The airport as an energy hub

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Kort sammanfattning

Denna rapport utforskar flygplatsen som energihubb – ett koncept som potentiellt möjliggörs i samband med att transport- och energisystemen ställer om till minskat fossilberoende. Konceptet innebär att flygplatsen utökar sitt ansvarsområde och affärsverksamhet och därmed bidrar till flygtransportsystemets omställning från dagens flygbränslen till fossilfria alternativ så som elektricitet, vätgas eller biobränslen. I egenskap av energihubb kan därmed flygplatsen bidra till att minska flygets koldioxidavtryck. Utöver att tillhandahålla elektricitet för själva flygningen eller andra flygbränslen producerade av fossilfri el, skulle elektrifiering av flygplatsens markverksamhet ytterligare integrera flygplatsen i elnätet, minska lokala utsläpp och bidra till global minskning av växthusgaser. Med sina befintliga transport- och logistikförbindelser kan flygplatsen också spela en samordnande roll för framtida transportenergibehov, bidra till lokala energimarknader och stödja nätstabilitet. Att integrera produktion av förnybar energi, energilagring och potentiellt även produktion av fossilfria bränslen positionerar flygplatsen som en dubbelriktad hubb i både transport- och energisystemen. I och med detta balanseras ett flertal behov vilket kan bidra till att uppnå de övergripande hållbarhetsmålen för hela ekonomin.

Nyckelord

Flygplats, elflyg, energihubb, transporthubb, elektrifiering, minskning av koldioxidutsläpp, elnät.

Abstract

This report explores the concept of the airport as an energy hub in the decarbonizing transportation and energy systems. The airport, transitioning from petroleum-based fuels to carbon-free alternatives like electricity, hydrogen, or biofuels, could help reduce the aviation sector's carbon footprint. Beyond providing electricity for flight itself or producing fossil-free aviation fuels, electrifying airport ground operations would further integrate the airport into the electricity grid, reduce local emissions, and contribute to global greenhouse gas mitigation. With its existing transportation and logistics links, the airport could also play a coordinating role in future transportation energy demands, contribute to local energy markets, and support grid stability. Incorporating renewable energy and storage systems and potentially producing fossil-free fuels positions the airport as a two-way hub in both the transportation and energy systems, helping to balance multiple objectives in achieving economy-wide sustainability targets.

Keywords

Airport, electric flight, energy hub, transport hub, electrification, decarbonization, electricity grid.

Glossary

Term	Explanation
A2G	Aviation to grid.
AC	Alternating current
APU	Auxiliary power unit. Small onboard engine on aircraft used to generate power when main engines are off. Typically runs on the same fuel as the aircraft's main engines (i.e., jet fuel).
CHP	Combined heat and power, a power plant that provides both electrical energy and heat for local (i.e., high-temperature industrial process heat) or municipal (i.e., low-temperature district heating) use.
Clean hydrogen	Hydrogen produced without emitting GHGs, such as via electrolysis of water using renewable energy.
DC	Direct current
Energy, kWh, MWh	Capacity for doing work, usually either electrical or heat, commonly in units of kilowatt-hours (kWh) or megawatt-hours (MWh). Energy is the integral of power over time.
Energy commodity	A homogeneous energy carrier, distinct from other energy carriers, and with defined physical, chemical, electrical, etc., properties and energy content. Examples include coal, oil, natural gas, electricity, and (e.g., low-temperature district) heat.
Energy hub	A confluence of different types of energy production, storage and/or consumption, actively managed to meet the needs of energy producers and consumers and the energy system itself.
EV	Electric vehicle. May be any vehicle or vessel, to include aircraft and ships, and may be fully or partially driven by electricity. Variations include battery electric vehicles (BEV), fuel cell electric vehicles (FCEV), plug-in hybrid electric vehicles (PHEV). For simplicity, this study assumes that all EVs are BEVs in a fully decarbonized future, but this assumption does not drive any of the conclusions.
GHG	Greenhouse gas, such as carbon dioxide (CO_2) or methane (CH_4). Most, but not all, are associated with the combustion of fossil fuels, such as coal, oil, and natural gas.
GPU	Ground power unit. Generator, battery, or other source of electrical power external to an aircraft and connected to an aircraft while it is on the ground, to avoid using the aircraft's own engines or APU.
LEM	Local electricity market, in which production and/or consumption of electricity is scheduled/managed to meet a system objective (i.e., least system cost) using prices as a signal to producers and consumers. This can be done with a (simplified) bidding system like the national and European electricity exchanges (i.e., Nordpool).

MCS	Megawatt charging system.
Microgrid	A small, local electricity network with limited or no connection to a larger network. Typically includes a variety of electricity producers and consumers, and ideally the energy produced is close to the energy consumed.
Power, kW, MW	Instantaneous energy, either produced, consumed, or transmitted, commonly given in units of kilowatts (kW) or megawatts (MW). The capacity, and cost, of an electricity network is driven by the peak of the power distribution over time, since greater power peaks could cause network failure.
Renewables	Solar, wind, geothermal, hydroelectric, and other carbon-free forms of energy production that do not consume appreciable feedstocks.
Solar, PV	Solar photovoltaic generation of electricity.
Transport hub	A confluence of different transport modes, usually including both long- and short-distance transport modes, potentially including both passengers and freight. Actively designed and managed to support the efficient, safe, and economic transport of passengers and goods from origin to destination across the entire transport system.
V1G	Smart charging, a back-formed derivation of the acronym V2G. Controlled charging of EV batteries to avoid charging at times of highest electricity prices, or otherwise to help manage the grid balance. Unlike V2G, power only flows from the grid to the EV battery, but the rate of charging varies depending on the state of the battery and grid conditions.
V2G	Vehicle to grid, two-way charging of EVs such that the EVs battery may either be charged or discharged by the grid depending on grid and battery conditions. V2G is designed to use EV battery storage to help regulate the grid or to minimize the net energy cost of EV charging.
VRE	Variable renewable energy or variable renewable electricity. Energy created by non-dispatchable renewable resources, such as wind or solar. Most marketed VRE is in the form of electricity.
VTI	Statens väg- och transportforskningsinstitut (The Swedish National Road and Transport Research Institute).

Sammanfattning

Denna studie undersöker skärningspunkten mellan transport- och energisystemen på svenska flygplatser inom ramen för Sveriges mål att uppnå klimatneutralitet till 2045. Batteridrivna elflygplan identifieras som en möjlig komponent för att minska koldioxidutsläppen i den regionala luftfarten, med potentiellt öppnande av nya kortdistanslinjer och vidareutveckling av de regionala flygplatserna. Med en bred användning av elflyg skulle förhållandet mellan flygplatserna och energisektorn genomgå förändringar, vilket kan innebära både utmaningar och möjligheter. En huvudsaklig sådan möjlighet är det framväxande konceptet med flygplatser som utvecklas till integrerade energi- och transporthubbar. Rapporten introducerar begreppen transporthubb och energihubb, och betonar energisystemens föränderliga roll i Sveriges fossilfria framtid. Vidare diskuteras den regionala flygplatsens potentiella roll för att främja ekonomisk utveckling bortom flygplatsverksamhet. Analysen bidrar till att förstå dynamiken i utvecklingen av elektrifierade flygplatser och dess bredare konsekvenser för flygsektorn och den regionala utvecklingen i Sverige.

Studien är baserad på en genomgång av befintlig litteratur, med syntes och analys av författarna. Eftersom mycket av den befintliga litteraturen om transport- och energihubbar avser hamnar för sjöfart utforskas den hamnrelaterade litteraturen och en jämförelse görs mellan hamnar och flygplatser. Hamnar har två fördelar jämfört med flygplatser i detta avseende: enklare godshantering (jämfört med passagerare) och möjligheten till koppling till energiproduktion offshore. Bortsett från detta finns det många paralleller i elektrifieringsmöjligheterna för flygplatser och hamnar, och erfarenheter från den pågående transformationen av hamnar till regionala energinav kan ge lärdomar för flygplatserna.

Förutom att elektrifiera flygplatsverksamheten inklusive markfordon och fordon som kommer till flygplatserna förväntas övergången till fossilfritt flyg, särskilt elflyg för kortdistansflygningar, öka efterfrågan på elektrisk energi och effekt på flygplatserna, vilket gör flygplatserna till mer betydande noder i energisystemet.

Analysen syntetiserar möjliga effekter av elflyg i samband med förnybar elproduktion, batterilagring och annan elektrifieringsteknik så som produktion av hållbara flygbränslen eller vätgas. Exempel på projekt är RES-Flyg koordinerat av Uppsala universitet, som studerat integrationen av solcellsproduktion och storskalig batterilagring på flygplatser. Flera internationella forskningsinsatser, såsom de i USA, EU och Kina, utforskar att optimera flygplatsdriften, integrera förnybara energikällor och föreslå innovativa lösningar, såsom likström (DC) i flygplatsers mikronät.

