extent to final customers as well. For society as a whole the expected value of annual benefits is about 15 million €, under current circumstances. Electricity use is however growing, which means that benefits are growing over time adding another 6 million € by 2040. Upscaling of these benefits may be driven by one the abovementioned underestimation, and by the option that also solar power could benefit from the improved forecasts. The upscaled expected benefits amount to 27 million € per year.

Applying a lifetime of 12 years (2029 – 2040), the estimated cumulative benefits would amount to 240 million €, if only the base year levels without expansion are used. This can be regarded as the lower level estimate for the two assessed sectors. For the same lifetime period the estimated cumulative benefits would rise to 495 million €, if the maximum values per sector are used. This gives an indication of the upper level estimate for the two assessed sectors. The overall lifetime of the satellite constellation is more than 12 years, but at least for this period the full capacity should be available. No discounting has been applied to the above reported cumulative values of annual benefits. Since also a significant part of the costs spreads out over the lifetime of the satellite constellation the introduction of discounting would probably not significantly weaken the benefit-cost ratio (BCR).

Other sectors that may benefit significantly are the buildings sector, tourism, urban operational management (traffic, public transport, street maintenance, first aid). More pertinent estimates for these sectors would require further study. A coarse assessment for the Finnish building sector suggests expected annual benefits of about 1 million €.

The forecast improvements enabled by EPS Sterna can affect other sectors than the ones mentioned above. Furthermore, the better forecasts may enable development of new smart services and improvement of existing smart services, which may for example affect property management at large, and thereby propagate induced economic effects throughout the economy.

The realization pf a part of the benefit potential contained in the EPS Sterna data would require dedicated weather service development for specific applications, e.g. through user friendly visualization. It may also require better or expanded data integration with non-meteorological data. In this respect one could think of smart road and smart city related applications, among others. On the other hand, in the long run the extra observation potential from EPS Sterna may be partly captured by other evolving remote sensing options, and large distributed sensory networks. It is therefore recommendable to establish a CBA data and results repository, in order to facilitate current and future valuations of existing and planned satellite constellations.

1. Introduction

EUMETSAT is considering a constellation of small polar orbiting satellites providing passive microwave soundings of the atmosphere with frequent revisit times, called EPS-Sterna. The deployment of the initial set of satellites should happen in 2029, with replenishment launches every 3 years or so. The foreseen lifetime of the system runs until 2042. (Canestri 2023)

As part of the planning trajectory for EPS-Sterna EUMETSAT commissioned a combined meteorological and economic study regarding the foreseeable effects of the Sterna constellation for meteorological forecasts and the consequent socioeconomic benefits at high latitudes. This report discusses the socioeconomic benefits that could be engendered by EPS Sterna with a focus on applications at high latitudes. Effects on day-ahead forecasts and nowcasts were assessed in separate Tasks 1 and 2, carried out by MetNorway and SMHI respectively. The results of Task 1 are reported in Guedj et al 2023 and of Task 2 in Rydberg et al 2023.

For a multitude of reasons the socioeconomic benefit study is highly explorative. Furthermore, the available economic assessment alternatives, the jargon and the currently available knowledge on the economics of earth observation are not (yet) customary elements of EUMETSAT study reports. Therefore, it was agreed that the report would also contain an overview of valuation methods and of hitherto cumulated knowledge and experience on application of such valuations to weather and climate services and satellites, next to a valuation of the socioeconomic benefit potential of EPS Sterna.

In chapter 2 we present first a quick overview of earlier studies relevant to the topic of this report. In chapter 3 we explain the main assessment approaches, while including some examples of applications and their limitations. In chapter 4 we discuss the assessment of benefit potential of EPS Sterna with respect to three application areas, related to civil aviation, electricity supply, and road maintenance respectively. These sectors were selected on the basis of pre-screening information impact propagation in various sectors based on literature review and interviews. Chapter 5 summarizes and discusses the results.

2. Previous studies

This short review focuses on valuation studies of short-term forecasting. In recent years, besides short-term forecasting, especially the valuation of seasonal forecasts and climate information at various time scales has been studied. By valuation is meant to establish an estimation of the economic value engendered by the use of the provided (extra or improved) information, i.e. the benefits accruing to the users or the clients of the users, and to society at large. Since the assessment context and often also the methods are different for seasonal forecasts and climate information services, these studies are left out here.

As far as we can tell the majority of the valuation of short-term weather services in Nordic countries was carried out in Finland. There are also some European studies available that refer – among others – to conditions in Northern Europe. A rising trend is the integration of the operational – wholly or partly automated – management of large equipment (e.g. power generation, building management) with ambient environment observations and forecasts, e.g. as part of smart building and smart grid developments. Such integration presupposes knowledge of specific weather sensitivity of the considered systems, as well as of sufficient evidence that it pays off to add this feature to the operational management system.

Leviäkangas and Hautala (2009) assessed the weather service portfolio of the Finnish Meteorological Institute for various sectors, considering in particular those more sensitive to weather conditions. Their approach was based on a kind of value chain representation of weather service generation and delivery. For various types of weather information services was analysed how the information generation process and eventual reception and use by the end-user (in selected sectors) was organized. The stagewise information processing pathway is often referred to as value chain (Anderson et al 2015; Lazo and Mills 2021). Subsequently, based on the representation of the information process the effectiveness of the service was evaluated in terms of responsiveness and avoided cost. Effectiveness and response indications were largely based on interviews, supplemented by literature. At the same time this approach allowed to identify associated cost, with special reference to attribution of the various joint cost that typically occur in weather service generation, as many data, models and visualization tools are used for many information products. The results indicated a benefit cost ratio ranging between 5:1 to 10:1.

As part of the EU research project EWENT the Weather Service Chain Analysis (WSCA) was applied (Nurmi et al 2012; Nurmi et al 2013) to road (accident proneness) and train traffic (delay risks). WSCA was originally developed in a development cooperation project for Nepal (Mäkelä et al 2012), but the formal specification got better established in the EWENT project. WSCA describes and formalizes the effectiveness of the information propagation process throughout the value chain. It aims to both clarify underlying causes of decay in information effectiveness and estimate the eventual remaining information effect on behaviour. When applied to existing services WSCA can produce results with fairly high confidence. WSCA has been also applied to service innovations (Pilli-Sihvola et al 2016) as part of the EU research project TOPDAD. Such exploratory use implies higher uncertainties of the outcomes.

Frei et al (2012) conducted a study of the socioeconomic benefit generation of weather services for road transport in Switzerland. In its outline it has commonalities with Leviäkangas and Hautala (2009), but the study is more pertinent in terms of involved price and unit-cost levels, as well of the character of benefits achieved. The results show that the use of meteorology in the road transportation sector in Switzerland generates an annual economic benefit to the national economy of 66 to 80 million Swiss francs (1 Swiss franc ~0.90 €). Similar to Leviäkangas and Hautala the results found by Frei (2010; 2012) indicate a BCR of around 5:1. His study also included to some extent the induced economic effects of the initial benefits.

The aforementioned EU research project ToPDAd contained the assessment of different cases (Perrels et al 2015). For the present study a relevant case from TOPDAD is a hypothetical real time warning information service for car drivers. That assessment contains a lot of detail on modelling individual and household responses within the context of how individuals and households organise their daily schedules, and the implied costs and obstacles to change plans. It also accounts for network effects, if people respond by adapting route. All in all, the assessment indicated that there are behavioural, technical and economic boundary conditions, that can curtail the maximum attainable benefit of real time information for a sector or population as a whole.

There is a rather limited number of studies on benefits from satellites. London Economics (2015) published a review study of cost-benefit studies of space activity investments, including earth observation, telecommunication, navigation, space technology, and space related R&D. For earth observation the bulk of the reported benefit-cost ratios vary between 2:1 and 4:1. NOAA ordered studies in 2018 and 2020 more specifically dealing with effects of incremental improvements in earth observation. For the USA as a whole the benefits are substantial, with an order of magnitude 10 billion $, but the costs are substantial too. Especially the 2020 study (Adkins et al 2021) is comparable to the approach followed here (value chain based – see sections 3.1 and 3.2) and cautions for sweeping claims. For example, it may be better to cast it as *benefit potential* of earth observation, as a part of the benefit realization based on new or improved data requires additional investments downstream in the value chain among users. Adkins et al (2021) can be regarded as a study of academic standing.

Even fewer studies are conducted that assess induced economic effects of investments in satellite services. The conducted studies often tie in with advocacy related to innovation efforts for the space sector (e.g. OECD 2020; ESA see below). That is indeed a relevant and important angle, and of growing significance. Nonetheless, separate independent macro-economic studies, similar to those conducted for transport investments (e.g. Purwanto et al 2017), would be welcome.

Florio and Moretta (2021) discuss the economic significance of earth observation (EO) in an overview article. For a start EO can facilitate economic analysis and comparison with respect to impacts and changes regarding economic activities or the capital stock in flexibly defined areas (rather than prefixed areas from register datasets). That ability as such can already produce benefits through better prevention and better policy compliance. More generally EO can support the efficiency enhancement of all kinds of activities as it helps to better foresee risks and opportunities arising from geophysical and natural processes. Florio and Moretta underline that with respect to valuation shortfall in data and the challenge to quantitatively evidence the differential effect on costs and benefits are common obstacles. They also refer to the value chain approach as the preferred method.

Cló et al (2019) describe the knowledge and service generation based on the output of an Italian satellite constellation (Cosmo SkyMed), which is primarily aimed at natural hazard management. The paper stops short of providing monetized estimates, but in fact it illustrates how this could be realized by assessing the uses of the satellites' information output and the associated achievements.

Tassa et al (2022) discusses the endeavor of the European Space Agency (ESA) to evaluate the socioeconomic benefits of EO and its methodological challenges. She also emphasizes the value chain approach. ESA has published a collection of case studies of value formation of quite different types of uses of satellite information. The case study that comes closest to the types of benefits considered relevant for EPS Sterna is about winter navigation in the Baltic Sea, with emphasis on shipping to and from Swedish and Finnish ports. The study was conducted by the European Association of Remote Sensing Companies (EARSC 2015) for ESA. In essence, the satellite-based ice information implies efficiency improvements in the operations (fuel saving and time saving) and some degree of avoidance of damage. Benefits accrue to ice breaking services, cargo ships using the ice breaker service, and to the serviced ports. Furthermore, indirectly the efficiency gains engender benefits for Swedish and Finnish companies and citizens. Overall annual benefits exhibit a significant uncertainty and variability (24 ~ 116 million €), depending on actual responsiveness in the logistic chains and on the inter-annual variability in ice conditions.

Moretta et al (2023) present a study on the overall economic benefit potential of EO for Italy. After identifying the typical value chains of EO services used by Italian companies and organisations a broad literature review was used to select the most significant sectors for targeted surveys of experts and end-users on (1) the use of the EO services, (2) the types of benefit mechanisms involved, and (3) the approximate estimates of the benefits engendered (as % change). The variability in the estimated percentage changes of avoided costs and/or enhanced revenues was used to generate a Montecarlo simulation of benefit outcomes per sector. For *all* EO services together the macroeconomic benefit potential was estimated at roughly 0.7% – 0.9% of Italian GDP, which amounts to about 14 to 18 billion €. It should be emphasized that it concerns a benefit *potential*. The estimated benefits from the surveys cannot be rigorously verified, whereas upscaling from several representatives of a sector to a whole sector is tricky. Indicated benefits may concern latent effects or innovation related benefits which build up slowly over time. It may also concern changes in market share without significant change in the overall revenues in a market. Furthermore, other studies usually find that the uptake of this kind of services in different sectors remains well under 100% (Tart et al 2019; Perrels 2018).

More academic involvement and more rigorous standardization and classification of methods would be helpful. In some application areas one can observe an increase in peer reviewed publications on benefit assessments of very specifically described value chains, such as in the case of risk management of certain crops (Vroege et al 2021) or for natural hazard management.

3. Review of valuation methods

3.1 Types of evaluations and valuation methods

3.1.1 Identifying the nature of the benefit propagation by application

Weather and climate services (WCS) are often valued by using techniques that are compatible with cost-benefit analysis (CBA)[1]. CBA is an economic toolbox used to compare the benefits against the costs of a given project or activity. Common methods to evaluate weather and climate services (WCS), as *part of a* CBA or otherwise, are contingent valuation, revealed preferences, economic decision modelling, avoided cost assessments, benefit transfer, and participatory methods. These methods are explained below, in conjunction with Table 2. The right method(s) is(are) selected depending on several factors including the aim of the evaluation, the type of WCS under examination, the current or intended users of the service, as well as budget, time, and available expertise to implement methods. The resourcing angle is important as some methods that reveal more precise data, such as surveys, require significant resources, whilst others such as benchmarking and benefit transfer are less resource intensive, but may lack detail. (Anderson et al., 2015). Different valuation methods for evaluation can be compared by examining their main features, sensitivity to incomplete data, level of complexity and ability to use qualitative or semi-quantitative data instead of quantitative.

It should also be noted that the socio-economic benefits associated with meteorological and hydrological services are highly context and location dependent. Therefore, it's important to understand the societal, economic and cultural context of the country as researchers determine how weather (or water) related information is useful and where it creates value. Each study needs to be designed for the context. For example, in developing countries, where there is often little information about economic and societal performance factors, producing a thorough qualitative analysis can also serve the purpose of demonstrating the benefits to society. A thorough qualitative analysis is often better than a shaky, highly uncertain, quantitative analysis. Nevertheless, policymakers often prefer quantitative, monetized, results (Pilli-Sihvola et al 2014). In conclusion, valuation studies should strive for quantitative to the extent possible and warranted by available data, while not eschewing qualitative methods when better fitting the available information and processes involved.

When studying the value of socio-economic benefits of forecasting, especially in high latitudes, it's important to understand natural hazards in northern countries. For example, compared to many other countries in the world, the human losses caused by natural hazards are smaller in Nordic countries, which is due to the low population density in the exposed areas, while well-developed warning services further decrease the losses. Nonetheless, the economic losses can be significant and the geohazards' profile varies among the countries. The predominant natural hazards in Nordic countries are floods, landslides, and snow avalanches (except for Denmark). Volcanoes and

[1] In North-American publications usually referred to as benefit-cost analysis (BCA).

earthquakes are major geohazards in Iceland, and parts of Norway are susceptible to seismic activity. Slide triggered tsunamis also represent a threat to parts of the coastal areas of Nordic countries and Greenland. (Nadim et al 2008). The main natural hazards in Finland are all meteorological (Gregow et al 2021; Perrels et al 2022), such as winter storms (in combination with extreme snowfall and/or coastal storm surge), convective storms in summer and early autumn, urban downpours and associated local flooding. Moreover, quick snowmelt associated with riverine floodings (possibly in connection with prolonged precipitation), droughts and associated forest fires, and heat waves are also notable hazards, but these have slow onset features, making them less relevant with respect to the improvements enabled by the space-based information i.e. EPS Sterna.

In principle better information on (near) future weather conditions enables to reap the following types of benefits:

- avoidance of damage to capital goods (real estate, equipment, vehicles)
- enablement of further optimization of the use of capital goods and associated consumables (i.e. creating savings from improved efficiency)
- avoidance of disturbance or disruption of operations (delays, extra consumption of fuels and materials, extra labour cost, non-delivery, etc.), this partly overlaps with the previous point
- new opportunities due to better predictability, e.g. increasing the radius of action in logistics or adding new destinations to a network

In general terms economically relevant differential effects of improvements of *short-term oriented forecast*s pertain to:

- timing, i.e., giving a user more time to decide/be prepared (also more opportunities to update if information frequency is high)
- significant reduction in the variability of the accuracy, implying much less risk of regret for the user
- significant improvements in spatial (and temporal) resolution - enabling users to avoid unnecessary precautions and/or have more precise optimization of operations

Based on discussions between the project teams of MetNorway (Task 1), SMHI (Task 2) and FMI (Task 3; see Introduction), and internal consultations in the respective organisations a preliminary assessment was made of the relative importance of the three effects mentioned above. Regarding the incremental effects of EPS Sterna satellites, we can assume that forecast accuracies (expressed as functions of central moments of the distribution of key weather variables) are generally already quite good, which makes significant improvements less likely. We will learn in chapter 4 that this depends on the information sensitivity and the information processing capability of various economic sectors. Yet, for a start it seems safe not to expect too much from this effect.

For the third bullet on improved resolution, at least for the NWP part, the satellite will not be expected to be an enabler for higher spatial resolution models. For this reason, the most relevant improvement in relation to EPS Sterna in high latitudes and socio-economic benefits is most likely the first bullet: timing. This can tie in with the second bullet, if it means that uncertainties reduce earlier, i.e. more hours ahead of a time threshold for the user. The new satellite may enable to provide forecasts of equal quality earlier, thereby widening the lead time to events or conditions of interest. Furthermore, more frequent microwave sounding revisits will allow more frequent update of information. The size of the time benefit will be established on the basis of output of Task 1 and Task 2, as reported in Guedj et al (2023) and Rydberg et al (2023) respectively, and supported by consultations with operational forecasters and experts from user sectors.

3.1.2 Selecting evaluation methods suitable to the cases

Due to the characteristics of the value of weather data, decision-analytic studies of the economic value of weather and climate forecasts can be distinguished – for a start – into two categories, being prototypical decision-making models and case studies (Katz & Lazo 2010). The literature review by Clements, Ray & Anderson (2013) used a variety of methods to quantify the value of climate services, including: decision theory, avoided cost calculations, partial equilibrium models, game theory, stated preference, benefits transfer, and econometric models. These methods for inferring value of a particular weather information service can be used or at least interpreted in different ways depending on the overall evaluation approach. Table 1 provides an overview of the methods used to infer value from different types of changes enabled by the use of WCS.

An important difference lies between effects that are explicitly or implicitly priced (i.e. physical damage and excess travel time) and effects for which – at best – a cost per unit can be obtained either by comparison with priced substitutes or by assessing willingness to pay (WTP) for avoidance among relevant actors. In the present study the applications start as avoided cost assessments. However, to be able to capture some of the effects also decision analysis (to represent rearrangements in queuing) and econometric studies (pre-existing results about the electricity market) as well as the valuing of ecosystem services (additional environmental cost features of chemicals used) are included.

Main type of evaluation approaches:

- **cost-benefit analysis**: evaluate whether the total effort in terms of investment and operational costs can be justified by the benefits that the realized project is expected to enable over its lifetime; cost and benefits can include monetized and originally monetary effects
- **cost-effectiveness analysis**: evaluate how given objectives (e.g. a specified service level) can be achieved against lowest cost, in that case benefits don’t need to be assessed, making the entire evaluation easier to conduct (as cost are often easier to infer than benefits)
- **financial analysis**: analyses the monetary in- and outflows of a project over time for key actors by type of source (e.g. public/private; domestic/foreign), risk levels, and financing cost levels

- **economic impact / benefit potential study**: analysing how and to what extent an investment or measure, often with innovation features, is affecting one or more economic sectors or region(s)
- **market uptake study**: assessing to what extent a new (service) product will be taken into use by current users of comparable products and by new users depending on user characteristics, obstacles to take-up, and performance features of the service product
- **multi-criteria analysis**: an evaluation, usually conducted by group of experts and/or stakeholders, of an investment project or measure on the basis of set of criteria to which scoring functions are applied, and – possibly – weighing functions depending inter alia on the expertise level of participating decision makers and/or the significance of the effect type

The present study can be regarded as an economic impact / benefit potential study organised in a way that facilitates extension into a cost-benefit analysis. In each of the evaluation methods can be applied various valuation methods. A summary is presented in Table 1.

Table 1. Applicability of valuation methods for different types of evaluations

<table>
<tr><th></th><th colspan="5">Type of economic evaluation</th></tr>
<tr><th>Valuation method</th><th>cost-benefit analysis</th><th>cost-effectiveness analysis</th><th>economic impact / benefit potential study</th><th>market uptake study</th><th>multi-criteria analysis</th></tr>
<tr><td>(market-) transaction based</td><td>included next to other elements</td><td>only for costs</td><td>included next to other elements</td><td>can be; core topics are elsewhere</td><td rowspan="12">can be, but input is indirect (via scoring of valuation results)</td></tr>
<tr><td>non-market valuation:</td><td></td><td></td><td></td><td></td></tr>
<tr><td>WTP</td><td>for new products</td><td>usually not</td><td>for new products</td><td>for new products</td></tr>
<tr><td>avoidance behavior</td><td colspan="4">historic observations; engineering-economic or econometric methods</td></tr>
<tr><td>hedonic price</td><td colspan="4">based on historic observations; using a ready model or estimating one</td></tr>
<tr><td>substitute ecosystem service</td><td colspan="4">using ready models/estimates or creating new one, may have to involve WTP study depending on type of ecosystem service</td></tr>
<tr><td>economic models:</td><td></td><td></td><td></td><td></td></tr>
<tr><td>decision models*</td><td>possibly as building block</td><td>less likely</td><td>possibly as building block</td><td>less likely</td></tr>
<tr><td>sector/market models</td><td rowspan="2">for sector CBA or large project</td><td></td><td>often included</td><td>key element</td></tr>
<tr><td>macro-models</td><td>if comparing instrumental effectiveness</td><td>can be included</td><td>unlikely unless long term scenario study</td></tr>
<tr><td>benefit transfer</td><td colspan="3">can save time & resources, e.g. if no case data available, but can introduce biases</td><td>not recommendable</td></tr>
<tr><td>value chain analysis (VCA)**</td><td>indirectly, based on results from potential or uptake study</td><td>usually not or only some segments of the VC</td><td>very suitable</td><td>very suitable</td></tr>
</table>

*) e.g. The so-called Cost-Loss approach belongs to this category; often used in WCS evaluation.

**) The principal analytical frame for the evaluations in this report (explained in §3.1.3)

3.1.3 Brief explanations of the evaluation types and valuation methods

Evaluation

Cost-benefit analysis: Cost-benefit analysis (hereafter CBA) refers to a type of project or policy appraisal, which aims to represent effects in monetized terms, including effects of non-economic origin. CBA encompasses a large variety of methods, can be scoped in many ways, and be combined with other risk appraisal and decision support approaches.

The purpose of a CBA is to evaluate whether the total effort in terms of investment and operational costs can be justified by the benefits that the realized project is expected to enable over its lifetime. A CBA can be conducted for a particular actor, such as an infrastructure owner or a public authority. This is called a private CBA or a financial analysis. A CBA is often conducted to assess the net benefits for society at large. This is called a social CBA. In the case of EUMETSAT both the private CBA and the social CBA are relevant. Private CBA's concerning use of satellite enhanced services in a certain sector provide insight into the attractiveness of that service for that sector and thereby gives indications of the probable amount of uptake of that service in that sector, i.e. it indicates where the markets are for the service assessed. A social CBA is relevant for EUMETSAT since the funding is wholly or largely public and also motivated by the public duties of constituent organisations of EUMETSAT. It gives an indication of the net welfare gain for the involved countries.

CBA can be conducted at various levels of sophistication, depending on the stage of the project and data availability. The effort for the CBA should be proportionate to the size of the project. Conducting a CBA means application of a collection of methods to harmonize inputs and results, as well as to allow the comparison and (dis)aggregation of results.

Key aspects to be considered when conducting a CBA:

- *Data availability and quality*: estimation or approximation of not directly distinguishable effects, standardisation of differently measured data
- *Uncertainty*: expected values, uncertainty ranges, weighing of different inputs, scenarios
- *Monetization*: approaches for originally non-monetary effects, such as related to environmental effects and changes in the provision of public goods
- *Discounting* of costs and benefits over the project lifetime
- *Distribution of costs and benefits* within society; accounting for market failures

CBA may be the principal type of evaluation used, but it can also be part of a more comprehensive decision-making process, employing multi-criteria analysis (MCA) or a formalized risk analysis.

Cost-effectiveness analysis (CEA): CEA is used for projects where the result (target) is prefixed, such as fulfilment of a safety level. In CEA the investments have to be judged in terms of cost effectiveness with respect to achievement of given physical risk reductions (norms). CEA requires less data and hence is cheaper and quicker to conduct than CBA.

Economic impact or benefit study: This approach is about analysing how and to what extent an investment or measure or conversely a hazard is affecting one or more economic sectors or region(s). If first the effects of a hazard are assessed, subsequently the benefits of hazard management measures can be assessed. This is the type of assessment conducted in the present study. It provides building blocks for a CBA or CEA, yet it does not have to strive for completeness. It may also be used to illustrate the benefits of hazard management services to potential users. The valuation methods are the same as can be used in CBA.

Market uptake study: Next to estimating the value to users or particular types of users this kind of assessments also review obstacles to uptake, and may also include projections of temporal and/or spatial development pathways of the uptake (market penetration curves or saturation curves).

Multi-criteria analysis (MCA): Even though MCA is eventually using expert and/or stakeholder weighed scoring on diverse criteria, it can contain valuation as one criteria domain, and within the valuation domain in principle the same valuation methods can be used as in CBA. Yet, eventually the economic results are weighted against effects in other domains.

Valuation

Transaction based: This is the ideal default case for CBA. Of all effects the quantities and prices are known. This is applicable in the wind power case. A part of the costs in the aviation case can also be handled this way. Yet, cost attribution of increments of capital costs requires particular treatment (see also benefit transfer)

Non-market valuation methods: These are required if the supposed or observed response (to a hazard and/or counter measure) is expressed in terms of unpriced effects, e.g. if people choose to avoid or select an option more than earlier. For stated preference by using willingness to pay, for revealed preference by the implicit price (cost) of a choice made (e.g. through paying more tax or using more time) such as:

- *stated preference* – by using surveys or interviews one can inquire about the inclinations of potential (types of) users to use a proposed, but not yet available, product or service in relation to attributes of the new product or service (price, technical requirements, user skill requirements, expected effect, etc.); there are several approaches within the stated preference method family; stated preference investigations can also produce estimations of the willingness-to-pay for (improvements of) the service;
  stated preference methods may also be used to valuate the effects on public goods (i.e. non-priced goods), including environmental resources
- *revealed preference* – if the involved costs and benefits concern products and services which have prices, i.e. are provided through market transactions, the sensitivity of the transaction volume with respect to changes in attributes of the product is observed through the market data; however additional effort is needed if it concerns utilization of capital goods and joint cost of facilities for different applications;

- *resource cost proxies* (to some extent applied in aviation e.g. for travel time loss) – some effects, like with respect to travel time or land use or water use, may not have an own market price as such, but nevertheless associate closely with closely related concepts which do have a price, such as labour time (wage).
- *ecosystem services* – ecosystems provide all kinds of services, which have also an economic value; if a new project positively or negatively affects the supply levels of ecosystem services, there are dedicated methods, being WTP or the costs of manmade substitutes or the costs of a compensatory ecosystem enhancement project, to assess the value of the change in provision level(s) of ecosystems.

Benefit transfer: Takes the finding of an original evaluation and applies them to a new geographic or policy context. The transfer can be at several levels (outcomes, equations, parameter levels, equation type) and have different levels of sophistication.

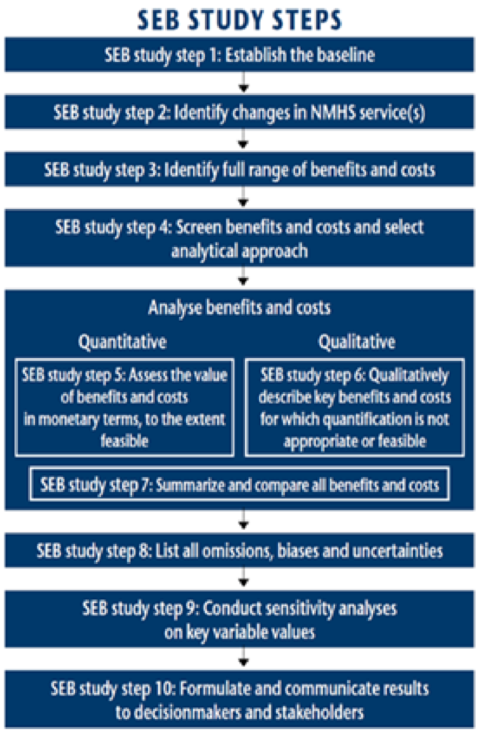
Avoided cost / cost-loss framework: This an approach typically used for valuating (improvements in) weather services (e.g. Katz and Lazo 2010). The cost-loss framework represents a binary decision process in which up to a certain threshold no protective action regarding a possible hazard is triggered while beyond the threshold protective action regarding that hazard is taken. The action has certain costs, while the occurrence of the hazard causes larger costs. Improving the precision regarding the thresholds can save action cost, while not increasing the expected hazard costs or even lowering them.

Value chain analysis (VCA): Value chain analysis has a special position in this table as it can be regarded both as an approach, due to its versatility, and as a method, as it also stipulates or guides to use certain (combinations of) methods and emphasizes the interaction of information processing actions and associated actors as important mechanism propagating the information emerging from the value chain. VCA has been used in this study as the principal analytical frame.

3.2 Valuation logic for atmospheric information services

In order to valuate a new service the differential effect of the service for the users in terms of extra benefits (which may also be avoided cost) as compared to non-use or use of older version is to be established and compared with the cost of production, delivery and use. Since the production and use of a new service may entail also substitutions at the production and the use sides it is recommendable to define the system and processes involved as well as the system boundaries. Cost-benefit analysis offers a well-structured framework to conduct and connect all these analytical steps. Anderson et al (2015) provide one of the first comprehensive guidelines for examining the socioeconomic benefits of met/hydro services framed in a CBA logic (figure 1 left). The research methods can be tailored to different users and benefit streams (avoided costs or damages, higher profits or increased social welfare). Some methods, particularly where more precise results are required, will involve extensive data collection, surveys of user preferences and willingness to pay (WTP) for services, or economic modeling, while other methods such as benchmarking and benefit transfer are reasonably inexpensive to apply.

In this exploratory limited size study inputs for calculations are taken as much as possible from earlier studies and statistics. No surveys have be conducted, nor were economic models used for sectoral or macroeconomic impact assessments. Simplified simulations of slot rescheduling and capacity allocation were used, whereas output of econometric models was used in the case of wind power. Interviews were used to underpin the selection of the most relevant sectors and to apply the right focus in the impact representation for the selected sectors (steps 1 – 5 in figure 1).



#	phase description in this study
1	Problem definition → potential differential effect and possible types of benefits
2	Selection of sectors in conjunction with expected WCS improvements
3	Assess information propagation pathways and consequent differential effects on operations and decision making by selected sector
4	Design preliminary formalized representations of information propagation and generation of differential effects with benefit potential
5	Review preliminary formalized representations of information propagation with sector experts and sector-meteorologists; assess data availability
6	Check differential effect from satellite, NWP output, and now/forecast with test results from Tasks 1 and 2*
7	Update formalized representations and input data and conduct calculations of benefits per selected sector; apply upscaling within sector / Nordic countries
8	Summarize direct economic effects and indicate induces (macroeconomic) effects
9	Present and evaluate results and methods; further comments

Figure 1. The principle steps in this study (right) and in general in a WCS oriented cost-benefit analysis (CBA); elaborated from Anderson et al 2015

To describe and analyse the information propagation process *value chain analysis* can be very helpful and can be seen as a way to represent the CBA process steps. Use of the value chain will often also help to determine manageable system boundaries and identify side effects, alternative production pathways, etc. (figure 2).

The value chain concept has also been used to assess how the improved weather forecast information propagates through the decision making and operational systems of selected sectors. Specific flowcharts for these are presented in sections 4.2 and 4.2 were the approaches for aviation and wind power are explained in detail.