Rapporten diskuterar några av utmaningarna och alternativen för att ladda elflygplan. Den belyser det potentiella högeffektbehovet för laddning av elektriska flygplan, kylningskrav och potentiella konfigurationer av laddinfrastruktur. Olika laddningsalternativ, inklusive fasta och mobila stationer, beskrivs, inklusive överväganden som operativ flexibilitet, skalbarhet och tillhörande kostnader. Detta är ett område som adresseras av det pågående projektet ”Flexibel och automatiserad laddning via energilager på flygplatser” (FAACE).

För att maximera fördelarna med flygplatser som energihubbar föreslås i rapporten samtidig optimering av transport- och energiverksamhet. Flygplatsmyndigheter, som är vana vid att hantera transporter, uppmuntras att samarbeta med flygplatsanvändare om energiproduktion, lagring och förbrukning för att hantera flygplatsens nettobelastning på ett effektivt sätt. Rapporten betonar behovet av ett nytt perspektiv, där flygplatsen betraktas ha en balanserande dubbelriktad roll i de bredare transport- och energisystemen.

Slutligen avslutas rapporten med områden för framtida forskning, som tar upp kritiska frågor relaterade till utvecklingen av flygverksamhet, energiinvesteringar på flygplatser, snabbladdning för elektriska flygplan, produktion av vätgas och hållbara flygbränslen, interaktioner mellan flygplats och elnät, energihantering och barriärer inom regelverk och standardisering. Dessa forskningsfrågor spänner över operativa, systemiska och ekonomiska överväganden och är avgörande för flygplatser

som förbereder sig för sin nya roll som energihubb i en fossilfri framtid. Sju forskningsfrågor och flera underordnade frågor identifieras:

1. Hur kan flygverksamheten (t.ex. flygplanering, gatetilldelning, flight turnaround, lastlagring, nätuppkoppling, genererande kapacitetsinvesteringar) utvecklas när flygplatsen tar en mer central roll i energisystemet?
2. Vilka energiinvesteringar skulle ge störst avkastning till en flygplats?
3. Vilka alternativ för snabbladdning av framtida elflygplan är mest kostnadseffektiva, och vilka är mest robusta mot framtida osäkerheter i tillväxten av elflyg?
4. Vilken är potentialen för produktion av vätgas och andra hållbara bränslen på flygplatser, antingen för intern konsumtion eller för handel? Under vilka förhållanden (kostnad, marknadsutveckling, pipelineinfrastruktur, framväxande industri, etc.) skulle bränsleproduktion på flygplatser uppmuntras/avskräckas i framtiden förutsatt att de gäller både inom och utanför flygplatsen?
5. Hur stor potential finns det i aviation-to-grid (A2G)?
6. Hur skiljer sig hanteringen av kraftnätet på en flygplats som ett energinav från det för alla andra distributionsnätverk (d.v.s. ett nätanslutet mikronät)?
7. Finns det befintliga regelverk som skulle kunna innebära hinder för att en flygplats tar en större roll i energisystemet? Finns det standarder som skulle behöva fastställas för att underlätta den rollen?

Summary

This study examines the intersection of the transportation and energy systems at Swedish airports within the context of Sweden's goal to achieve climate neutrality by 2045. Electric aircraft are identified as an option for decarbonizing regional aviation, potentially opening new short-haul routes and expanding regional airports. The relationship between airports and the energy sector would undergo changes with broad adoption of electric flight, which would present challenges and opportunities. One of these opportunities is the emerging concept of airports evolving into integrated energy and transport hubs. The report introduces the concepts of transportation hubs and energy hubs, emphasizing the evolving role of energy systems in Sweden's decarbonized future. Additionally, it discusses the potential role of regional airports in fostering economic development beyond airport operations. The analysis contributes to understanding the evolving dynamics at electrified airports and their broader implications for the aviation sector and regional development in Sweden.

This study is based on a review of existing literature, with synthesis and analysis by the authors. Since much of the existing literature on transport and energy hubs relates to maritime ports, the port literature is explored and a comparison is made between ports and airports. Maritime ports have two advantages over airports in this regard: simpler cargo handling (compared with passengers) and the possibility of connection to offshore energy production. Otherwise, there are many parallels in the electrification options for airports and maritime ports, and the experiences of ports becoming regional energy hubs can provide lessons for airports.

In addition to electrifying airport operations, including ground vehicles and vehicles coming to airports, the shift towards emission-free aviation, especially electric aviation for short-haul flights, is expected to increase the demand for electric energy and power at airports, making airports more significant nodes in the energy system.

The analysis synthesizes the role of electric flight in conjunction with renewable electricity generation, battery storage, and other electrification technologies. Examples of projects include the RES-flyg project coordinated at Uppsala University in Sweden, which explored the integration of solar photovoltaic production and large-scale battery storage at airports. Several international research efforts, such as those in the United States, European Union, and China, explore optimizing airport operations, integrating renewable energy sources, and proposing innovative solutions, such as direct current (DC) airport microgrids.

The report discusses some of the challenges and options for charging electric aircraft. It highlights the potential high-power demand for electric aircraft charging, cooling requirements, and potential charging configurations. Different charging options, including fixed and mobile stations, are described, including considerations such as operational flexibility, scalability, and associated costs. This is an area addressed by the ongoing project "Flexible and automated charging via energy storage at airports" (FAACE).

To maximize the advantages of airports as energy hubs, the discussion proposes simultaneous optimization of transport and energy operations. Airport authorities, accustomed to managing transport operations, are encouraged to cooperate with airport users on energy generation, storage, and consumption to manage the net airport load effectively. The report emphasizes the need for a shift in perspective, viewing airports as balancing dual roles in the broader transport and energy systems.

Finally, the report concludes with areas for future research, addressing questions related to the evolution of aviation operations, energy investments at airports, fast charging for electric aircraft, hydrogen and carbon-free fuel production, airport-to-grid interactions, managing power networks, and regulatory and standards barriers. These research questions span operational, systemic, and economic considerations and are crucial for airports preparing for their roles as energy hubs in a decarbonized future. Seven research questions, and several more subordinate questions, are identified:

1. How might aviation operations (e.g., flight scheduling, gate assignment, flight turnaround, cargo warehousing, grid connectivity, generating capacity investments) evolve as the airport takes on a more central role in the energy system?
2. Which energy investments would be most economic for an airport?
3. Which options for fast charging future electric aircraft are most cost effective, and which are most robust to future uncertainties in the growth of electric aviation?
4. What is the potential for hydrogen and other carbon-free fuels production at airports, either for internal consumption or for trade? Under which conditions (cost, market development, pipeline infrastructure, emerging industry, etc.) would fuel production at airports be encouraged/discouraged in the future?
5. How much potential is there in aviation-to-grid (A2G)?
6. How does managing the power system of an airport as an energy hub differ from that of any other power distribution system (i.e., a grid-connected micro-grid)?
7. Are there existing regulations that could create barriers to an airport taking a greater role in the energy system? Are there standards that would need to be established to facilitate that role?

Foreword

A large part of existing research targeting a sustainable transformation of aviation focuses on flight technology, propulsion technology and on-board energy management. These are indeed critical research and development areas but to enable a sustainable transformation of the aviation transport system, a holistic perspective is required and with more focus on infrastructure issues. An important subset of this concerns the infrastructure at the airports themselves.

This report is an initial result from the research project “Flexible and automated aircraft charging via energy storage at airports” (FAACE). The project is delimited to focus on novel concepts for charging battery-powered electric aircraft, which may play a limited but important role in the future air transport system. As there are currently major uncertainties surrounding the future development of technology, operational concepts, and business models for electric aviation, designing for flexibility in the airport infrastructure is desirable.

Rather than zooming in on specific technical charging solutions, this report contributes to the broader picture of how the relationship between the transport and energy systems may develop to support the sustainable transformation of aviation. A potential new role for airports is proposed and discussed from various perspectives, expanding the current scope for the airport of being a transportation hub to also becoming an energy hub.

We thank the Swedish Transport Administration and VTI for financing this work, and hope that the report will provide useful insights on challenges and opportunities for airports and related actors as aviation decarbonizes, in this way contributing to the decision support for future infrastructure developments.

Linköping, January 2024

Magnus Eek
Project leader

Granskare/Examiner

Jennifer Leijon, Uppsala University

Contents

1. Background: Electric aviation and the future of Swedish airports

To reach its goal of becoming climate neutral by 2045 (Hermansson et al. 2023), Sweden has developed a roadmap for decarbonizing the Swedish air transport sector (Fossil Free Sweden 2018). This roadmap shows that “domestic air transport shall be fossil-free by 2030 and how all flights originating from Swedish airports (domestic and international) shall be fossil-free by 2045. This is in line with the Swedish government’s climate goals but is more ambitious than both European and global climate goals for air transport. The path to achieve this is primarily through energy efficiency measures, renewable jet fuels and electrification” (Swedavia 2023). While biofuels may contribute toward this goal in the near term, uncertainty about secondary consequences from large-scale increases in biofuel production (Bryngemark 2019; Mustapha, Kirkerud, Bolkesjø & Trømborg 2019) may lead to growing shares of electricity and electricity-derived fuels, such as emission-free hydrogen (Jaramillo et al. 2022, Al-Ghussein Norrman & Talalasova 2021).