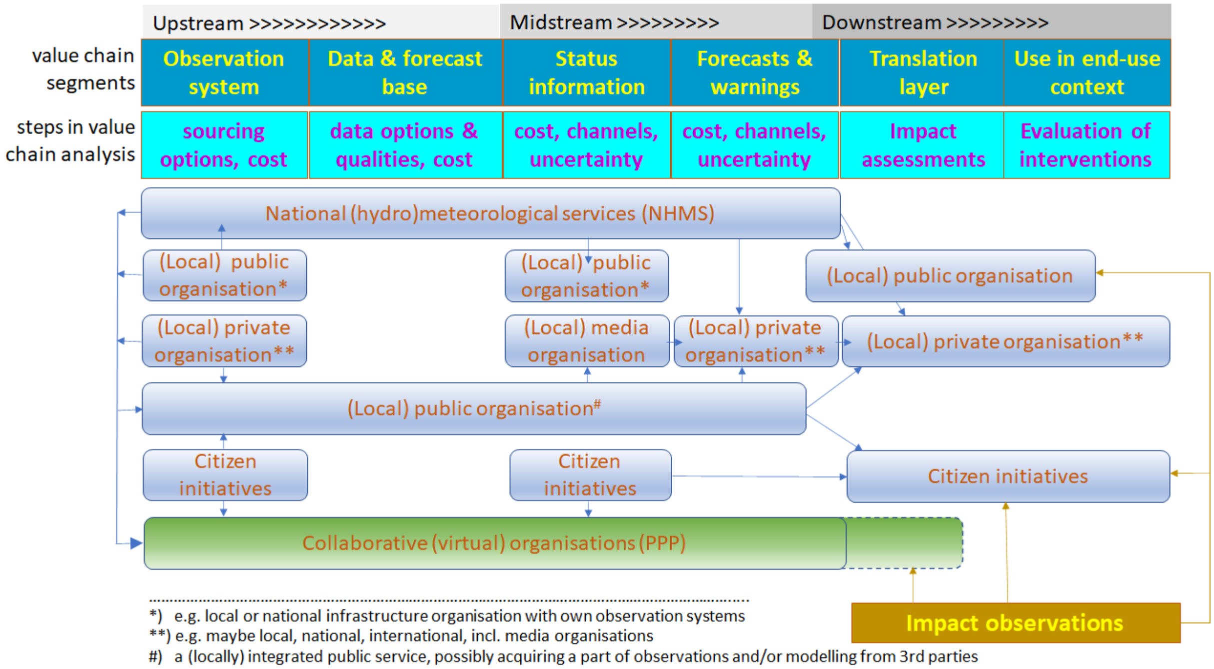


Figure 2. Value chain for urban integrated services (source: Perrels and Berninger forthcoming)

The generation of benefits from weather and climate services are often depicted in a *value chain* since it's linking the production and delivery of services to user decisions and the outcomes and values resulting from those decisions. The value chain (presented above) can be used to illustrate the production and delivery of the entire suite of met/hydro services or to describe a single new or existing service. The presentation of the value chain depends on the met/hydro services being evaluated and the reasons for conducting the valuation study – it can be designed to validate the current provision of individual or all met/hydro services, to justify new investments in these services, or to demonstrate the value of met/hydro services in key sectors such as agriculture, aviation or energy (Anderson et al, 2015). On that note, met/hydro services do not generate economic and social value unless users utilize and act according to the new improved climate data or services, even if the services would be the highest of quality. Furthermore, met/hydro services of the same quality in different countries may vary significantly in terms of their benefits, depending on the relative nature of weather and climate risks, the number and types of users, and their ability and capacity to take action to increase economic output or avoid harm.

4. Valuation of EPS Sterna benefit potential for selected sectors

4.1. Introduction

A comprehensive valuation of the benefits from EPS Sterna would require a combination macroeconomic modelling and sector specific modelling, which is however impossible at the current stage, as input data for such modelling are largely lacking and moreover would entail a very significant research effort. At this stage it is feasible to assess the benefits of EPS Sterna for selected sectors and particular types of users. By extending the array of bottom-up estimated benefits one may be able to develop in next stages an appropriate set of input data for a macroeconomic assessment aiming at a comprehensive valuation.

Studies that analyse a single agent or entity that is responsible for making decision(s) to maximize (or minimize) an objective function typically employ economic decision models (for example, represented by a utility function, production function, cost–loss model of two alternatives or other economic models). These studies assume that the decisionmaker makes decisions based solely on the effect of the decisions on their payoffs. In the context of met/hydro services, these studies often assume that decisionmakers have some level of prior climate knowledge. Without updated climate information, the decisionmaker uses the prior knowledge to make decision(s). If updated information is provided, the decisionmaker will use this information to make optimal choices. The value of met/hydro information and WCS is then equal to the difference between the benefits when the information (that is, updated knowledge) is used, compared to the benefits when prior knowledge or no forecast is used (Katz and Lazo 2010).

Selection of sectors of application

In an early stage of the study, in collaboration with the other partners, several sectors were identified as potentially relevant and suitable for analysis. These were civil aviation, electricity production and distribution, road and rail transport, arctic shipping, building and infrastructure construction, and rescue services. After a few months of progress in Tasks 1.1 and 1.2 (Guedj et al 2023) and after interviews with operational meteorologists (with affinity for needs in various sectors) it was decided that service improvements enabled by EPS Sterna seem to be in particular relevant for *civil aviation, wind power production, and winter road clearing & salting*, all at high latitudes. The construction sector was regarded as too diverse and therefore as too complex for this study. In principle also the tourist sector can be beneficiary of the extra data from EPS Sterna through forecast improvements, but that value chains are often not very well specified in this case, notably downstream at the user side (e.g. Damm et al 2020).

As regards civil aviation it was decided to focus on the effects regarding efficient airport operation in winterly conditions, with risks of inadequate scheduling of de-icing capacity and other ground services and facilities. In principle also flight route planning and international air traffic control can benefit from improvements enabled by EPS Sterna, but that topic area was regarded as too complex for proper treatment in this study. To some extent it is still included through effects of late arrival of airplanes.

With respect to electricity production and distribution it was decided to focus on wind power production in the Nordic countries, in particular in relation to poorly forecast icing episodes, which significantly reduce output of affected wind turbines, and the consequences for price levels on the common Nordic electricity market (Nordpool).

Thirdly road clearing, notably salting, in winterly conditions was chosen. However, for this application we were not able to produce quantified estimates of the benefits. The sector will be discussed qualitatively.

Application of methods by sector

The following sections will present how the analyses were conducted for each of the selected sectors. The table below provides a summary of the used valuation methods, as presented in chapter 3, for each of the sector assessments.

Table 2. Application of relevant methods for selected sectors

	aviation	**wind power**	**other (road salting; building)**
(market-) transaction based	basis for involved expenses of airports, airlines, and travellers	key role; cost are generated and distributed via power market	basis for involved expenses of road authority and salting operators
non-market valuation:			
Willingness to pay WTP Value of statistical life VSL	option for travel time delay valuation; various norms are steered by VSL, but no direct effect in this study		(non-)achievement of safety standards
avoidance behaviour			traffic behaviour
hedonic price			
substitute			
ecosystem service	[effects of glycol use]		ecosystem effects of salting
economic models:			
decision models	minimization of delay time subject to various boundary conditions		
sector/market models		[Nordic power market] (implicit via price response parameters)	
macro-models			
benefit transfer	cost per minute	price response parameters	environmental cost
value chain	representation of the propagation of the information improvement through forecast and use stages		

The value chain approach has been used in order to get a better view on how the improved forecast propagates benefits in the considered systems, i.e. what is the pathway of information and decisions or actions. For particular steps within the value chain, notably the response steps of the final users, the various valuation methods of table 2 have been used to assess degree of response and the eventual value created or enables by that decision or action.

4.2. Aviation sector and delay sensitivity

Poor visibility, low cloud ceilings, or crosswinds can make it unsafe for aircraft to take-off or land, resulting in disruptions to flight schedules. Winterly conditions affect ground handling activities, such as baggage handling, aircraft servicing, catering and de-icing management; precipitation and freezing temperatures may require additional precautions or de-icing operations on aircraft to remove snow, ice, or frost from their surfaces to ensure safety. De-icing procedures add time to aircraft turnaround and require additional equipment and personnel resources. Also, icy or snow-covered runways may require clearing, which can cause additional delays.

Delays can be caused by multiple reasons and often other stress factors exacerbate initial delays due to a single cause and multiply delays throughout the system. According to Perrels et al (2014) weather causes about 10% of the primary (initial) delays in aviation in Europe. Since the duration of delays caused by adverse weather exceeds the average of all delays, adverse weather is also a substantial contributor to so-called reactionary delays in aviation (in combination with the utilization rate of airports and flight corridors). The total annual costs of delays in aviation in Europe amount to 1.25 billion Euros for the year 2009 (Cook and Tanner 2015). This estimate does not include other delays outside the realm of air traffic flow management (ATFM).

Costs accrue in particular when delays are long; delays of more than 30 minutes represent only about 12% of all arrival delays, and yet generate about 60% of all (assessed) delay costs. Perrels et al (2014) also noted that in Europe the share of weather in causing daily delays is three to four times larger in winter (around a quarter of primary delays) as compared to summer months. In the Nordic region weather conditions vary a lot, and airports must be well-prepared for challenging weather especially during winter months.

All major airports in Europe employ integrated real-time management systems to optimize the allocation of facilities and services (and their staffing) to airplanes, crews and passengers over the course of the day. Next to the original schedules of arrival and departure, and traveler volume forecasts, airports use weather forecasts and nowcasts to plan and revise their operations. Furthermore, flight arrival schedules can get revised as well over the course of the day due to adverse weather and other causes of delay elsewhere (notably in Europe in this case). Eurocontrol runs integrated real-time air traffic management systems in which the impacts of such delays on current flights and upcoming flights is assessed in terms of routing and timing. Finally, adverse weather may cause travelers and crews to arrive with delay at the airport.

The best possible bottom-up analysis of the effects of EPS Sterna on aviation relevant weather forecasts and nowcasts, and on consequent delay reduction would be to use the output from the experiments of Tasks 1 (Guedj et al 2023) and 2 (Rydberg et al 2023) as input for a selection of scenarios fed into test versions of both an integrated real-time airport management system and the Eurocontrol air traffic management system. That would require a much larger study than the current one. **The quantification exercise therefore focuses on the effect of improved probability of timely recognition of adverse winter weather on the main airports in Scandinavia and Finland (Copenhagen, Oslo, Stockholm and Helsinki) in terms of avoided or reduced delays.** Even though the exercise in this study focuses on the Nordic countries the benefits from EPS Sterna for airport management will also be relevant to a varying degree for many other European airports.

4.2.1. Basic concepts in delay management for civil aviation

Since civil aviation is a sector where all operations are meticulously planned and coordinated, while also being subject to many safety and security regulations, the overall functioning is reminiscent of a clockwork. This means delays somewhere in the chain of operations may escalate in much more wide-spread disruptions in the system. Furthermore, the high capital intensity of aviation and the strong tendency towards significant advance commitments throughout the value chain imply that the costs of idle time rise quickly. Delay management is therefore a core feature of civil aviation. More specifically delay management is associated with Air Traffic Flow Management (ATFM), which includes both flight time and ground time.

The complexity of the value chain and the large number of factors wholly or partly outside control of ATFM have led to the practice of including *buffer time* both in the scheduled flight time and the scheduled ground time. The challenge is to insert sufficient buffer time so as to be able to absorb most (moderate) delays without upsetting the planned departure times. Yet, buffer time means extra cost because it requires an airline to have more staff and equipment for the same number of daily flights. On the other hand, absence of buffer time would render an airline a very unreliable company, due to a very high delay rate, which in turn would deter a part of the customers and/or requires the airline to have low prices to retain a customer base.

As the choice of the size of the buffers is airline specific (and can vary to some extent across connections serviced by that airline) the impact of a delay on schedule deviation differs between different airlines at the same airport. Furthermore, it means that initial delays in the ground service chain may eventually just not show in the realized departure time or despite a late departure the arrival can still be according to schedule. The latter is important as it helps to prevent the spread of delay problems at one airport to other airports. Such induced delays are formally termed *reactionary delays.* Despite the practice of buffers reactionary delays are a very significant element of the total delays. On average the multiplier from *primary delays* to *reactionary delays* is about 1.8 in Europe (Cook and Tanner 2015), i.e. every minute of primary delay causes an additional 0.8 minute of reactionary delay. According to Cook and Tanner the multiplier rises the longer a delay is (from 1.67 for 15 minutes primary delay to 4.61 for 180 minutes primary delay).

In this study estimated primary delays owing to adverse weather and reduced delays attributable to EPS Sterna are first expressed in minutes. Subsequently, based on the parameter values in Cook and Tanner (2015) reactionary delay is calculated in accordance with the spread in the lengths of primary delays. In the terminology of Cook and Tanner this study assesses the propagation of tactical primary delays to which delay length differentiated costs per minute are applied to obtain costs of primary delays. Costs of total delays are calculated by applying the temporal multiplier for reactionary delays to the monetary values of the primary delays.

Cost of primary delays in the method by Cook and Tanner comprise of cost for fuel, maintenance, crew, ground services (aircraft, passengers, luggage, cargo, facilities, airport aeronautical charges; en-route ATC, costs of compensation and care for passengers experiencing delay above a certain threshold length, and costs of market share loss due to loss of punctuality. As Cook and Tanner used data from 2013 – 2015, the cost are also approximately corrected for rises in jet fuel prices and the approximate rises of business cost in the Nordics.

The measurement method by Cook and Tanner means that the value of time loss for passengers is only partly included. Therefore, we also calculate the value of travel time losses for passengers as an own additional cost. The chosen approach for delay cost estimation also means that cancellations are not represented in the system, even though in the underlying parametrization from Cook and Tanner cancellation is to some extent accounted for. Cancellations are much rarer than delays, but the costs per case for the traveler and the airline are obviously higher.

4.2.2. Interviews – significance of winter weather for delays and de-icing capacity allocation

Interviews were held with a leading expert on coordination of ground services (APRON) at Helsinki-Vantaa airport, as well as with FMI meteorologists with special responsibilities for aviation. Especially with the Finavia APRON specialist was checked what seemed to be an acceptable simplified representation of the interaction between winter weather conditions and airport ground services and eventual delay propagation, with special reference to de-icing.

De-icing is the process of removing snow, ice, or frost from the surfaces of aircraft prior to take-off. Furthermore, next to the removal of snow, ice, or frost aircraft are spayed with glycol-based compounds in order to prevent new attachments of snow or ice in the time up to take-off. Depending on the weather conditions the time span after spraying (so-called hold over time) can vary significantly, roughly from 45 minutes (frost, no precipitation or fog) to under 5 minutes (heavier snow or freezing rain). If the need for de-icing is adequately anticipated, meaning at least 12 to 18 hours ahead, delays may remain quite moderate on Nordic airports, as the de-icing capacity is usually sufficient on those airports. However, not timely anticipated adverse conditions or unanticipated longer continuation of adverse conditions usually leads to cumulation of delays, especially during the periods of the day with high utilization of airport capacity (see Annex 2).

Different countries and airports may differ at detailed level as regards coordination of de-icing as part of the array of ground services and preparations up to take-off, but the same safety restrictions and regulations apply for everyone. Furthermore, the wide-spread use of quite similar airport management software and the large commonality in main airlines serving the various airports results in large similarities in delay propagation processes across airports. Nevertheless, differences in utilization capacity patterns over the day and over the seasons as well as in proneness to particular weather patterns can result in different delay patterns and different sensitivities to weather conditions in terms of eventual aggregate delay effects.

Figure 3 provides an overview of the monthly delay pattern for two recent years (2019 and 2022). The Nordic airports tend to have a higher share of their delays in the period November – March as compared to European airports overall and Warsaw airport (added for comparison), while there may be also an occasional difficult summer month. In non-Nordic airports the summer (holiday) season has typically a higher share, owing to very high utilization rates in many airports and on various flight routes. This means that improved forecast and nowcast of weather conditions in winter is relatively important in Nordic countries, even though in absolute numbers of avoided delay the benefits may be expected to be still notably larger in various major airports in Western and Central Europe.

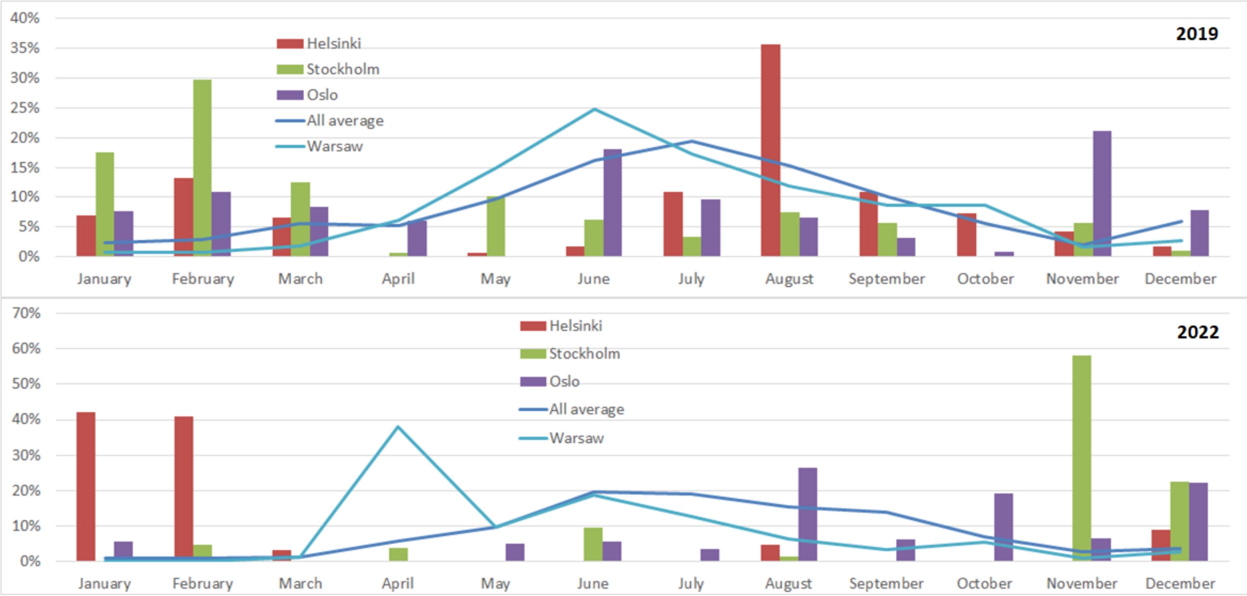


Figure 3. *Monthly shares in aggregate annual delays by airport 2019 and 2022 (2019 was the last 'normal' year prior to the corona period; 2022 is to some extent still influenced by the corona period) In absolute numbers Helsinki has the least aggregate delay in the period 2018-2022, while Oslo and Stockholm have similar absolute numbers.* source: Eurocontrol Data Portal

To properly inform the three de-icing service providers Finavia's supervisors receive forecasts and information about the next 12–24-hour weather conditions (precipitation, snow, temperature development) twice a day from the Finnish Meteorological Institute. Based on the forecast the supervisors advise on the de-icing capacity for the next 12 hours and indicate also the next 12 hours, as well as the allocation by runway. All major airlines serving Helsinki-Vantaa airport have agreed on this way of coordinated dispatch of de-icing capacity, which supports the overall predictability of the system.

As stated before well anticipated deicing demand can result as such in very modest amounts of average delay. However, adverse weather conditions, especially if more prolonged, often cause delayed arrivals as well. A part of these delayed arrivals propagates into the departure schedules. Furthermore, various other ground services than de-icing will also be more prone to deviations from their schedules. Yet, as long as there is quite some spare capacity in terms of gates and departure slots for the runways delays will not escalate.

From an environmental point of view it is worthwhile to mention that delay avoidance reduces kerosine consumption of queuing airplanes and hence emissions of CO_2. The order of magnitude is around 200 ~ 600 liter of kerosine per airplane, which implies CO_2 emissions of 0.5 ~ 1.5 ton.

All in all interaction of delay factors and propagation of delays through consecutive allocation decisions is summarized in figure 4, based on the organizational structure of ground services at Helsinki-Vantaa airport. This is the basis for the formalization of the delay propagation process and the calculation of (avoided) delay cost.

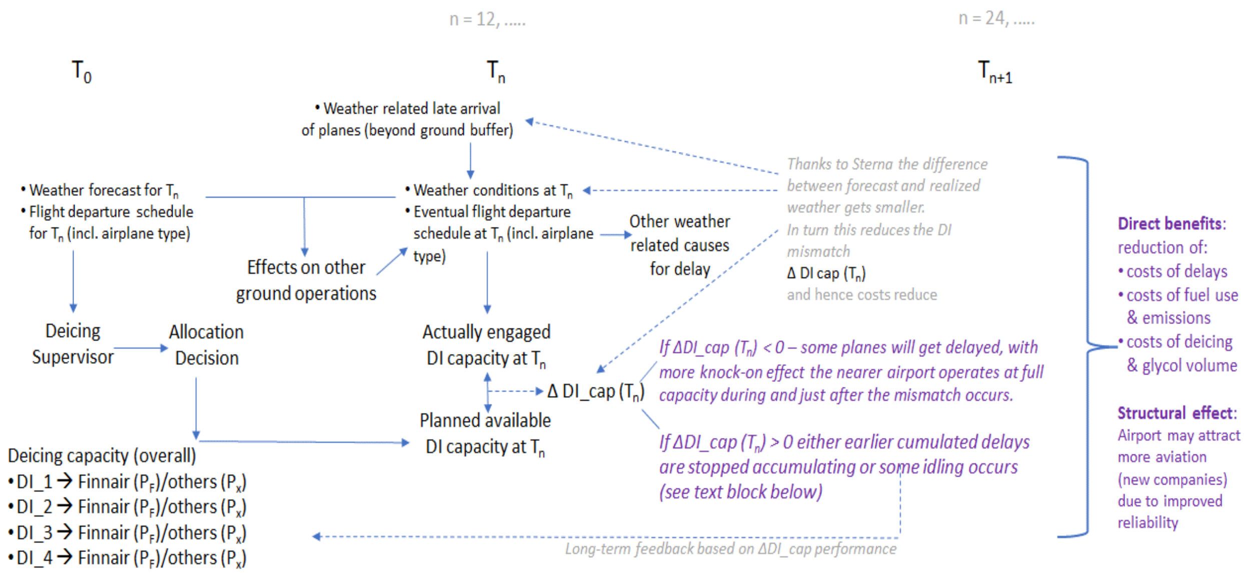


Figure 4. Causal flowchart of deicing (DI) allocation at Helsinki-Vantaa airport (based on interview with Finavia official)

4.2.3. Formalized assessment of the benefit potential for aviation

There is an ordered set S{ } of allocated slot clusters AC_t, being a series of 5 minutes sparsed clusters of slots, covering a period of max. 12 hours, with 0 ~ 3 airplanes allocated to each AC_t (a_1, a_2, a_3). Each airplane has a set of characteristics (c = 1…k) with respect to departure requirements affecting deicing cost, duration, and validity time, as well as required spatial and temporal distance to preceding and next plane. S{ } has two states, a planned state $S_{P,\,Ti}\{\ \}$ and a realized state $S_{R,\,Ti}\{\ \}$. Both states occur subsequently for consecutive times T_i. For $n \leq N$ the planned set and the realized should be the same or at least the pairwise difference between characteristics per plane in the same *AC* should be zero. The following outcomes may occur at T*n*:

1. $S_{P,\,Ti}\{AC_1, \dots AC_t, \dots AC_n\} = S_{R,\,Ti}\{AC_1, \dots AC_t, \dots AC_n\}$ - ideal situation where for each pair of planned and realized slot the plane is the same

2. $\forall c_{k,aj}\ (c_{k,aj,P} - c_{k,aj,R}) = 0$ – despite possible rearrangements, the characteristics of pairs of planned and realized planes per slot still (essentially) match, so no time frictions expected

3. $\exists c_{k,aj}\ (c_{k,aj,P} - c_{k,aj,R}) \neq 0$ – rearrangements between original plan and realization include mismatches which cause capacity exceedance; the higher the mismatch rate the more delays

For Helsinki-Vantaa we assume 12 slots per hour with each max. 3 airplanes departing during the same slot number. There are in principle many combinations possible of adding A departures to a partly filled queue with 12 places of which at most 12-A are filled. Yet, by taking the average of the combination with lowest and highest extra time possible, one obtains the expected extra time.

C = 36 under normal circumstances and C = 24 under limited visibility circumstances

$D(S_r) = \sum_{AC=1}^{12} \sum_{a=1}^{3} S_{r,t1} \{AC_1(\mathrm{a}_i). \dots . AC_n(\mathrm{a}_i)\}$,

where a_i= 0 (open slot place) or a_i =1 (filled slot place), so $0 \leq D(S_r) \leq 36$

- *A* denotes a variable number of departures to be rescheduled during the following period of the day (hour) *h*. During that coming period *h*, certain amount of slot positions/places are already reserved (R); hence a key criterion is whether *A*, the number of flights to be rescheduled from period *h*, exceeds *C-R*, which is the remaining capacity available when accounting for the slot positions already reserved (R)
- $C = 36;\ D(S_r) \leq 12$: (practically) all rescheduled planes can be allocated to the earliest possible new time slot, ordered by new expected feasible departure times; under these circumstances it virtually always holds that A < C-R
- $C = 36;\ 12 < D(S_r) \leq 24$: rescheduled planes can be allocated the earliest possible new time slot, ordered by new expected feasible departure times; yet, if A > 12 a few airplanes may face more than the minimal delay, this can be exacerbated if the current or extra departures include wide body airplanes, which reduces the effective slot capacity as wide body aircraft cause larger amounts of turbulence impacting a larger space and timeframe
- $C = 36;\ 24 < D(S_r) \leq 36$: a limited number (1 .. 12 depending on C-R) of rescheduled planes can be allocated in the next hour, but some of the flights may face some extra delay; this can be exacerbated if the current or extra departures include wide body airplanes (which reduces the effective slot capacity)
- If *C* = 24 the above logic can be repeated, but under those circumstances the following hours have much less spare capacity and large delays can accrue.

The above logic can be further formalized by the following segmented estimations of expected delay:

- $A_{h0} \leq (C_{h1} - R_{h1})$:

  $E\left(D_{A_{h0}}\right) = [\sum_1^n (5. A_{h0}) + \sum_1^n (12 - A_{h0}). 5]/2$ if *one* place per slot is free during hour h1 (implying that $1 \leq (C_{h1} - R_{h1}) \leq 12$)

- $A_{h0} \leq (C_{h1} - R_{h1})$:

  $E\left(D_{A_{h0}}\right) = [\sum_1^n (5. A_{h0}) + \sum_1^n (12 - A_{h0}). 5]/4$ if *two* places per slot are free during hour h1 (implying that $13 \leq (C_{h1} - R_{h1}) \leq 24$)

- A_{h0} > (C_{h1} – R_{h1}): $E\left(D_{A_{h0}}\right) = A_m.60 + A_{n*}.120$ if rescheduling cannot find slot positions in the original hour *h* and hence next hours *h+1* and *h+2* have to be considered (see figure 6)

  where A_m={1, …., (C-R)} and A_{n*}={(C-R+1), …., n}

Subsequently, the expected sum of delays by consecutive hour (of original departure) are aggregated over all affected hours of the day. The expected sum of lost minutes can be multiplied with delay cost indicators (per minute) developed by Cook and Tanner (2015) as commissioned by Eurocontrol. In addition, estimates can be provided of excess fuel consumption and CO_2-emissions, as environmental indicators, based on the delay estimates.

The above presented exercise is in fact only dealing with effects on curtailed runway capacity, which can occur when a reduced visibility regime is invoked owing to adverse weather conditions. If this is not timely anticipated it will as such cause delays, even if there is no bottleneck in the de-icing capacity. It is however not very likely that a day-ahead forecast would entirely miss such a situation. Instead, it may err several hours in the timing of it, which would subsequently be corrected in the nowcasting phase. All in all, it means that expected values for delay sums, which are purely due to unanticipated capacity restrictions owing to weather are probably quite low, i.e. between 500 and 1500 minutes per event (see Annex 2 for details).

In fact, situations where no runway capacity restrictions are imposed, but nevertheless sufficient de-icing capacity is needed, may result in larger delay sums per event. This has been assessed in a separate analysis simulating effects of insufficient de-icing capacity on queuing time of airplanes. Figure presents the resulting graphs for two durations of de-icing treatment. Next to the duration of 10 or 15 minutes treatment it is assumed that it takes 2 minutes to move out one plane and move in the next. Other disturbances can add queuing time, as would inclusion of large (wide-body) aircraft. Conversely, occasional long delay and cancellation of some flights may cause reductions or stabilizations in delay times for the remaining aircraft. In the simulated configuration the de-icing capacity amounts to 24 departures per hour in case de-icing lasts 10 minutes and 16 departures if it lasts 15 minutes. Helsinki-Vantaa airport has also quite some hours with less than 60% utilization (<24 departures), in which case no delay would occur and previously accumulated delays can be absorbed, as shown in Figure .

The simulation indicates that typical *average* delays are 15 minutes in the 10 minutes de-icing case and 35 minutes in the 15 minutes de-icing case. Yet, actual delays vary from zero minutes (for the first few airplanes) to over 30 or over 70 minutes respectively, depending on the duration of the de-icing. The variation in delay duration counts because costs per minute are higher for longer lasting delays. In aggregate this can amount to either fairly modest delay sums (~ 800 minutes), if the situation lasts only several hours and is not hitting the main peak of the day, or to quite significant delay sums (~2700 - ~5000 minutes), if the situation lasts a good part of the day, including the main peak time. It should be realized that the airport revises the de-icing schedule every 12 hours and also uses a preliminary schedule for the next 12 hours (hours 13 – 24). Furthermore, in case of essential changes in circumstances it will revise all relevant ground services plans as soon as possible. Therefore, delays may turn out not to be as large as indicated here for the hypothesized cases. On the other hand, adverse weather may also lead to combinations of failures in different segments of the value chain, such as late availability of crews. These may cause significant additional delay not counted for in the current approach.

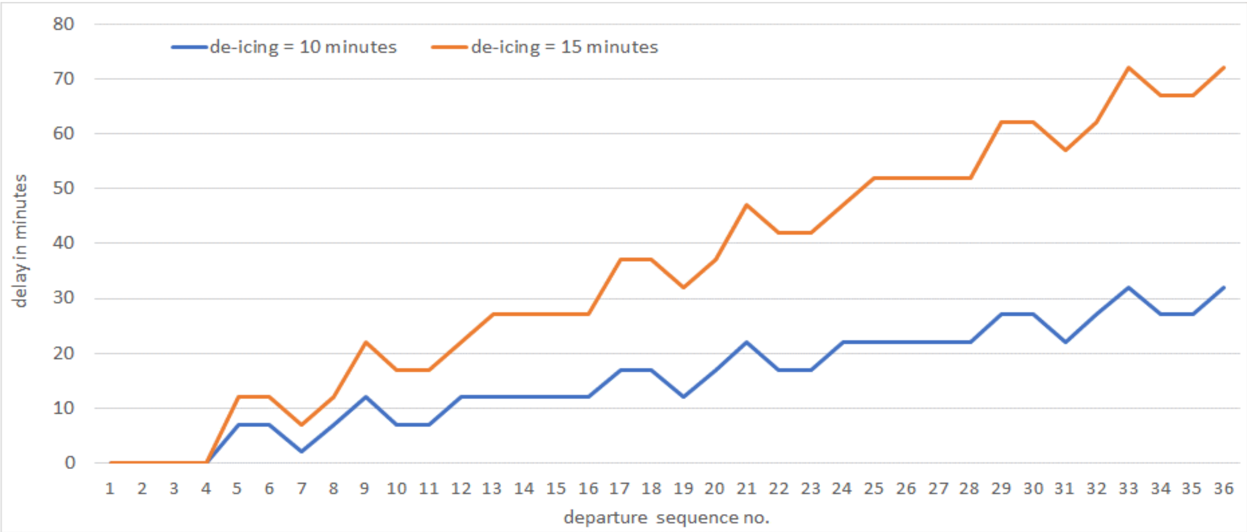


Figure 5. Development of delay by consecutive departure in case of 4 de-icing units instead of 6 when 36 departures in batches of 3 by 5-minute slots were scheduled in one hour (full capacity utilization); 2 minutes slack time between consecutive treatments.