Several studies have shown the potential for electric aircraft in decarbonizing Swedish regional aviation over the long term (Jüriado, Wigler, Wargsjö, Spångberg & Eliasson 2022; Trafikverket 2020; Solomonsson & Jussila Hammes 2020; Sager, Alfredsson, Esbjörnsson & Holmberg 2022). Two of these studies point out that the performance characteristics of electric aircraft may also open the potential for new commercial short-haul routes and the development or expansion of new regional airport hubs in Sweden (Trafikverket 2020, Salomonsson & Jussila Hammes 2020).

In the future, if electric flight is adopted throughout Sweden, the relationship between airports and the energy system could change, bringing both challenges and opportunities. A recent academic analysis of the increasing penetration of electric aircraft into a busy airport shows how the expansion of electric aircraft charging increases the need for charging points and total aircraft stands to maintain air traffic flows (Doctor, Budd, Williams, Prescott & Iqbal 2022). A Swedish doctoral thesis project shows that, for one regional Swedish airport, charging electric aircraft does not create an issue for the airport’s energy consumption, but only for its instantaneous power draw from the regional network during aircraft charging events, and that this issue can be mitigated with battery storage (Risvall 2023). Another Swedish research project, this one coordinated by the Research Institutes of Sweden (RISE), also models the introduction of electric aviation into airport operations, but at the aviation network level and with more operational specificity (Alfredsson, Nyman, Joborn, Staack & Petit 2022). The model tracks electric aircraft across specific routes, which allows the state of charge (SoC) to be estimated and charging to be optimized for the next flight. Importantly, charging is optimized both to minimize impact on peak power at airports (i.e., energy cost) and to minimize disruptions to flight timetables (i.e., scheduling cost). Thus, this RISE model is one of the few to incorporate the trade-off between transportation operations and energy operations at an electrified airport. In the published report, the model is applied to electric flight operations at Visby Airport and Umeå Airport.

Transforming the aviation sector will have effects beyond the boundaries of airports in Sweden. The indirect costs associated with airport operations, such as from noise, poor air quality, and the damage associated with airports’ contributions to climate change, are not restricted to the airport itself, but extend into the surrounding local area as well (Wolfe, Yim, Lee, Ashok. Barrett & Waitz 2014). Electrifying flight may mitigate some of these effects. Regional airports in Sweden also play a significant role in their respective regions’ economic development beyond the airport operations themselves (Sveriges Kommuner och Regioner [SKR] 2021). For example, the Northvolt lithium-ion battery gigafactory in Skellefteå will not use the regional airport for shipping batteries, but the presence of the airport was one of the factors that led to Northvolt choosing the site (Northvolt, 2017). As more industries relocate to access low-cost renewable electricity, regional airports’ role as joint transportation and energy hubs may foster greater regional economic development.

2. Foundational concepts: Transport hubs and energy hubs

In this section, we describe and distinguish the roles of hubs in a transportation system and hubs in an energy system. An energy system can imply any type of energy carrier, including fossil fuels, but in Sweden's decarbonized future its energy system is expected to include increasing amounts of electric power and fuels derived from electricity, including hydrogen and ammonia, with fossil fuels and biofuels decreasing over time (Energimyndigheten 2023a). Accordingly, this report restricts the discussion of future energy hubs to those focused on carbon-free electricity and electricity-derived energy carriers, but historical examples also include hubs of the fossil energy trade.

2.1. Transportation networks and their hubs

Transportation systems have historically grown as networks of interconnected nodes, with transport links moving people and goods between these centers of social and economic activity (Alexandrov 2004). Topological analyses of road and rail infrastructure (Jiang & Claramunt 2004), and of sea lanes and air routes (Garrison & Marble 1962), show that the interconnected node structure of transportation networks is ubiquitous across different transport modes Figure 1 illustrates one such network for air traffic in Europe, with airports located near major cities serving as network nodes.

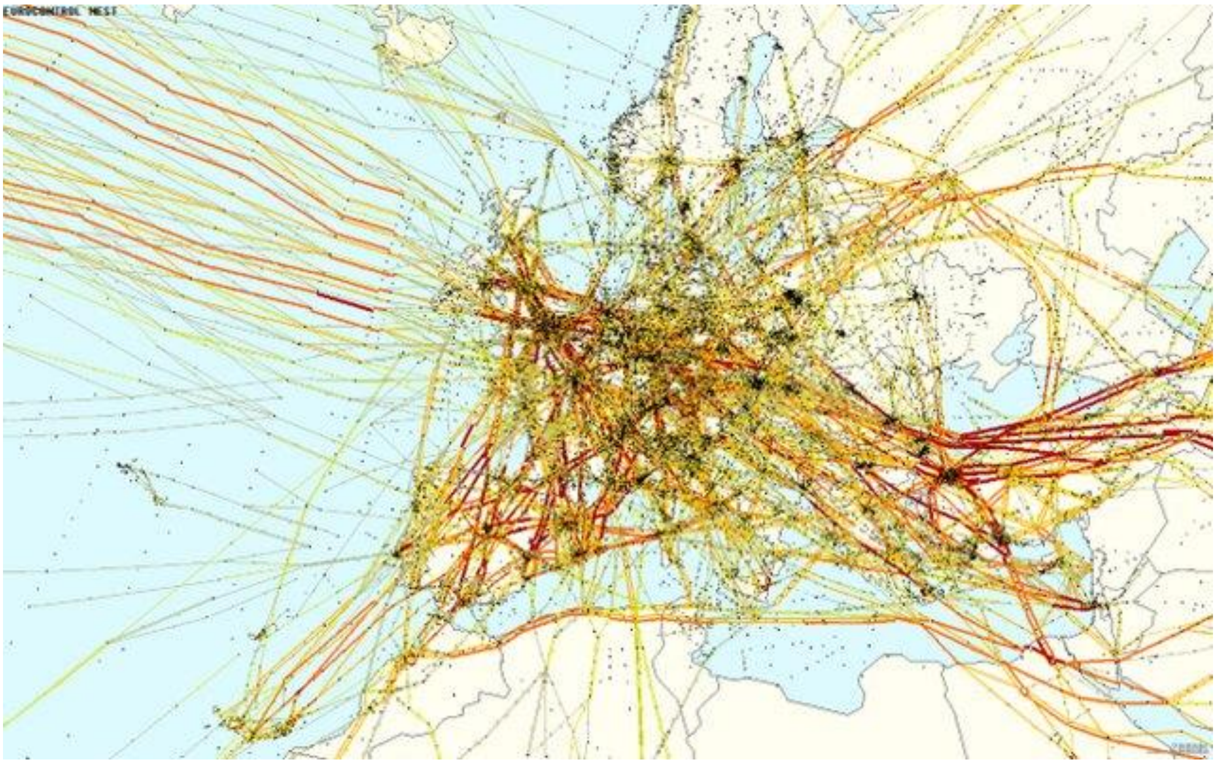

Figure 1: Density plot of air trajectories across Europe in 2019 (Standfuß, Fricke, Hirte & Fichert 2023).

One notable feature of most transportation networks is the general balance of traffic in both directions along each route (i.e., each link between nodes). This is illustrated in the middle (transportation) layer of the 3-layer transport and logistics model of Figure 2. While logistics (top layer in Figure 2) is concerned with directing the flow of goods and other material from production to consumption and the transportation infrastructure (bottom layer in Figure 2) is generally fixed in place, vehicle flows into and out of a transportation node general balance each other. Of course, at different times vehicle traffic may flow predominantly in one direction or the other (e.g., commuting into a city center in the morning, out in the evening; event, weekend, and holiday congestion), transportation infrastructure can route traffic in one direction along a slightly different path than traffic in the opposite direction (via, e.g., one-way roads), and the flow of goods can be asymmetric along a route (e.g., imports of raw materials, export of finished products). However, since most vehicles follow closed paths, returning periodically to a home or depot location, the time average of vehicular traffic along the transport links into and out of a transport node tends to be roughly equivalent. This bidirectionality implies that no node in a transportation network can be a net supplier or consumer of transportation services. (A logistics node can, of course, be a net supplier or consumer of goods which must be transported, but not of the transportation itself, since the vehicles must always return.) Without an obvious direction to transportation networks, nor dedicated supply or demand nodes, all transportation nodes can also be considered hubs. The bidirectionality of transportation networks is in contrast with the flows in traditional energy networks, as is discussed in the next section.