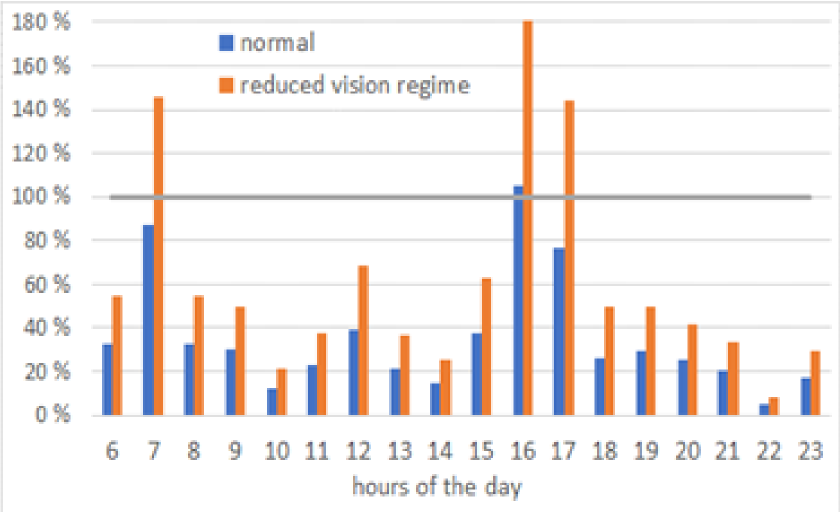


Figure 6. Typical hourly utilization rates of departure capacity on Helsinki-Vantaa airport

Helsinki-Vantaa airport has a busy period for departures between 7am and 8am and a longer period of high utilization in the afternoon between 4pm and 6pm. The other hours have utilization rates that allow for a significant leeway to accommodate multiple rescheduled departures (Figure 6). Therefore, disturbances in the morning tend to cause delays that die out before it gets busier in the afternoon. Busier airports have longer lasting rush hours or may even be full most of the daytime hours.

The largest airports in Europe (London Heathrow, Paris CdG, Frankfurt, Amsterdam Schiphol) have more hours with high capacity-utilization rates and hence unanticipated adverse weather can cause long lasting delays, as well as some cancellations, for the greater part of the day. Also, Copenhagen Kastrup airport tends to have less free capacity and according to the Eurocontrol data is more prone to delays than the other major Nordic airports (see Annex 3).

The other main element in analyzing the expected cost of delays and its reduction thanks to the extra data from EPS Sterna is the assessment to what extent less cases of unanticipated adverse winter weather will occur. This is based on the changes in the RMSE of various weather forecast variables as estimated in the various experiments conducted in Task 1 (Guedj et al 2023) and Task 2 (Rydberg et al 2023). The change in RMSE is translated into an approximate improvement of the measure of fitness (correlation coefficient), which in that case represents the forecast probability. We apply the Cost-Loss model framework to assess changes in first and second order errors, presuming that conditional and unconditional forecast probabilities are known. By multiplying the change by the climate average number of occasions with adverse weather conditions in the period October - April (source FMI data) one obtains an indication of the reduction number of surprises. This is explained in Annex 4. The expected change in better forecast events (i.e. less surprises) is estimated to include 50% of a larger and longer lasting event, affecting a significant part of the day, and two minor events, affecting only a few hours at best. In this case the complement mismatch, i.e. the fraction of precipitation events which is not realized but was forecast, changes by approximately the same amount as the mismatch of prime interest (i.e. not forecast but realized events). Reducing unforeseen precipitation events has the most significant cost reduction effects, but reduction of unnecessary warnings will also save at least in terms of preparedness costs. In the calculations we nevertheless focus on the reduction of unforeseen precipitation events.

All in all two sources of delay generation were identified in relation to untimely identification of adverse weather conditions, being:

A. adverse weather conditions implying the switch to a limited visibility regime* which limits runway capacity
B. adverse weather conditions necessitating the provision of de-icing services, yet without switching to a limited vision regime which limits runway capacity

*) ICAO (2016) distinguishes between Reduced Aerodrome Visibility Conditions (RAVC) and Low Visibility Procedures (LVP). The former refers to all (outside) operations on the aerodrome platform (both aircraft movements and ground services actions), whereas the latter refers to take-off and landing (and closely related actions). A moderate level of RAVC may exist without LVP being invoked. Option A means LVP is invoked. Option B means RAVC level 2 or 3 is invoked.

Ad. A. Low Visibility Conditions

Switching to limited visibility procedures (LVP) at major airports is normally announced well in advance. ICAO (2016) refers to at least 12 hours ahead. Yet, by way exception it can be implemented upon shorter notice, if inevitable, e.g. when the nowcast revises the forecast in a way that implies the announcement of LVP well within the 12 hour bound. This may be expected to create more delay over and above the delays that would generated by timely announced capacity restrictions.

Simulations have been conducted for different levels of LVP for the consecutive hours of an average day (in terms of number of departures). The delay effects per hour in Helsinki-Vantaa hover around 40 to 60 minutes and 60 to 90 for non-peak hours and between 400 and 1800 minutes for peak hours, depending on the severity of the capacity limitations. As the mismatch as meant under option A is expected to affect only a couple of hours the expected value of avoided delay thanks to EPS Sterna is quite moderate, being 480 minutes in the less strict LVP and 1220 minutes in the strict LVP, when using 3 hour moving averages. On top of these primary delays the reactionary delays should be accounted for. The average multiplier for reactionary delays is 1.8. Adding those delays to the aforementioned primary delays would result in approximately 900 and 2100 minutes. However, in the cost calculations the distribution of delay length is taken into account by using delay length differentiated multipliers.

Ad. B. Changes in De-icing Needs without Limited Visibility Conditions

A change in forecast that affects the need for de-icing service which is happening well beyond the 12 hour advance notice limit (i.e. being too late) entails high risks of insufficient de-icing capacity for a few hours up to a significant part of the day (6 ~8 hours). Simulations were made for de-icing service taking 10 and 15 minutes respectively, with 4 instead of 6 units available. With just a few hours of mismatch the expected volume of delays hovers between 800 and 2000 minutes depending on the strictness of the limitations. These figures represent the delay sum over all affected airplane departures. For example, as hypothetical example, there may be 50 departures involved in a delay sum of 2000 minutes, of which e.g. 20 departures incur approx. 20 minutes each, while 20 departures incur 45 minutes delay each, and 10 airplanes approx. 70 minutes. For higher impact weather forecast mismatches delays hover roughly between 2000 and 3500 minutes and even higher scores are possible. Just as for delay mechanism A, also in this case the reactionary delay multiplier (1.8 on average) is applied to the primary delays to obtain an overall delay sum.

Scaling up

Above, under cases A and B, the calculations for both types of delay mechanisms were explained for one event. The number of avoided events per winter period is however estimated at 50% of one more significant and two smaller (limited duration) events. The total expected primary and reactionary delay by case type and the associated monetized benefits for one airport are summarized in Table 3 and Table 4 respectively. For the conversion from minutes to Euros typical unit-cost per minute and reactionary delay multipliers as published in Cook and Tanner (2015) were used as basis, while counting for differentiation in the length of delay and associated unit-costs. Since 2015 costs for aviation have increased, notably of fuels, but also staffing and maintenance. Therefore, the unit-cost as published by Cook and Tanner was increased by 25%.

Table 3. Expected reduction in delays for Helsinki-Vantaa airport in minutes per year (by case type)

Helsinki-Vantaa	a few hours		significant part of the day	
	primary delay	primary & reactionary	primary delay	primary & reactionary
de-icing 10 min.	800	1320	2000	3880
de-icing 15 min.	2020	3840	3500	7000
de-icing 10 min. & LVP	1280	2110	3220	6250
de-icing 15 min. & LVP	2500	4750	4720	9440
expected value of change in total delay sum for one winter season	equivalent of 2 shorter and 0.5 longer event ~9300 minutes/year			

Table 4. The estimated monetized values of primary and reactionary delays by case type for Helsinki-Vantaa airport

Helsinki-Vantaa	a few hours		significant part of the day	
	primary delay	primary & reactionary	primary delay	primary & reactionary
de-icing 10 min.	33 036 €	104 267 €	54 510 €	202 278 €
de-icing 15 min.	134 325 €	255 090 €	255 218 €	510 181 €
de-icing 10 min. & LVP	78 636 €	220 167 €	129 750 €	427 124 €
de-icing 15 min. & LVP	179 925 €	370 990 €	341 858 €	741 981 €
expected value of change in total delay sum for one winter season	equivalent of 2 shorter and 0.5 longer event ~ € 710 000/year			

For upscaling towards Nordic totals we select the four largest airports in the Nordic countries and use Helsinki-Vantaa benefits as the basis, adapted for the number of flights of each airport. Copenhagen has approximately 70% more flights, Oslo approximately 60% more, and Stockholm about 50% more. Table 5 provides a summary of the benefits of delay reduction in money terms.

It is important to understand these overall cost estimates have a large uncertainty. For a start the degree of weather forecast mismatch will vary over the years, whereas there remains an uncertainty regarding the estimated size of increased accuracy of the weather forecast and nowcast. Therefore, the figures should be understood as estimated annual averages of a multi-year period. The periods of the day that avoided mismatches will vary and hence the number of potentially affected flights can vary considerably depending on whether it concerns busy or silent hours at an airport. The actual delay propagation on an airport has also erratic components, and is less mechanistic as – of necessity – simulated in the calculations. Finally, the use of estimated standardized unit-cost for 'pricing' delay minutes is also an inevitable simplification of how actual costs can work out. For these reasons also a value range has been added, which represents on the one hand shorter duration cases combined with 10-minute deicing times and on the other hand longer duration cases with more peak hours combined with 15-minute deicing times.

The unit-cost parameters from Cook and Tanner refer only the costs for the civil aviation sector and does not explicitly include the value of (lost) travel time for travelers, even though compensation and care cost for airlines regarding travelers with significant delays are included. We apply the typical practice from transport to value travel time based on (a fraction of) hourly wage rates of travelers. In this case we assume a net (post tax) wage rate of € 20 per hour, which is based on hourly wage rates in Nordic countries, while assuming that the wage rate of the average air traveler is somewhat above the national average. The care and compensation, which a part of the delayed passengers receives, does overlap somewhat (~25%) with the value of lost travel time.

Inclusion of smaller airports in Nordic countries may increase the benefits by about 10% to 20%. During the interviews was emphasized that systematic predictability improvements, also small ones, may incite small changes in operations and their planning. Cumulative effects of small changes may lead to more significant changes. For example, it may invite new flight connections to an airport from airlines that hitherto regarded the schedule deviation risks too large compared to the expected net revenues.

Table 5. Estimated values of delay reduction per year per airport

Nordic major airports	**value of reduced direct + reactionary delay in € per year**		**value of reduced travel time loss (to travelers) in €/year**
	expected value	**range (x 1000)**	**expected value**
Copenhagen Kastrup	€ 1 208 000	€ 526 ~ € 1892	€ 316 200
Helsinki-Vantaa	€ 710 000	€ 309 ~ € 1112	€ 186 000
Oslo Gardermoen	€ 1 137 000	€ 495 ~ € 1780	€ 297 600
Stockholm Arlanda	€ 1 065 000	€ 464 ~ € 1669	€ 279 000
TOTAL	**€ 4 120 000**	**€ 1796 ~ € 6455**	**€ 1 078 000**

The expected value of reduced delay cost refers in the first place to benefits for the airline companies. The expected value of reduced travel time loss for passengers refers the benefits for citizens from different countries. Considering that a significant number of flights is between Nordic destinations, it seems likely that about 65% of the benefits of reduced travel time loss remains within the Nordic countries. In order to obtain the aggregate social benefit for the Nordic countries the values cannot just be added, due to the overlap related to paid compensations (25% assumed) and due to the 'leakage' of reduced travel time losses and compensations paid by airlines to non-Nordic passengers. All in all, this would mean that about 4.6 million € expected value remains in the Nordic countries and approximately 0.6 million € would go elsewhere, mainly the rest of Europe.

4.3. Electricity production – wind power sensitivity to icing

In Nordic countries weather conditions affect both production and consumption of electricity. Wind speed and solar radiation have immediate impacts on power production. Precipitation affects hydro power with a certain time lag, while snow and ice have immediate and to a varying extent lasting effects on wind and solar energy. Temperature affects in particular consumption of electricity, while these effects can be moderated (heat) or aggravated (cold) by wind. Deeper freezing temperatures (< -10 ^{o}C) may affect wind energy and transmission capacity.

The increasing share of renewable energy sources in the Nordic generation mix, notably through the growth of wind and solar, boosts the sensitivity of the electricity markets with respect to weather conditions. The large output variability of these power sources remains a key problem for managing electricity systems, and the implications of multi-day to multi-year variability are still not fully understood. In recent years various studies indicated that increasing shares of renewables tend to increase the volatility of the wholesale power market price formation (e.g. Staffell & Pfenninger 2018; Spodniak et al 2021). However, as also discussed in Spodniak et al (2021) not all studies have such results. Possibly, one reason for this is that several studies were conducted in years (say before 2017) when the share of wind power in the total production mix was not large enough for clearly detectable effects.

An antidote to the growing price volatility due to higher shares of weather dependent generation capacity is more and better weather and seasonal forecasts. Weather forecasts are one of the input sources for planning electricity production, trade and demand responses to changes in the weather. Roulston et al. (2003) evaluated the benefits of weather information to optimize wind power production and found that profits doubled when using 1 and 2-day forecasts. On the basis of interviews with operational meteorologists and with wind power generation and electricity trading experts it was decided to focus in this study on possible effects of the extra EPS Sterna data via the NWP and the resulting forecasts on the ability to better anticipate icing risks and hoar frost risks for wind turbines. These phenomena can reduce the output of affected wind turbines by 20% to 40%. Better anticipation of the occurrence probability of these conditions promotes a smoother and hence more efficient functioning of the wholesale electricity market, in this case in particular in the Nordic countries (Nordpool see also Text box 1).

4.3.1 Wind Power – Production and Trade

When considering wind energy-based electricity production it's obvious that the weather has a big influence on how much energy is produced - the higher the windspeed, the more energy can be produced, until the windspeed attains levels that may damage a wind turbine, in which case wind turbine blades are turned away from the airflow. In fact, the energy contained in the air flux relates to the third power of the wind speed. In short, the energy per unit of time (power) is formulated as: $P = C_p . \pi r^2 . \rho . V^3$, where Cp is the conversion efficiency of the wind turbine, r is the radius (blade length), ρ denotes the air density, and V wind speed. This cubic relation between wind speed and eventual electricity production has consequences for how wind speed accuracy affects wind power production forecast accuracy.

Also icing, as undercooled water, snow or frost on the blades, affects the production of wind turbines. The reduction effect can go up to 40% of the production capacity of affected wind turbines. The icy layers on the blades cause imbalance and hence tend to precipitate wear and tear of the wind turbine. Furthermore, there are physical risks to third parties when icy lumps depart from the blades, while these are revolving. A part of the wind turbines in the Nordic countries is fitted with de-icing facilities, which however consume electricity and hence net output of the wind turbine reduces. If a high icing risk is forecast or significant icing is observed, a wind turbine may also be stopped for some time to avoid both acute damage and precipitated wear and tear.

As regards the benefits of Sterna for optimizing wind power production on the basis of OSSE results of Task 1 (Guedj et al 2023) we assume that these concentrate on (1) improved accuracy of lower atmosphere humidity and temperature forecasts, which associates with the icing risks for wind turbines, and (2) somewhat improved accuracy of wind speed forecasts. The experiments for nowcasting in Task 2 (Rydberg et al 2023) indicate that the RMSE for nowcasting precipitation in the next four hours could reduce by 5% to 20%. The higher scores refer here to summer conditions, while for the winter period the reduction is between 5% and 10%.

When considering (improvements of) the accuracy of forecasts of weather variables in relation to wind energy it is important to realize that the propagation of the meteorological accuracy effects runs via *a compound effect on the wind power production forecast* to some extent supplemented by effects on production forecasts of other generation as well as consumption forecasts (Figure 5). Furthermore, the eventual effects on wholesale electricity prices in the Nordpool area[2] during a certain period of a particular day will depend on the utilisation rate of the (effective) generation capacity and its constituent elements and of the transmission capacity within and between countries during that period. When utilization rates of the generation capacity are low, such as on Sunday morning, forecast errors have less effect on prices. When utilization rates are high, e.g. on the morning of a working day in winter, maybe exacerbated by low effective capacities (e.g. no wind or low hydro levels), forecast errors can cause strong price variations.