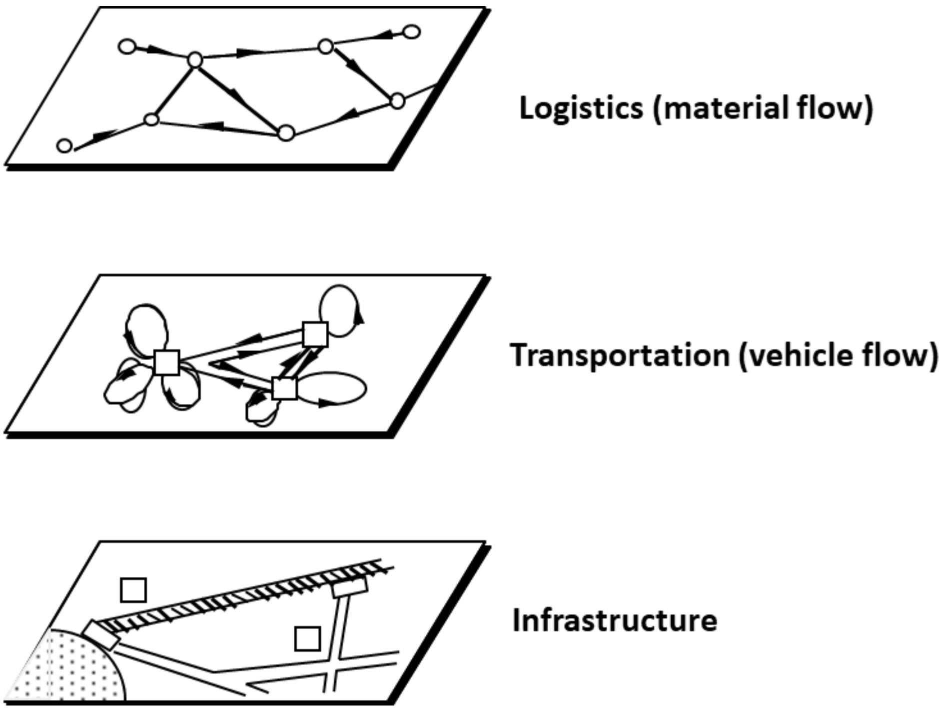

Figure 2: Three-layer model of transport and logistics. Based on Wandel, Ruijgrok & Nemoto, 1991.

Centers of the traffic flows of one transport mode (i.e., maritime) can be located near (or collocated with) hubs of a different mode (i.e., rail), creating the potential for intermodal transport hubs. These become important to the logistics of moving goods (Bock 2010; Zhou, Kundu, Goh & Sheu 2021) and people (Heddebaut & Palmer 2014). Airports have been identified as such intermodal transport hubs (European Conference of Ministers of Transport [ECMT] 2005). Moreover, colocation of population and economic centers, and shared transportation infrastructure for freight and mobility, suggest a natural synergy between the movement of people and the movement of goods (Rodrigue 2020).

2.2. Energy systems and their nodes

Energy systems are structured differently from transportation systems, and the nodes in an energy system can play different roles than the hubs in a transportation system. Energy systems have historically been organized as supply chains, moving energy commodities such as coal, oil, gas, or electricity from centralized production facilities to (often distributed) points of consumption. The heterogeneous geographical distribution of energy resources and energy demand suggests a systematic transfer of energy commodities from sources to sinks, without the need for commodity flows in the reverse direction. This directionality is evident in energy infrastructure and in the designs of energy system models.

Figure 3 illustrates the structure of one of the earliest computer models of the U.S. energy system, where the authors have included arrows along the links between nodes, indicating energy flows from left to right in the diagram.

Energy networks are formed when multiple supply chains overlap at common nodes. Historically, more energy supply chains were established as new energy resources were developed to satisfy the increasing energy demands of multiple activity centers (Liu, Zhang, Wang, Wei & Gu 2020). These supply chains shared common transportation networks (e.g., pipelines, railroads, ports, transmission networks) and fixed infrastructure (e.g., refineries, liquefaction terminals, power plants), creating energy nodes. The larger energy networks grow, the more potential pathways there become to get energy commodities from sources of supply to demand centers. Thus, energy networks are used to facilitate energy trade (i.e., finding the least cost pathway from supplies to demand, otherwise known as pathway efficiency) and to increase system resilience through pathway redundancy (Ganin, Kitsak, Marchese, Keisler, Seager & Linkov 2017).

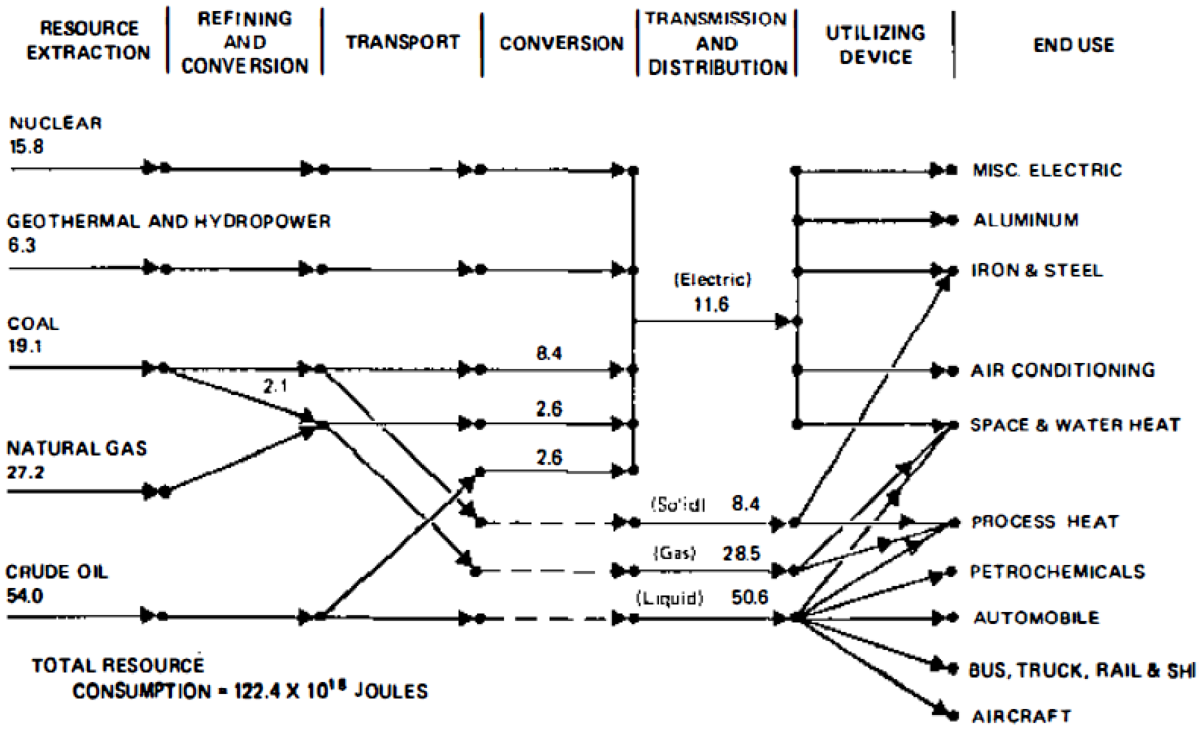

Figure 3: 1974 projection of U.S. energy system flows in 1985, in exajoules (Hoffman & Wood 1976).

With an emphasis on efficiencies of scale, nodes in a traditional energy system serve as points of aggregation or disaggregation to enable efficient shipment, conversion, and distribution of energy commodities from sources of supply to demand centers. Examples of energy nodes include import/export terminals, refineries, natural gas processing plants, liquefaction facilities (for natural gas), distribution terminals (for oil), and central power stations or transformers (for electricity).

2.2.1. Energy nodes and directionality

The different network structures of transportation systems and energy systems create different roles for energy nodes and transport hubs. While transportation hubs can also aggregate transportation services to gain efficiencies of scale, there is no net direction to the transportation flows at a given hub, where those flows are measured by vehicle activity. Energy nodes generally receive energy flows from a set of "upstream" supply nodes and pass those supplies to a set of "downstream" demand nodes.

1974 projection of U.S. energy system flows in 1985, in exajoules (Hoffman & Wood 1976).

This directionality is beginning to change in electric power networks. Historically, power systems were composed of large, central power stations which energized transmission and distribution grids, sending power to electrical loads. As loads varied over time, power output from the dispatchable power stations could be adjusted to match load and maintain system balance. However, with the increase in non-dispatchable variable renewable electricity (VRE) generation in power systems, the remaining dispatchable generation may be insufficient to match demand. At the same time, the advent of distributed electricity generation, from such sources as rooftop solar photovoltaic (PV) systems creates correlations between generation and net load, which also makes it difficult to anticipate the call on dispatchable generation. One solution is to connect electricity storage to the network, which could store energy at times of low net demand (or high net supply) and return it to the grid when needed. Another solution is to manage demand, reducing demand for power when supply is insufficient to meet it or shifting demand from peak times to off-peak times. A node in the electricity system between generation and load with its own supplementary generation or storage capacity or with the ability to manage downstream demand could begin to contribute to bidirectional flows in this system.

2.2.2. Energy nodes for multiple commodities

When a compelling reason exists to collocate the nodes from the supply chains of different energy commodities, multi-commodity energy nodes can arise. A multi-commodity energy node brings in more than one energy commodity or produces more than one energy product and is limited by a fixed processing capacity which can be allocated between commodities and products. Common examples include energy conversion facilities, such as petroleum refineries or electricity generators. Although energy still flows from sources to uses, these nodes can be called hubs because they allow for different commodities to flow into and out of them. A complex refinery, for example, can process different types of crude oils to produce different slates of refined products, and some thermal power generators can be co-fired with coal, solid waste, or biomass fuels.

Without a compelling economic motivation to collocate the nodes from different types of energy commodities, traditional energy nodes tend to be located where they can optimize the economics of a single energy commodity or conversion process. For example, gas processing plants tend to be located close to field production, while oil refineries are more likely to be located near deepwater ports to facilitate waterborne trade, and coal-fired power plants are often found near population centers. Similarly, the siting of green hydrogen hubs currently being commissioned in Europe and the USA appears focused on minimizing the cost of hydrogen production from carbon-free energy sources and delivery to end-users in order to encourage a green hydrogen economy (Talus & Maxwell 2022; Wolf 2023), although one analysis did find synergies between a potential hydrogen pipeline network and the existing electric transmission grid in Europe (Neumann, Zeyen, Victoria & Brown 2022). The focus on cost-optimizing the supply chain of a single energy commodity means that nodes in the supply chain of one energy commodity may not be co-located with those of another energy carrier, and this limits the potential for multi-commodity energy nodes.

2.3. Energy hubs

The symmetry of transportation networks makes it natural to describe its nodes as hubs, with each being both origin and destination for similar amounts of transportation across all modes; the clear concept of a hub in an energy system has been slower to emerge (Abdel Aleem, Zobaa, Calasan & Rawa 2022). Prior research had noted the potential utility of collocating energy infrastructure (Geidl, Koeppel, Favre-Perrod, Klöckl, Andersson & Fröhlich 2007), but a more recent review found inconsistent application of the energy hub concept (Mohammadi, Noorollahi, Mohammadi-ivatloo & Yousefi 2017).Figure 4, taken from that review, shows four alternative schematic representations of energy nodes that had been called energy hubs. Three of these involve the conversion of one type of energy into another (i.e., into heating and/or electricity), while the fourth involved energy storage.

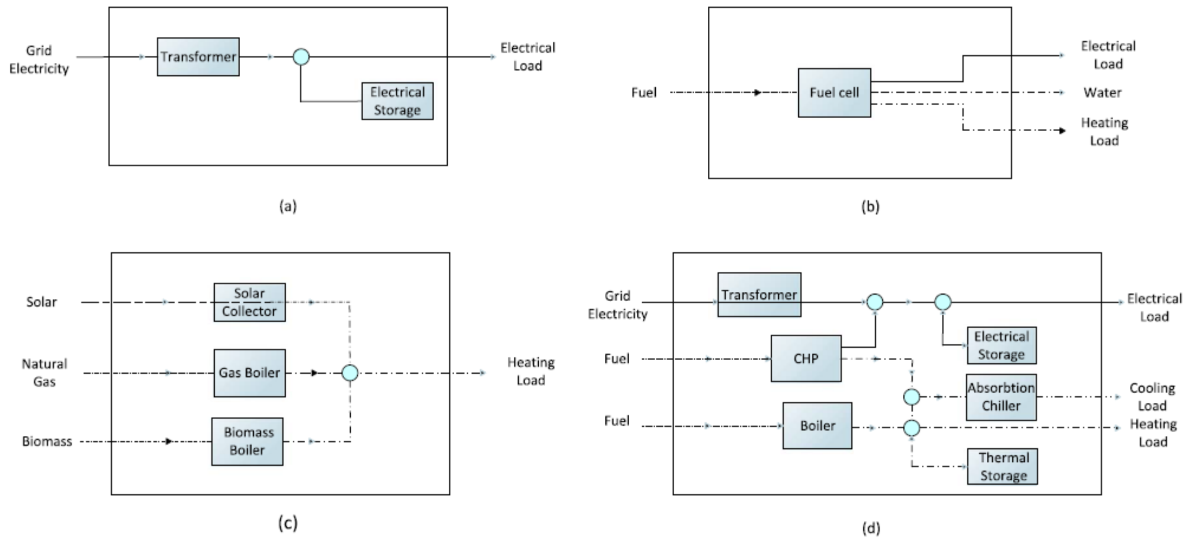

Figure 4: Schematics of various concepts of an energy hub (Mohammadi, Noorollahi, Mohammadi-ivatloo & Yousefi 2017).

Another review just two years later, though, found a clearer picture emerging (Sadeghi, Rashidinejad, Moeini-Aghtaie & Abdollahi 2019). Figure 5, taken from that review, shows a representative schematic of an energy hub. It has multiple energy commodities coming into the hub from the "upstream" supply side on the left, being converted into electricity or heat, which leaves to the "downstream" side on the right, and a small arrow representing vehicle-to-grid (V2G) sending electricity upstream back into the energy hub. This concept of an energy hub captures two elements, multiple energy commodities and the potential for bidirectional flows of energy.

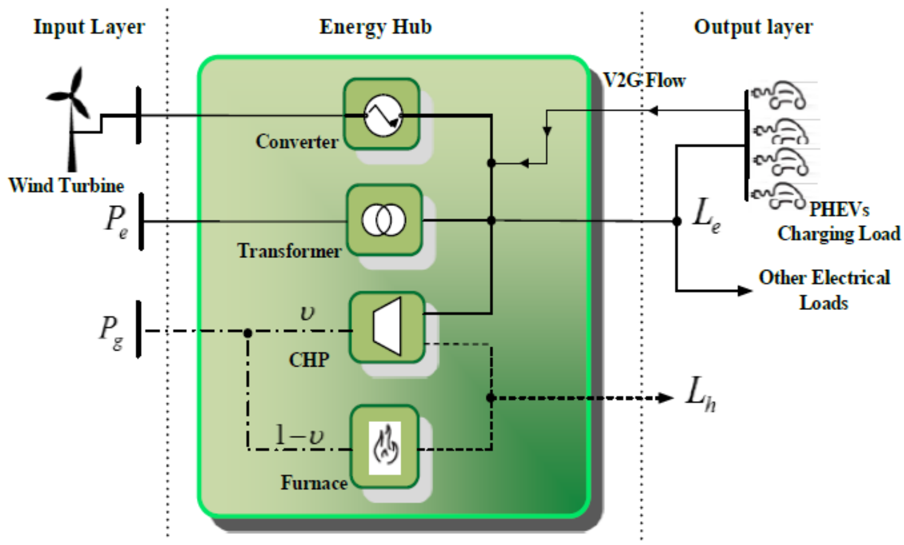

Figure 5: A renewable-based energy hub (Moeini.Aghtaie, Farzin, Fotuhi-Firuzabad & Amrollahi 2017). Here, PHEVs stand for plug-in hybrid electric vehicles; P stands for production and L for load; and the subscript e represents electricity, g is natural gas, and h is heat.

This concept of a multi-commodity, bidirectional energy hub is motivated by the transition away from energy sources that emit greenhouse gases (GHGs) toward renewable and fossil-free energy. This transition entails greater electrification of end uses, including transportation, and a growing share of variable renewable energy (VRE) generation, such as from wind or solar, in the power sector (Clarke et al. 2022). To facilitate this transition, electricity transmission hubs capable of connecting both existing (dispatchable) power sources and new (non-dispatchable) sources have been proposed (Guler, Çelebi & Nathwani 2018), which would be a form of multi-commodity hub to facilitate VRE integration. As the VRE share of generation increases, energy hubs could also contribute directly to energy system stability. New high-power demands, such as for fast-charging electric vehicles (EVs) combined with the variable nature of wind and solar resources could yield episodic imbalances between electric power supplied to the grid and that drawn from it. These imbalances would occur stochastically but are correlated at different spatio-temporal scales (Ernst, Wan & Kirby 1999). Thus, relocating either energy supply or energy demand in either time or space could rebalance the system. An energy hub that can aggregate and/or schedule multiple power demands, draw from multiple sources and types of energy supply, with access to energy storage and power markets, could balance net energy supply and demand for its connected parties.

Although this articulation of the energy hub concept is recent, the concept itself has existed for at least another decade. The European Union's Seventh Framework Programme supported a research project called E-Hub from 2010-2014, which demonstrated some of the modern energy hub concepts for an urban neighborhood (E-hub 2014). This project considered the management of production, storage, and end-use consumption of two energy commodities, electricity and heat, in an urban neighborhood with connections to external energy networks. It developed several simulation and energy management tools, and it conducted a physical pilot (electricity only, no heat) at one site in Leuven, Belgium (E-hub 2023). Although the end uses of energy in this context are very different from those at an electrified airport, the concept of a semi-managed local areas environment with heterogeneous agents and connections to larger energy networks shares some similarities with an airport.