[2] See Text Box 1 for a brief description of the Nordic electricity market.

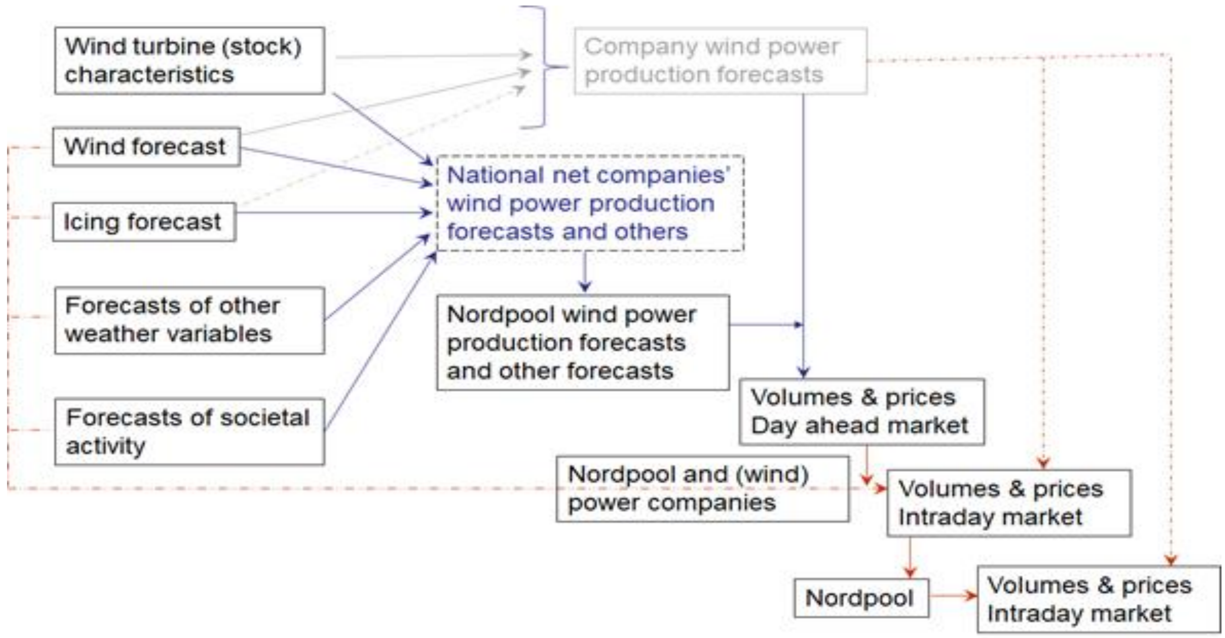


Figure 5. Causal flow chart of weather and wind production forecast error propagation and correction in the electricity market

The occurrence of the forecast errors for two different months in the Nordpool electricity market system is illustrated in Figure 6. On the left-hand side there is a persistent overestimation (difference between blue, black and yellow curve) occurring in the last week of November related to icing issues. On the right-hand side is the situation illustrated for the end of March 2023 where during a few episodes significant wind speed changes were projected with delay, causing more important mismatches. The two graphs also reflect the rapid growth of the wind power capacity (the upper blue straight line in the graphs), being 500 to 700 MW higher in March 2023, as compared to November 2022. The installed capacity also increases in both months.

Figure 6. Forecast and realized wind power production (MWh/h) in Finland in November 2022 and March 2023 source: Fingrid data portal. The bule curve represents the day-ahead forecast wind power production and the black curve the realized production, and the yellow curve the continuously updated wind power forecast (down to 1 hour ahead).

Text box 1. The Nordic electricity market in a nutshell

The Nordic electricity market in a nutshell

Norway, Sweden, Finland and Denmark cooperate closely in terms of planning and operation of generation capacity and high-voltage transmission capacity in the Nordic regional coordination centre of ENTSO-E (the European umbrella organization of transmission companies).

In addition, the bulk of the electricity generation traded in the Nordic and Baltic countries is handled through the Nordpool power exchange. In addition, power companies from the UK, the Benelux, Germany and France do also trade on Nordpool.

For the purpose of this study three closely related electricity sub-markets in Nordpool are relevant, being the Day ahead market (DA), the Intraday market (ID), and the Regulating power market (RP).

At the latest at 12pm of the preceding day power companies submit their offers for 24 consecutive hours of the next day, each offer states the production volume (MWh in hour X) and price (€/MWh). These offers per hour are ordered by price level (low to high) and matched with forecast demand for that hour. The demand forecasts and wind power forecasts by the national network companies of the Nordic countries. These national demand forecasts use weather forecasts alongside other data. Many electricity producers also produce private (not shared) forecasts of at least of their own production, and to a varying extent also of total production and consumption, so as to better understand price pressures in the market and possible actions of competing producers.

The day ahead production forecasts of wind power and neither the consumption forecasts are highly accurate. This means that original matching of hourly supply and demand for electricity does not hold when the day unfolds. For this corrective purpose, functions the Intraday market where a secondary bidding takes place to correct the scheduled production of the Day ahead market. Eventually in the last hour usually smaller mismatches are handled via the Regulating power market, where the regulator auctions production up or down to the required level. It should be noted that for the latter two markets producers may also make use of load management contracts with their clients (large industries and regional distribution companies), thereby adapting consumption rather than production in a certain hour.

The share of wind power in the total generation capacity is growing and is already substantial in Denmark, Sweden and Finland (> 20% of generation capacity). This reinforces price effects of forecast errors. It should be noted that there are ever more electricity users – small, medium and large – which have own – often renewable – production capacity, while their electricity contract is based on momentary prices in Nordpool. This means that the responsiveness in the overall power system gets ever more complex and probably the need for forecasts, including the use of weather information, is ever more spreading and contributes to sophistication of the system (smart power nets).

4.3.2 Estimation of the benefits of Sterna induced forecast improvements

The current accuracy for day ahead forecasts of precipitation events hovers between 75% and 80% at resolutions of 2.5 km. The simulated approximate percentual reductions of the RMSEs for humidity and zonal wind (Guedj et al 2023) are 5%~6% in the first three to six hours of the forecast. After which these gradually decrease, with some variation by altitude (table 5). This translates into improvements of forecast accuracy of precipitation (and temperature) of about 2%-points. The other experiment by Rydberg et al (2023) suggests that somewhat higher scores may be possible for precipitation forecasts, at least for the first four hours. In addition, for both experiments is emphasized that the feedback of the considered extra observations and consequent forecasting improvements into the global model is not taken into consideration. Inclusion of the feedback is expected to result in further – modest – improvements in accuracy of selected weather variables in the Nordic area.

Table 6 Simulated percentual reductions in RMSE by forecast hour for day ahead forecasts of selected weather variables (based on Guedj et al 2023)

	1	**2**	**3**	**4**	**5**	**6**	**12**	**24**
precipitation accuracy	6 %	6 %	6 %	6 %	6 %	6 %	6 %	3 %
wind speed accuracy	5 %	5 %	5 %	4 %	4 %	3 %	2 %	0 %

Even if the changes in RMSE of meteorological forecasts imply better meteorological forecasts for precipitation, temperature and wind speed, these do not necessarily translate one to one to accuracy scores of hourly wind power production forecasts. As is explained above (Figure 5) there are more factors affecting the accuracy of matching hourly supply and demand of electricity, with their own uncertainties, some of which related to weather. Furthermore, production estimations of wind power are subject to heteroskedasticity[3], hence especially if larger amounts of wind energy are traded forecast uncertainty is somewhat larger. These considerations hint at lower reductions of the RMSE of wind energy forecasts. However, with respect to the occurrence of icing the meteorological forecast improvement may have a relative strong effect on the management of that risk, which suggests that at least for the winter months, the reduction of the RMSE of the wind power production forecast may even be somewhat stronger than that at the meteorological side. Therefore, we will apply a more cautious benefit estimate and an estimate in which a stronger reduction of the RMSE of the wind power production forecast is assumed.

The consequence of a lower RMSE for the wind energy production forecast means a reduction in the use of the Intraday market and the Regulating power market. The use of these corrective markets can be understood as paying (or receiving) a premium for adjustment. Spodniak et al (2021) found that an error of 1 standard deviation in the wind *power* forecast causes 0.1 ~ 0.3

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[3] Heteroskedasticity refers to the phenomenon where the average deviations between estimates and observations increase with increasing values of the observations. As a consequence, estimated functions exhibit increasing uncertainty for increasing values.

€/MWh change in the price spread between Day ahead market and Intraday market and around 0.5 €/MWh for the price spread between the Intraday market and the Regulating power market. One standard deviation in wind power forecast amounted to 80 ~ 100 MWh/h for most trade areas. These results were based on electricity market data for 2015–2017. In the meantime, the share of wind power has grown substantially in Sweden and Finland, and hence price responsiveness may have increased. Jantunen (2023) assessed the period 2019–June 2022 and found indeed a growing impact. Figure 7 shows the price spread observations for 2021 (L) and the first half of 2022 (R) and the associated regression lines. Jantunen's analysis indicates that a forecast error of 100 MW has in recent years an *average* price effect of approximately 2.5 to 3.5 Euro per MWh. There may be other reasons for the tenfold difference between Jantunen and Spodniak et al related to filtering in the estimations and differentiated price elasticities by type of generation power, but the growth of the wind power capacity does certainly play a role. For this study we will assume a price effect of € 3 per MWh for 1 standard deviation or 100 MW forecast error.

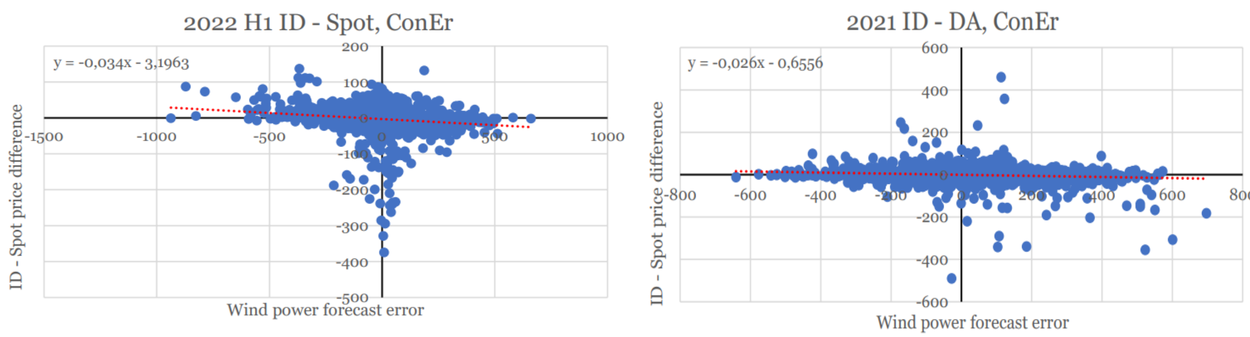

Figure 7. Relation between wind power forecast error and price difference between day ahead market and intraday market in 2022 (R) and 2021 (L) after filtering for hours with large consumption forecast errors; source: Jantunen, 2023.

For the entire Nordic market area (No, Swe, Fin, Dk) the Intraday market volume is about 2% of the Day ahead market at annual level. Jantunen (2023) finds for wind power production forecast errors a share of 18% in Finland. Hence, wind power forecast error correction is an important element of the Intraday market. Based on the analysis of Jantunen combined with Nordpool data we can infer that on annual basis approximately 40% of the Intraday market in Finland is related to wind power forecast error corrections. We assume the same percentage for the entire Nordic market area. In recent years the Intraday annual volume was approximately 6.6 million MWh, of which 40% amounts to about 2.6 million MWh (= 0.26 TWh). If the EPS Sterna would enable the elimination for the wind power forecast error driven share of the Intraday market the benefits amount to the amounts summarized in Table 7. Estimated annual benefits for wind power forecast error reduction in million €As indicated by Staffell & Pfenninger (2018) renewable generation variability is expected to increase in relation its growing share and effects of climate change, whereas overall electricity production is expected to increase. These notions indicate a quite high likelihood that the annual benefits enabled by EPS Sterna will increase steadily.

Table 7. Estimated annual benefits for wind power forecast error reduction in million €; prices are in €/MWh

	reduction of the Intraday market volume	price effect	Average Intraday price	benefit of less corrective trade (for wind turbine owners)	benefit of price reduction (for customers)
Optimist	-10%; 0.26 TWh	3 €	€ 70	2.6 10^5 . (70-3) = 17.4 mln €	€3 . 6.6 10^6 = 19.8 mln €
Cautious	-5%; 0.13 TWh	1.5 €	€ 70	1.3 10^5 . (70-1.5) = 8.9 mln €	€1.50 6.6 10^6 = 9.9 mln €

The benefit of less corrective trade refers to the owners wind turbines, which at the same time means that some other producers, who sold from surplus capacity, lose the same amount. On the other hand the benefit of price reduction refers to the customers (distribution companies), and could in principle benefit society at large.

Limitations

The above calculations about the benefits for wind power production and use have left several elements outside. Firstly, from the interviews was inferred that better anticipation of icing on wind turbines can help to reduce wear and tear and maintenance costs. It goes well beyond the remit of this study to try to quantify these benefits. Furthermore, electricity production is growing as the energy transformation entails a move towards more electricity-based applications in industry and transport (e.g. Andersen et al 2022). This swells the benefits of slightly lower prices. This effect will be tentatively included in the overview of upscaling in chapter 5. Finally, lower unit-cost of electricity, even small decrements, tend to have induced economic effects in the economy.

4.3.3 Solar power

The production of solar energy depends on the amount of solar radiation, which varies according to time of day, cloud cover, seasonal variation in solar declination, and possible snow cover and albedo effects in wintertime. Although the production of solar energy in the Nordic countries is still fairly small, its importance will grow substantially during the current decade. This means that also for solar power dedicated weather forecasts will be needed in the Nordic countries. Especially the speed of change in cloud cover and the pace of snowmelt and snow build-up in spring and autumn may be hard to forecast at local and regional level leading to significant over- or underestimation of solar production potential at hourly level in e.g. the next 24 hours. Therefore, it is not out of the question that the EPS Sterna data can also engender benefits for this type of power generation. Yet, it requires additional research, both in natural science and economics, before a benefit analysis can be conducted for solar power.

4.4. Transport and Road clearance

Interviews with the FMI's contact person to the DESTIA road management company in Finland pointed out that satellite data is mainly used to assess the need and best timing for salting. Observation of low clouds and breaking-up of cloud covers, as well as observation of clouds' microphysics for the delineation of freezing drizzle are relevant for judging possible changes in slipperiness. Salting is needed (or may be earlier needed than expected) in winter when the cloud cover opens or when there occurs consecutively a shower and a quickly clearing sky. Since next to the use of the current weather forecast and nowcast an extensive network of roadside sensors provides input as well to the slipperiness forecasts, it is not expected that the effect of data improvement from EPS Sterna via the NWP system would supersede the other data sources. However, there might be interest in a visualized version of the Sterna satellite output as a direct additional information source. The road management company (DESTIA) uses already one satellite product. The interpretation of satellite images in the sense of supplementing other information and possibly revising decisions is however challenging. An additional or substitute satellite-based visualization service would need to be very user-friendly. Furthermore, according to interviewed meteorologists of FMI, the resolution of satellite information should be in the order of kilometers to make a difference. Given the current state of affairs we decided that there is at the moment not a sufficient basis for a useful valuation regarding road clearing and salting.

DESTIA's resources and the time window for interpreting additional information are tight, since road clearing and salting mainly takes place before dawn and the morning rush hour and in the evening after the rush hour. Post-processed data e.g., a ready-made interpretation of different cloud classes that clearly states different cloud temperatures, composition and altitudes, would save time and resources for operational meteorologists. These kinds of post-processing models are already used in some meteorological application areas. Better and more accurate road temperature prediction and behavior (over 400 road weather observation stations are also used for plowing needs) would help to determine the need for plowing and salting for the next morning.