Another potential example of multi-commodity energy hubs are the emerging (clean) hydrogen hubs being created in the United States and Europe. The U.S. Department of Energy (2023) has recently announced funding for seven regional clean hydrogen hubs. These projects include different sources of energy, conversion technologies, and hydrogen distribution strategies. For example, the California hub plans to use renewable electricity (mainly solar) to produce hydrogen via electrolysis of water and use the produced hydrogen to power cargo handling vehicles and heavy-duty drayage trucks at ports as well as to provide backup electric power generation for community utility applications (drinking water wells) in the case of an electricity grid failure. In Europe, the European Regional Development Fund (EFRO) is supporting development of a hydrogen hub at the Groningen Airport Eelde in the Netherlands (New Energy Coalition [NEC] 2022). This project will also use renewable electricity to power hydrogen production via electrolysis, and the produced hydrogen will be used for both aviation and airport operations. Though the project descriptions focus on the production and use of hydrogen, this also implies that the hubs will also be centers of the electricity and/or natural gas networks, making them potential multi-commodity energy hubs.

2.4. Offshore energy hubs

One special case of a multi-commodity energy hub that involves seaborne transport is the concept of an offshore energy hub or energy island (Lüth 2022). This idea combines the potential for offshore energy production (e.g., from wind) with the need for emission-free fuels in the maritime sector. Electricity generated in offshore wind farms can be collected centrally (i.e., on an artificial island or via a subsea transmission cable back to shore) and, via electrolysis of water, used to create hydrogen and/or synthesized into other fuels. While the energy commodities (i.e., hydrogen) produced by existing port energy hubs are not yet widely used in maritime vessels or in port-related operations, creating an energy hub at a marine port is a potential first step toward creating an integrated transport-energy hub.

Several applications of offshore wind-to-hydrogen production have been announced recently. In 2023, the startup company Lhyfe announced that it had begun to produce hydrogen at a pilot platform with a 1 MW electrolyzer 20 km off the coast of France (Lhyfe 2023). Lhyfe has also announced a project, SoutH2Port, in partnership with Skyborn, owner of a 1 GW offshore wind farm near Söderhamn, Sweden, to build a 600 MW offshore hydrogen production facility there (Memija 2023). China's state news agency announced in June of this year a test of a small-scale floating offshore hydrogen production facility connected to an offshore floating wind farm in Fujian Province (Tianwen 2023). The offshore energy company Subsea 7 has announced partnerships with OneSea Energy, maker of hydrogen production vessels, to study the commercial viability of offshore hydrogen production in Scotland (Habibic 2023) and with the German energy company EnBW to study offshore wind-to-hydrogen (Durakovic 2023).

3. An integrated transport-energy hub

This section describes the integrated transport-energy hub concept, distinguishing it from the separate energy hub and transport hub concepts introduced in section 2. It illustrates the transition of a transport hub into an integrated transport-energy hub as it has been discussed in the context of maritime ports. Finally, it compares some of the features of maritime ports with analogous features of airports to suggest where the transition of airports to integrated transport-energy hubs might be similar to or different from that of ports.

Transportation hubs depend on energy, as energy hubs depend on transportation. For example, transport hubs supply fuel to the vehicles that visit the hub, and they consume energy in their own hub operations. Energy hubs use transportation services to bring goods and workers to the hub. But, for a transportation hub, energy plays a subordinate role as a supporting service; and for an energy hub, transportation supports the energy mission of the hub.

Transportation hubs and energy hubs can also be collocated. The natural connection between intermodal transport and a multiplicity of energy commodities has been noted (Peters, Han, DeLaurentis & Peeta 2014), and collocating hubs allows them to share common resources (e.g., labor pools, construction machinery). If there is enough separation between the transport and energy missions of collocated hubs, they can operate semi-independently of each other.

Transport electrification could couple the operations of a transport hub much closer to those of the energy system. The high powers required to charge large-capacity vehicle batteries in a short time can stress the ability of the energy system to deliver enough power. In order to maintain transportation system efficiency in this case (e.g., high vehicle capacity factors), the costs of securing adequate energy (and power) supplies could increase.

Integrated management of the transport and energy missions of a collocated energy and transport hub could resolve resource competition issues between the two hubs. Operational flexibilities in each system can be explored to see if they can help reduce operational constraints in the other (e.g., peak loads, congestion). The use of available space and infrastructure (e.g., energy storage) can be co-optimized, so they contribute as much as possible to the needs of both sectors.

It is unclear how an existing transport hub can extend its mission to include the role of energy hub. In the following sections, we explore how the concept of the integrated transport-energy hub is being applied in a maritime port context, and we evaluate some of the factors that may make these ideas compatible with airports as well.

3.1. Ports as energy hubs

Both academic (Salsas, Saurí, Rúa & Torrent 2022) and commercial (DNV 2020; New Energy Coalition [NEC] 2020) studies have made the business case for European ports to become green energy hubs in a decarbonized future. In a recent study by the Swedish Research Institute RISE, the role of ports as nodes in a future energy system and the potential evolutionary steps a port could take to get there are described (Bach et al. 2020).

The common features of these ports-as-energy-hub concepts can be characterized in several ways, but often from the perspective of the port itself (i.e., the port authority or other responsible agent). Thus, the report from RISE describes steps that take a port from being simply a consumer of energy to support its transport hub operations to one in which it is also an integral component in a larger decarbonized energy system (Figure 6). Implied in this transition is an expanded role for the port in furthering the energy transition, from decarbonizing its own energy consumption (step 2 in the figure) to facilitating the electrification of connected transport modes (step 3) and finally to enabling the electrification of the broader society beyond the direct influence of the port. At each step in this process the port engages with an expanding set of energy system actors, and it takes on more energy system responsibility while maintaining and broadening its transportation system role. Notably, in the final step, the port engages with energy system actors that are not directly connected to the port's transportation hub at all. Shifting from the process view of Figure 6, Figure 7 illustrates these expanding roles and relationships as concentric rings radiating outward from the port itself.

Figure 6: Port maturity model (Bach et al. 2022 [illustration by Sandra Haraldson]).

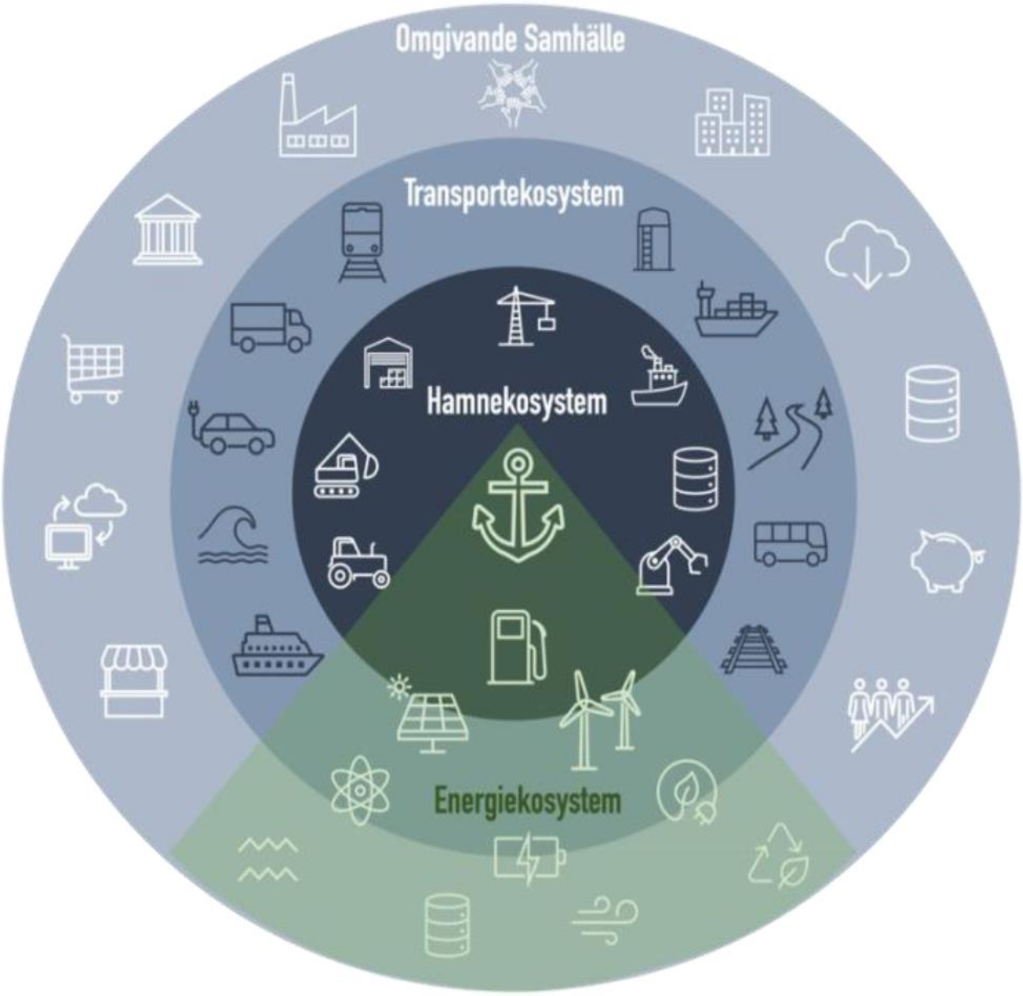

Figure 7: The port's expanding role in the energy system as it integrates more fully into the energy system (Bach et al. 2022). Icons and text (in Swedish) illustrate different sets of actors: those in the port ecosystem (inner circle), including maritime vessels represented as the anchor in the middle, the broader transport and energy ecosystems (middle ring), and the rest of society (outer ring). The wedge toward the bottom of the figure captures those actors whose principal focus is energy.