4.4. The building sector

Proper planning in the building sector does account for some amount of adverse weather conditions that can cause postponements of various activities (Etula 2013). Nonetheless, adverse weather has its shadow cost in the building sector. On the one hand the workforce present on a site, while work is not possible or useful due to weather conditions, has opportunity cost as they may have been able to work gainfully on another building site. Furthermore, a delay of one or two days may reverberate through the remaining schedule for weeks (Vesterinen 2019), which translates into extra cost of rented or duplicate machinery, longer lasting insurances, etc. and perhaps postponed reception of instalments from the project investor. On the other hand, a weather induced postponement of a building activity may sometimes result in delayed final delivery to the extent that it invokes penalties for being overdue. Usually such penalties are substantial (i.e. expressed as percent-points of the agreed construction price). Weather induced delays that lead to overdue delivery are however rare, among others because builders tend to increase efforts to avoid penalties.

Etula (2013) calculates for the Finnish building sector an excess cost of approximately 10000 Euro for a smallish project (4 terraced houses) when starting in November instead of May. Yet, that approximation may not capture all capital cost effects. At a certain point of time within one region (province) there are hundreds or even thousands of projects going on, which will however not be equally sensitive to adverse weather and be of different sizes. Applying the changes in predictability from the aviation case would mean the building sector would be enabled to minimize rescheduling cost twice during one winter in one or several provinces. Assuming that two rescheduling occasions for one project add another 5000 Euro to the excess winter cost, the benefit potential of EPS Sterna for the Finnish building sector may amount to *one million Euro per year*. Yet, realization of such a potential may be expected to require post-processing and customization of forecasts to arrive at a substantial utilization of the potential. Annual variations in potential can also be large, not only due to climate variations, but also due to the strong business cycle sensitivity of the building sector. The suggested crude estimate gives only an idea of the order of magnitude, while it is not the product of a more thorough analysis as was done for aviation and wind power.

5. A synthesis of the findings

As already mentioned in the Introduction chapter and repeated later on, the analyses conducted in this report are *exploratory* and provide insights on benefits of *selected applications in selected sectors*. Even though these applications are relatively significant within the total portfolio of possible applications, the estimated benefit potential represents only a fraction of the total benefit potential. There are other benefit potentials within these sectors, such as optimal routing for aviation and optimal solar power planning for electricity generation. Furthermore, these predictability improvements and associated economic benefits may incite further service and product development engendering additional benefits. A case in point is the decrease in buffer time that airline companies build into their schedules. A general improvement of predictability creates the opportunity to reduce buffer time somewhat. This in turn would enable the increase of the capital productivity of aviation.

As briefly sketched in chapter 4 there are also other sectors in the Nordic countries that can benefit from EPS Sterna, either via the improvement of the NWP based forecasts or nowcasts or via direct visualization applications, such as was mentioned for salting and road clearing. It can be expected that improvement in forecasts enabled by EPS Sterna will be beneficial for the building sector, tourism, outdoor leisure activities and sports (as events and as citizens' free time activity), agriculture, and operational management of roads and rail, public transport, and logistics.

Tables 7 and 8 provide an overview of the indicative upscaling of the initially found values, which refer to current or recent past years. The upscaling accounts for growth effects in case of electricity. For aviation is assumed that due to climate policies no significant growth will take place, counting from the 2018/2019 levels. The upscaling also accounts for not included elements, such as avoided delays on other Nordic airports, such as Billund, Gothenburg, Bergen, Trondheim, and Rovaniemi, and extension of benefits to the rest of Europe in the case of aviation. Some extensions are mentioned, even though no figure could be added for those.

Table 8. Tentative indications for economic impact upscaling for aviation

	Nordic aviation		
	impact	approx. amount (mln. €)	comments
1	delay cost to aviation sector	4.1	uncertainty range +/- 50%
2	+ travel time loss for passengers	1.1 (-0.27)	uncertainty range +/- 50% (deduction is for overlap)
3	+ adding other Nordic airports (+15%)	0.7	guestimate
4	+ adding routing benefits (all planes; fuel!)	?	stronger fuel save effect; mainly relevant for first and last section of the trip
5	+ adding benefits for rest of Europe	>7 ?	overall probably a larger effect than Nordic only
6	+ accounting for global model feedback	≥2?	sum of rows [1,2,3,5] above ~13* 0.15
7	+ further innovation effects	?	initially quite modest
	Overall upscaled benefit indication	≥ 15	

Table 9. Tentative indications for economic impact upscaling for electricity generation

	Nordic electricity		
	impact	approx. amount (mln. Euro)	comments
1	wind power matching improvement	15	median between low and high estimate
2	+ growth effect of power production	~5.7 (by 2040)	growth 1.8%/y until 2040*
3	+ adding services for solar power	?	order of magnitude may be similar to benefits for wind power
4	+ adding services for demand side management (DSM)	?	interacts with the above benefits
5	+ adding benefits for the rest of Europe (solar & DSM)	?	Probably higher value than that for the Nordic countries
6	+ accounting for global model feedback	≥6?	this further improves the forecast accuracy in the Nordic area and beyond; assumption: sum of rows above (27.5 + 11 +..) * 0.15
	Overall upscaled benefit indication	≥ 27	

*) Nordic Energy Scenario (Wråke et al 2021)

Based on the above indicative figures a crude estimate over the lifetime can be provided. A lifetime of 12 years is assumed, running from 2029 to the end of 2040.

- When using only base year level benefit estimate, the undiscounted benefits would amount to: (5 + 15) x 12 = 240 million €
- When the maximum values are inserted for the two sectors, the undiscounted benefits would amount to:
  $15 * 12 + \sum_{i=7}^{18} 1.018^{i} * 21 = 180 + 315$ = 495 million €

It should be realized that these benefits only refer to the use of the information in two sectors, and even for those some effects are not yet quantified, such as ‘en route’ efficiency gains for aviation and better market matching benefits for solar power at the Nordpool power market.

Furthermore, it was already illustrated that the building sector can probably also benefit, provided the concerned weather forecast information is more tailored and promoted for this user group. Also tourism, urban management and other sectors may be able to benefit, but would probably need an effort in terms of tailoring of the forecasts. More advanced integration into various types of management systems, such as electricity demand management of buildings and building blocks and integrated logistic planning and operation systems may also occur in the future. In this respect one can refer to, among others, the smart city developments (Tang et al 2022; Bibri 2019), notably in relation to so-called Integrated Urban Services (IUS; Baklanov et al 2020). Further innovation in visualization of satellite information may also help to find a broader scope of uses and users.

Especially if the use of the information is taken up more broadly and accompanied by service innovations, it can also engender a modest, but nonetheless relevant induced macroeconomic effect, as efficiency improvement options and new applications spread through the economy, such as was sketched in the study by Moretta et al (2023). All things considered, while acknowledging the caution of having only indicative partial results, the findings in this study seem to accord with the finding of the review study by London Economics (2015), cited in chapter of this report, that for satellites with this kind of application domains a benefit-cost ratio of 2 ~ 4 seems what may be expected.

Limitations and prospects

This study is an endeavour in creating bottom-up evidence on the benefit potential of a satellite constellation by actually reviewing the benefit generation mechanisms in particular contexts. Such an assessment tends to require unusual combinations of data, not publicly available data, a balanced reduction of complexity, and an understanding of the involved uncertainties. Of necessity the study had limited resources and should therefore regarded as indicative at best. It invites to collect more data on responsiveness and possible contextual limitations on responsiveness of the systems considered, and to better account for uncertainty and variability both regarding the onset of disruptions *and* the responsiveness (return to equilibrium) of the systems considered.

As regards uncertainties one should realize that are uncertainties both regarding the timing and intensity of forecast weather conditions, the initial conditions of the affected systems (notably the momentary capacity utilization), and the momentary capability of the system to respond adequately. The latter two dimensions can be further decomposed in endogenous and exogenous technical and human factors, related to maintenance cycles, staffing issues, physical or informational access, etc. etc. a thorough study would design a set-up in which all these dimensions could assume varying conditions leading to a large number of simulations.

Another consideration is that the comparison was – understandably – focused on the choice of an extra satellite constellation vs. none. In principle, it may be valuable to assess whether the baseline, i.e. societal development without EPS Sterna, equals to ‘nothing else in place’. It is not out of the question that in situ observation is expanding whereas its unit-cost are going down. Perhaps some of the sectors may decide that own mini-satellites serve their needs better, if only because data are less shared which may create more competitive edge (but not necessarily more social benefit). Important changes in technical processes of various sectors, e.g. the building sector, may make them less sensitive to weather, and hence the information value of better weather forecasts would be diminishing in that case. On the other hand, various informational service and technology innovations may also lead to still better use of the extra information from EPS Sterna. In that case there could be alternative scenario baselines.

All in all, this report has illustrated that application specific value chain-based analysis is feasible and gives insight in the order of magnitude of the benefits and the associated sensitivities. It invites to extend and revise the study over time. Over time a library of assessments and assessment results can be created, which will enable the improvement of the efficiency and confidence of conducting CBAs of satellite services, inter alia thanks to benefit transfer approaches.

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Annex 1 Description of Task 3: Socio-Economic Assessment of EPS Sterna at high latitudes

In Task3, the socio-economic impact of the AWS Constellation for high latitude regions and the Arctic should be assessed considering the output of Task 1 and Task 2. The assessment includes the expected socioeconomic benefit of a more frequent sampling of microwave sounding information - consistent with the selected AWS scenarios and spectral channels. This assessment can take the form of a case study (or various case studies), or consider any other method deemed necessary.

In case sufficient data can be collected about the differential effect of the enhanced information input on:

(a) quality characteristics of short-term forecasting services and

(b) benefits for end-users of such services attributable to the differential effect,

a more thorough quantitative analysis of the socioeconomic benefits will be possible. The choice of the method(s) will depend on the character and completeness of available data and the nature of the differential effect on users' decisions and operations. The selection of the method and the consequences of the choice will be discussed with EUMETSAT in cooperation with OSSE study partners SMHI and MetNorway during the early stages of the project.

Task#3 shall cover the following actions:

A. Summary of earlier comparable studies, with special emphasis on (1) the description of benefit engendering differential information effects, (2) methods employed, and (3) results obtained;
B. Identification and comparison of applicable evaluation methods, given the summary from action A, the expected types of information from Tasks 1 and 2, and the preliminary selected use options of the improved weather information;
C. Conceptual design of the valuation analysis, allowing for different levels of quantitative vs. qualitative valuation of the selected uses, and including interviews and possibly other elicitation methods necessary to underpin the design;
D. Realization of the valuations of the selected uses, with the best method(s) feasible given the data and resources available; different uses may be assessed by different methods.

Annex 2. Representation of rescheduling

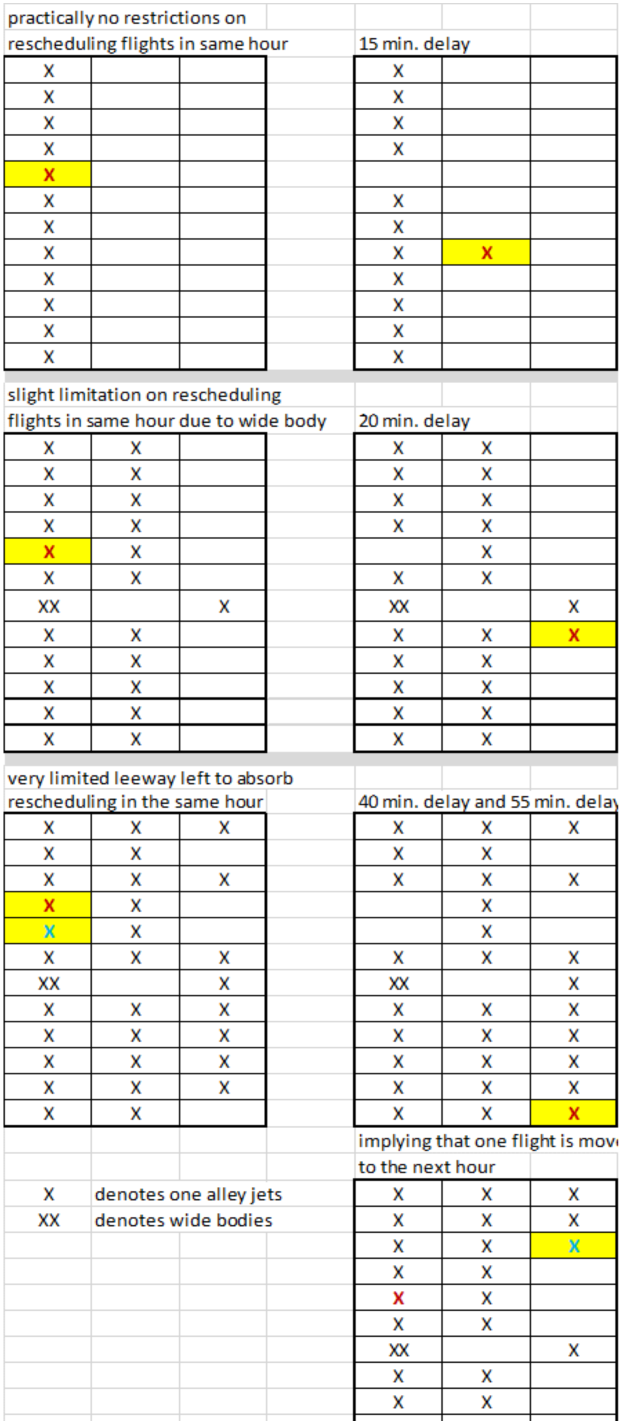


Figure 8. *Stylized representation of departure rescheduling effects on delays at different capacity utilization rates*

Helsinki-Vantaa airport operates usually with a runway for landing and another one for take-off. Other configurations are possible, but for simplicity we apply just one. An hour is divided in 5-minutes time slots during which three designated airplanes can take off. However, if such a 5-minutes time slot contains the take-off of a wide body aircraft usually only aircraft fit in such a slot. This means that under normal conditions at most 36 aircraft can depart in one hour. Under a limited visibility regime extra spatial and temporal distance is maintained and hence the departure capacity gets reduced. In this case it is assumed that the capacity gets reduced to 24 (standard) planes per hour. In the calculations we apply a minimum delay effect of 10 minutes for all airplanes in the affected period of the day.

In the top row of Figure 10 is shown that at a low utilization rate (=< 33%) rescheduling, even of various consecutively scheduled departures, will mostly not cause much extra delay, as there will be practically always another nearby slot available. In the next example, utilization has risen to about 67%, which is about the level where rescheduling may entail somewhat growing delays. Yet, if there are only occasional delays, the rescheduling can still be absorbed without enormous expansion of delay times.

The last example shows what happens when a high utilization level is reached (here ~92%). Two rescheduled departures entail doubling to tripling of the original 15~20 minutes delays, while in this example there is no switch to a limited visibility regime. In case of unexpected adverse weather starting ahead of rush hour periods part of the flights can experiences hours of delays, depending on slot reallocation protocols.

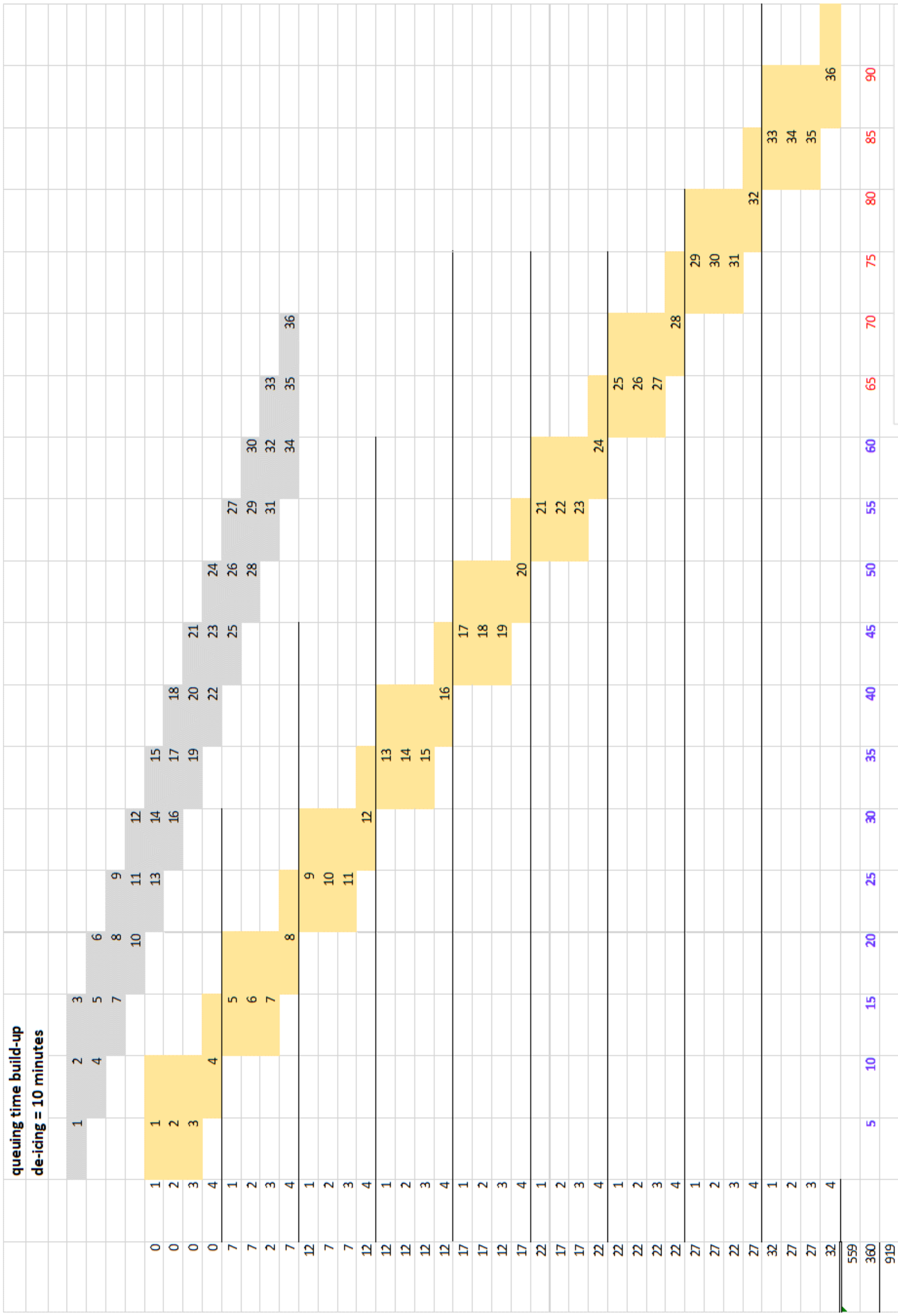


Figure 9. Delay build-up in minutes when original 36 departures spread over 5 min. triplet slots in 1 hour are served by 4 (instead of 6) deicing team using 10 min per (single aisle) airplane.

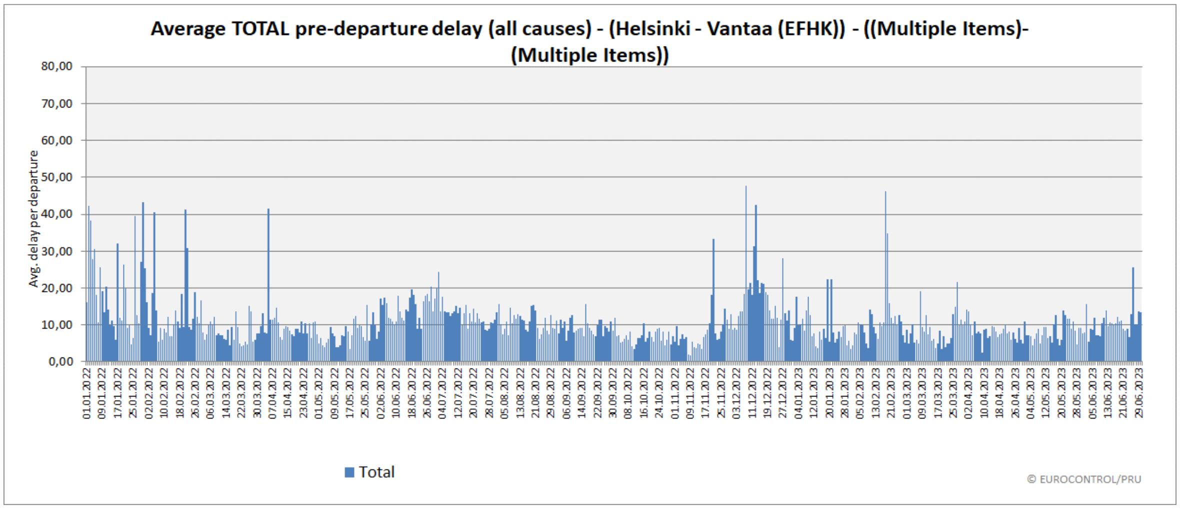
Moderated regime

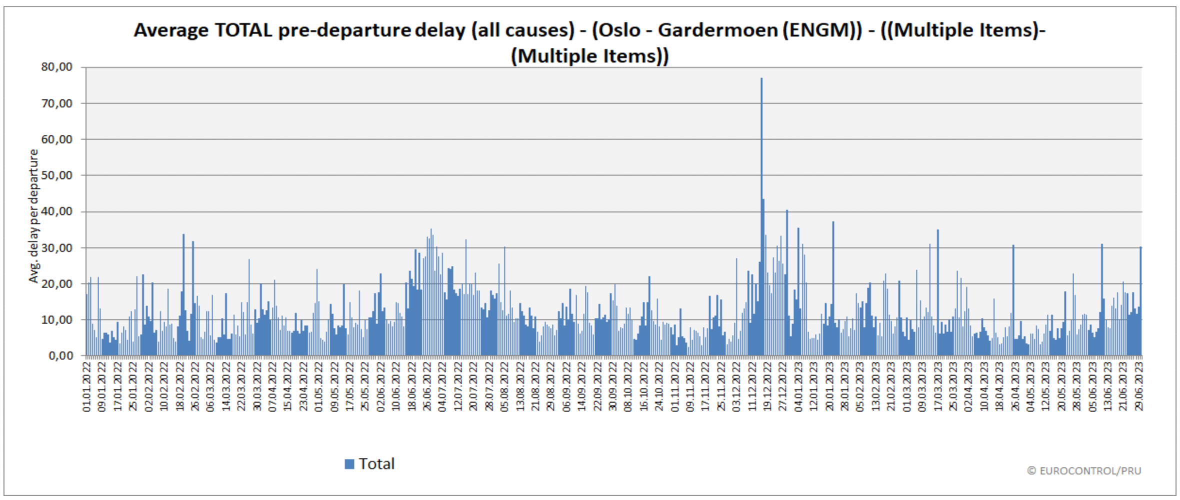
clock hour	average scheduled departures	full capacity	MLN incl widebodies	LVP incl. wide bodies	basic delays for all 10	5	A	E(DA)		E(DRA)	<15 min 29 €	~30 min 43 €	~90 min 91 €
0-6	4	36	30	24									
6	13	36	30	24	130	65	0	0	65	32,5	3 770 €	0	0
7	35	36	30	24	350	175	5	450	625	987,5	10 150 €	0	40 950 €
8	13	36	30	24	130	65	2	60	125	32,5	3 770 €	2580	
9	12	36	30	24	120	60	1	30	90	30	3 480 €	1290	
10	5	36	30	24	50	25	1	30	55	12,5	1 450 €	1290	
11	9	36	30	24	90	45	1	30	75	22,5	2 610 €	1290	
12	15	36	28	22	150	75	1	30	105	37,5	4 350 €	1290	
13	8	36	28	22	80	40	0	0	40	20	2 320 €	0	
14	6	36	30	24	60	30	0	0	30	15	1 740 €	0	
15	15	36	30	24	150	75	0	0	75	37,5	4 350 €	0	
16	40	36	28	22	400	200	10	600	800	1060	11 600 €	0	54 600 €
17	26	36	24	18	260	130	6	360	490	641	7 540 €	0	32 760 €
18	9	36	24	18	90	45	1	30	75	22,5	2 610 €	1290	
19	11	36	28	22	110	55	0	0	55	27,5	3 190 €	0	
20	10	36	30	24	100	50	0	0	50	25	2 900 €	0	
21	8	36	30	24	80	40	0	0	40	20	2 320 €	0	
22	2	36	30	24	20	10	0	0	10	5	580 €	0	
23	7	36	30	24	70	35	0	0	35	17,5	2 030 €	0	
	248				**2440**	**1220**		**1620**	**2840**	**3046**	**70 760 €**	**9 030 €**	**128 310 €**

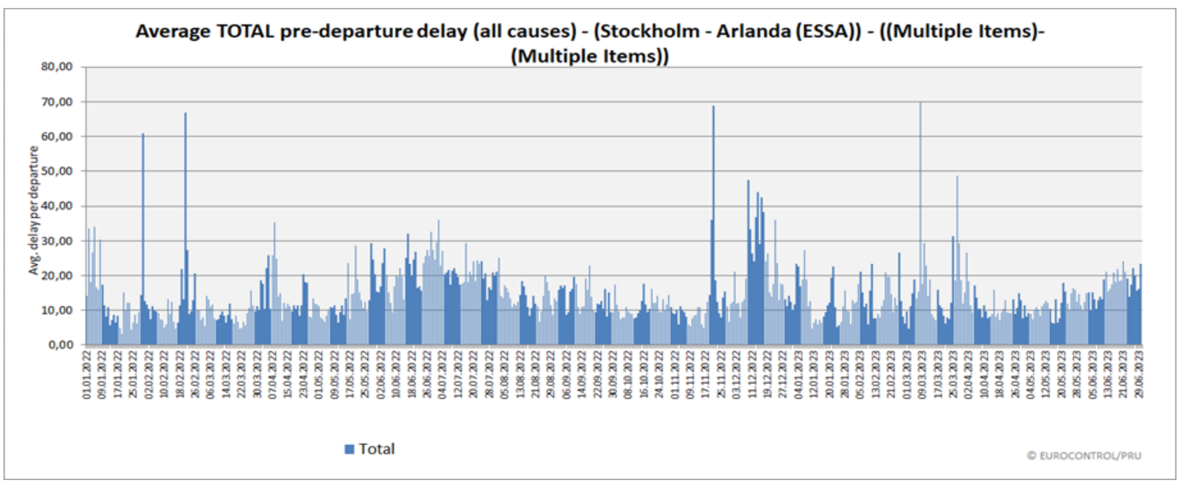
Limited Visibility Protocol in use

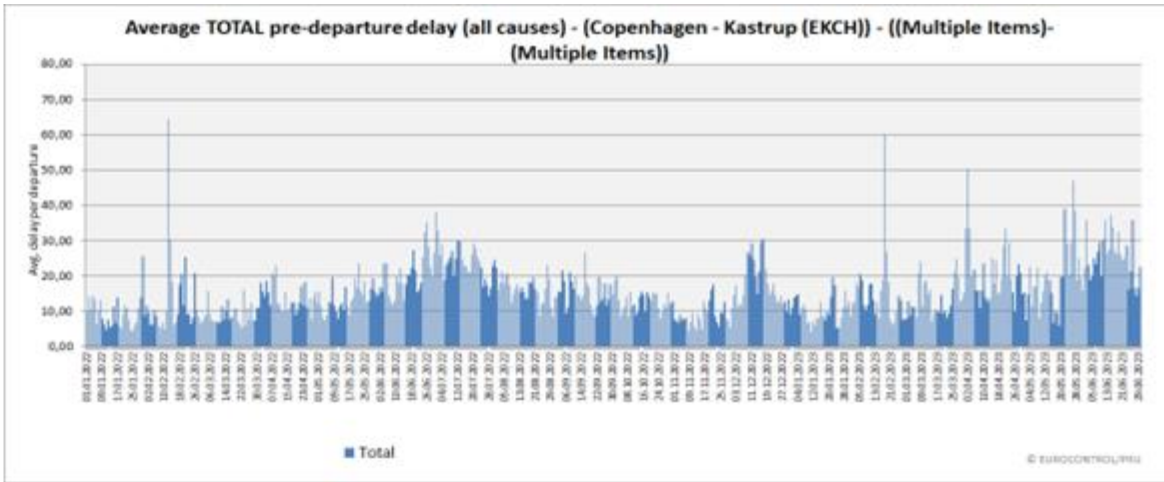
clock hour	average scheduled departures	full capacity	MLN incl widebodies	LVP incl. wide bodies	basic delays for all 10	5	A	E(DA)		E(DRA)	<15 min 29 €	~30 min 43 €	~90 min 91 €
0-6	4	36	30	24									
6	13	36	30	24	130	65	0	0	130	78	3 770 €	0	0
7	35	36	30	24	350	175	11	990	1340	2190	10 150 €	0	90 090 €
8	13	36	30	24	130	65	3	90	220	78	3 770 €	3870	
9	12	36	30	24	120	60	2	60	180	72	3 480 €	2580	
10	5	36	30	24	50	25	2	60	110	30	1 450 €	2580	
11	9	36	30	24	90	45	2	60	150	54	2 610 €	2580	
12	15	36	28	22	150	75	2	60	210	90	4 350 €	2580	
13	8	36	28	22	80	40	1	30	110	48	2 320 €	1290	
14	6	36	30	24	60	30	1	30	90	36	1 740 €	1290	
15	15	36	30	24	150	75	1	30	180	90	4 350 €	1290	
16	40	36	28	22	400	200	18	1260	1660	2256	11 600 €	0	114 660 €
17	26	36	24	18	260	130	26	1860	2120	3132	7 540 €	0	169 260 €
18	9	36	24	18	90	45	2	60	150	54	2 610 €	2580	
19	11	36	28	22	110	55	1	30	140	66	3 190 €	1290	
20	10	36	30	24	100	50	1	30	130	60	2 900 €	1290	
21	8	36	30	24	80	40	0	0	80	48	2 320 €	0	
22	2	36	30	24	20	10	0	0	20	12	580 €	0	
23	7	36	30	24	70	35	0	0	70	42	2 030 €	0	
	248				**2440**	**1220**		**4650**	**7090**	**8436**	**70 760 €**	**23 220 €**	**374 010 €**

Annex 3. Average delay of departures per day 2022 – 2023/6









Source: Eurostat Data portal


Jet Fuel Monthly Price - Euro per Gallon
Range 6m 1y 5y 10y 15y 20y
Aug 2013 - Jun 2023: -0.180 (-7.97%)
Euro per Gallon
4.09
3.74
3.38
3.02
2.67
2.31
1.96
1.6
1.24
0.89
0.53
Aug-2013
Feb-2014
Aug-2014
Feb-2015
Aug-2015
Feb-2016
Aug-2016
Feb-2017
Aug-2017
Feb-2018
Aug-2018
Feb-2019
Aug-2019
Feb-2020
Aug-2020
Feb-2021
Aug-2021
Feb-2022
Aug-2022
Feb-2023

Annex 4. Calculation of reduction in weather forecast mismatches

The changes in the RMSE of various weather forecast variables were estimated in the various experiments conducted in Task 1 and Task 2. If the original forecast accuracy in terms of correlation coefficient hovered between 0.8 and 0.85 a change of the RMSE by about 6% implies an increase of the correlation coefficient by a bit less than 2%- point. This improvement is subsequently applied to the Cost-Loss matrix in order to assess the change in forecast mismatches.

The climatic average number of days with precipitation of at least 1 mm during the period October – April was 83 for Helsinki-Vantaa airport. Similarly, there are 32 days with at least 10mm precipitation in the same winter period. A 2%-point forecast accuracy improvement would mean on average a reduction of unforeseen significant precipitation by 0.5 day and 1.5 day for minor precipitation events. Furthermore, it would also diminish the number of not realized but forecast precipitation events by about the same number. Reducing unforeseen precipitation events has the most significant cost reduction effects, but reduction of unnecessary warnings will also save at least in terms of preparedness costs. In the calculations we focus on the reduction of unforeseen precipitation events.

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