A different way to describe the concept of a port as an energy hub is to focus on the goal or end state rather than on the journey. DNV (2020) describes activities and identifiable features that an integrated port and energy hub would display, summarized here in the following seven categories:

1. **Decarbonization of marine transport** by fuel switching to alternative carbon-free fuels and electricity. In a fully decarbonized future, these fuels are likely to be derived from electricity, and this will necessitate changes to fuel production, transport, storage and fueling infrastructures in ports. It will likely also require more electric power than existing port bunkering operations.
2. **Electrification of other port-connected transport**, such as road, river, and short-distance sea transport. Since many business activities are located near ports to capture the logistical advantages of this proximity, these transport links tend to be short and readily electrified. Examples include short-haul drayage and warehousing but could also include long-haul trucking and shipping.
3. **Electrification of in-port activities**, such as freight handling with cranes and forklifts, cold storage facilities, in-port vessels such as pilot boats and tugboats, and port offices and other

buildings. An emerging in-port activity is providing power to marine vessels in port, so-called cold ironing.

4. **Electrification of near-port industry**. When industrial facilities are located near ports, it is often for easy access to imported raw materials and energy commodities such as oil, and for ready access to export capacity for manufactured goods. As industries decarbonize, the import of waterborne energy commodities will be replaced by the demand for large amounts of electricity.
5. **Aggregation of carbon-free electricity production**, especially off-shore wind. Off-shore wind farms will need to be associated with a port both as a home for construction and maintenance vessels and as a landing point for bringing produced electricity to shore.
6. **Production and trade of new energy commodities**, such as biofuels, hydrogen, ammonia, or drop-in fuels such as synthetic diesel or synthetic methanol from electricity. The amount of electricity produced from renewable energy sources is expected to increase, and many of the potential consumers are already associated with ports, such as near-located heavy industry and maritime vessels. Trade in these commodities can replace trade in fossil energy carriers, which ports already facilitate. With strong connections to the electric power grid and potential access to off-shore wind energy, ports are also good candidates for becoming production centers of these carbon-free energy commodities. Some ports could also use existing offshore oil and gas pipeline network terminals to facilitate the movement of carbon dioxide (CO_2) to offshore sequestration facilities.
7. **Electricity system integration**. The greater power demands from an electrified port would likely require an expanded connection to the larger power grid. Expanding this infrastructure also provides the port with the opportunity to take a more central role in the regional power network, coordinating electricity purchased from the power grid, potential sales of excess energy to the grid, and energy storage. This role is strengthened by the potential for integrating electricity production (e.g., from offshore wind). While coordinating the net loads across its diverse users inside and outside the port has not traditionally been one of the central roles of a port authority, it is one of the roles of an energy hub.

The first four actions in the list above (1–4) focus on changing the energy sources for existing activities in and around the port, both transport-related and non-transport-related activities. These are activities in which energy plays a supporting role, and the changes related to actions 1–4 would result in greater demand for electric power and a different load profile in and near the port. The next two actions (5–6) relate to the port's role in the energy system, where the transport activities of the port can play a supporting role. The combination of the first six actions (1–6) would result in a port that serves as a co-located transport hub and energy hub, but these roles may not be mutually beneficial. Integrating the (electrified) port into the electric power system (7) captures the benefits of co-location.

A fully integrated transport and energy hub leverages its roles in both the transport and energy systems to the mutual benefit of both systems. Ports today are primarily transport hubs, but as they take on a greater role in the energy transition, their importance as energy hubs is likely to grow. This balancing of roles could evidence itself in, for example, competition for space in the port between transportation equipment and energy equipment; or specific dual-use infrastructure in a port, such as utility-scale batteries that can be used both to store excess power for the port's own use later and to provide balancing services to the grid independently of port operations. Similarly, hydrogen production or energy storage might preferentially be used to serve the needs of the port or its users if the value to the port is greater than the value to the energy system.

These new port roles may not be supported by current governance structures, regulations, and standards; thus, business models and the regulatory environment may require changes to support some of the new activities that ports could undertake as an energy hub.

3.2. Comparing ports and airports as energy hubs

Maritime ports and airports have many similarities, and some of the features of ports as energy hubs are directly transferrable to airports. Both ports and airports are existing multi-modal transportation hubs; both have an ecosystem of service providers that benefit from their locations in and around the transport hub; both have a set of governance and management structures in place to coordinate the activities of these independent actors, to a greater or lesser degree; and, importantly, both have a mandate to decarbonize in transportation modes that are considered difficult to decarbonize (maritime, aviation). This means that both ports and airports can expect that: the principal vessels that use them as transport hubs (i.e., maritime ships, aircraft) to switch to decarbonized fuels; they electrify all or parts of the operations in, near, and related to the transport hub; they strengthen their interconnection with the electric power system; and they have a similar opportunity to coordinate their energy operations as they currently do their transport operations.

Yet, there are also differences between maritime ports and airports. Besides the obvious difference in waterborne or airborne traffic, and the associated difference in vessel size that implies, one difference is that maritime ports primarily carry goods, while airports carry relatively more passengers. This affects both the nature of operations in the hub itself and the associated transport services that are connected to the hub, and these differences imply different opportunities for port-related electrification. For example, maritime ports primarily carrying container traffic often have an associated dedicated fleet of short-haul medium- and heavy-duty drayage trucks shuttling containers along relatively fixed routes from ships to storage facilities, and these trucks may become electrified. With a strong business relationship between the port and owners of these trucks, it is in both of their interests to ensure that electrification proceeds smoothly so they may work collaboratively on it. By contrast, airports have connections to passenger ground transport, including passenger cars (e.g., private vehicles, rental cars, taxis) and buses. While these ground transport vehicles may also become electrified in the future, the relatively more complex ownership and operational profiles of these vehicle fleets suggests that the airports may not get any insight into their electrification. This makes planning for airport ground transport connections (e.g., charging infrastructure) more difficult than for ports.

Another difference lies in the potential for integrating electric power generation. While ports and airports have logistics connections to the sea and air, respectively, maritime ports often have a physical connection as well, and this can be leveraged to support their role in the energy sector. For example, while both ports and airports can use their own land for wind and solar electricity production, maritime ports can also collect the generation from large offshore wind farms. Existing subsea pipelines could also be reused to export CO_2 for sequestration, which gives ports another point of contact with the broader energy system.

One convenient way to contrast the potential of ports and airports to serve as energy hubs is to examine the existing ecosystem of service providers in and around them today. As described in the review by Alba and Manana (2016), the energy profile of an airport resembles that of a small city in both scale and complexity. An airport is delimited by the land used for the movement of aircraft, but the structures and equipment on this land also serve commercial, industrial, business and entertainment needs, and these activities constitute an economic system of its own.

Airport activities are divided into separate airside and landside operations, as depicted in Figure 8. On the airside, services are focused on the needs of the aircraft, and coordination is focused on their movements; on the landside, services are focused on the needs of the passengers, baggage and cargo, and coordination is focused on their flow. Other than the fuel for the aircraft themselves, much of the energy used to deliver airport services is electricity, and airports typically have a high-power connection to the regional electric power system. Still, demand for heating and fuel for airport vehicles can represent a significant non-electric energy demand; for example, these end uses accounted for approximately 7% of total energy consumption in Spanish airports from 2012-2014 (Alba & Manana 2016). On the air side, runway lighting is a significant consumer of energy, while the terminal buildings consume the most energy on the land side.

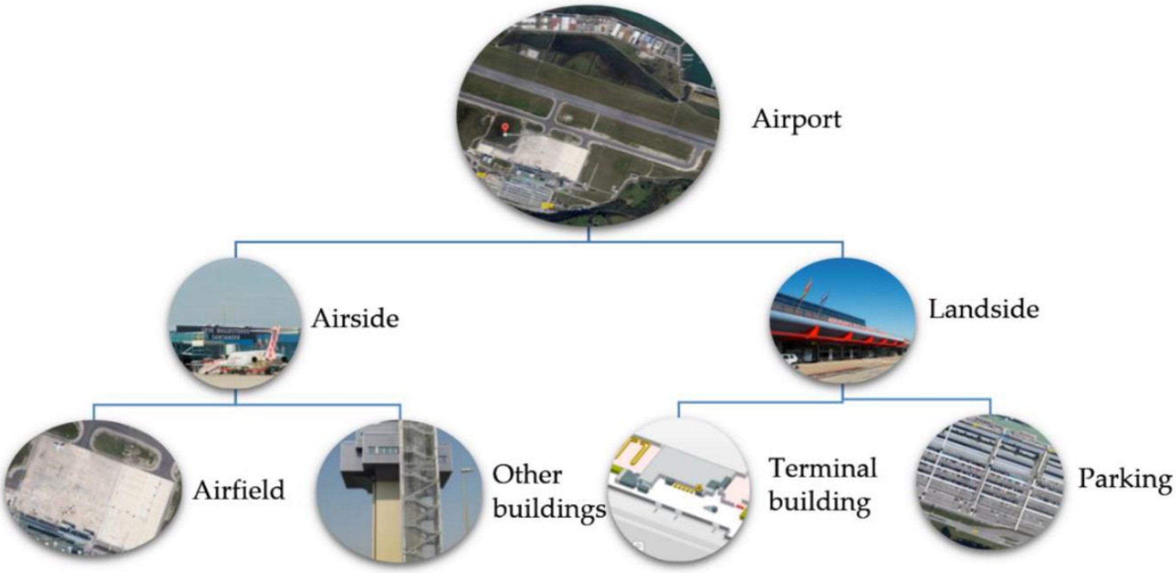

Figure 8: Airport services aligned with separate areas of activity (Alba & Manana 2016 [Source: Seve Ballesteros-Santander Airport]).

To satisfy this demand for energy (heat and electricity), some airports operate combined heat and power (CHP) cogenerating plants, at least one of which uses food waste generated at the airport itself as fuel. The large unoccupied land available at airports also creates opportunities for renewable generation, such as solar, wind and, where the resource is available, geothermal.

In a decarbonized transportation future, some of the aircraft and maritime vessels that use the transportation hub may become electrified or may transition to using another decarbonized fuel. While the vessel decarbonization decision may be outside the influence of most individual transport hub operators, the airport or port would be expected to support the needs of these vessels, whichever decarbonization option they pursue.

Table 1 categorizes similar types of transportation and energy activities for ports and airports, with examples of specific activities in each category for comparison. In a decarbonized port or airport, some of these energy activities could become electrified. For example, the specialized airside vehicles could be replaced by equivalent EVs, and the charging infrastructure to support their operation would need to be considered in an electrified airport. In the controlled environment of airside operations, there may be an opportunity to automate the charging and operation of these vehicles.

Table 1: Common services and activities in today's maritime and airports.

Service/Activity category	Maritime ports	Airports
1. Transportation hub vehicle operations	Ship scheduling, berth reservation, port traffic management	Flight scheduling, gate management, air/ground traffic control
2. Passenger and freight handling (in port)	Cranes, forklifts, drayage, (cold) storage, lightering	Airside busses, cargo vehicles
3. Fuel provisioning	Fuel storage, bunkering, cold ironing	Fuel storage, aviation bunkering, ground power for aircraft (GPU)
4. Other in-port services	Pilot boats, tugboats, lightering, dockside maintenance, security, and emergency response	Airside vehicles, airside maintenance, security and emergency response, terminal operations, retail, food service
5. Intermodal transport links	Long-haul shipping, rail, waterborne transport	Busses, metro rail, taxis, car rental, parking
6. Near-port transport hub related activity	Vessel repair/maintenance, warehousing, manufacturing, refining	Aircraft maintenance/repair, hotels
7. Near-port indirect activity	All other regional economic activity	All other regional economic activity

4. Airports as decarbonized transport-energy hubs

The concept of an airport as an integrated energy and transport hub is only recently emerging in the global aviation sector, and it is being further developed in Sweden. The World Economic Forum (WEF) has an entire initiative devoted to technologies for decarbonizing flight (WEF 2023). One editorial published in conjunction with the WEF initiative points out the potential for greater integration of airports into energy production and integration with the surrounding communities' energy systems (Barbarà & Desharnais 2023). Sveriges Regionala Flygplatser (SRF) have also initiated a project, Grön Flygplats, which has created a vision of Sweden's regional airports as combined transport and energy hubs, leading their associated regional communities into a decarbonized and digitalized future (Torstensson & Larsson 2022).

Efforts in Sweden airports are reinforced by a government priority toward fossil-free flight (Regeringskansliet 2017). After this statement, the Swedish Energy Agency initiated multiple projects under its Fossilfria flygtransporter 2045 (FFT-2045) innovation cluster to investigate the potential for decarbonizing flight (Energimyndigheten 2023b). These projects collectively investigate the potential for a wide variety of fossil-free aviation energy sources, such as biofuel, hydrogen, and electricity, and the role of the airport as the provider of energy is emphasized. A representative example is one recent report on decarbonizing air transport in Sweden, which notes the need for different airport infrastructure to support decarbonized flight, regardless of the energy source (Persson, Talalasova, Granberg & Eriksson 2022). The FFT-2045 final report outlines the actions needed to develop the markets required for fossil-free flight (Al-Ghussein Norrman & Talalasova 2021). This report notes the potential for greater integration of energy and transport operations and the potential for cooperation between actors within air transport and other transport modes.

Electric flight is developing alongside other electrification technologies, such as renewable electricity generation and battery storage, and airports could incorporate any of them in the future. The International Civil Aviation Organization (ICAO) has published a set of guidelines and case studies for airports wishing to integrate renewable electricity generation on airport land (ICAO 2023). Going beyond electricity generation, one of the FFT-2045 projects, RES-flyg, coordinated at Uppsala University, considered the possibility of using solar PV and large-scale battery storage, along with demand-side management, such as EV charging in the airport car park, to help manage airport loads, including charging electric aircraft, as depicted in Figure 9 (Thomas et al. 2023).

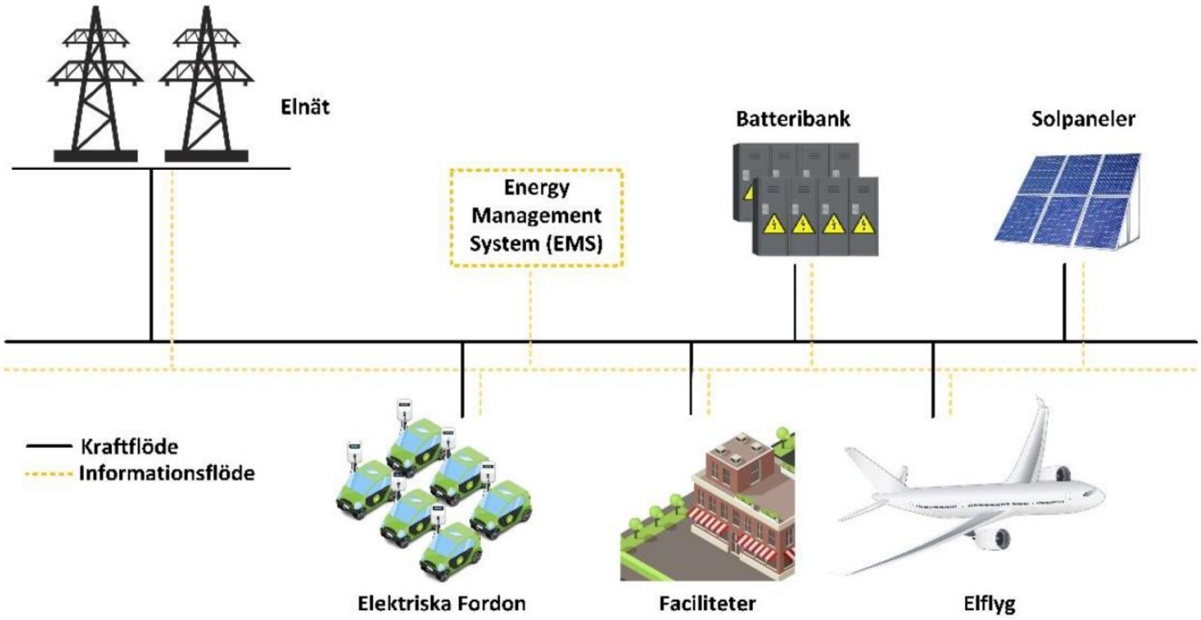

Figure 9: Illustration of the components of integrated airport flight and electricity management (Thomas et al. 2023). The airport has a connection the public electricity network (Elnät), onsite large-scale batteries (Batteribank), and solar PV (Solpaneler), which it uses to meet the managed demands from EV charging (Elektriska Fordon), the airport's own operations (Faciliteter), and electric aircraft charging (Elflyg). The solid lines represent power flows, while the dotted lines represent information flows needed to coordinate the power flows.

The focus on integrating electricity demand with transport operations at an electrified airport in the future is also demonstrated in some international research efforts. In the United States, a National Renewable Energy Lab (NREL) report demonstrates that the planning and operation of an airport e-bus fleet can be co-optimized (i.e., least cost optimized) to satisfy both transportation and energy needs of this service at an airport (Liu et al. 2023). An Italian research paper considers the charging demands from hybrid-electric aircraft and the operational loads from the airport to optimize battery storage capacity to minimize total system cost across both transportation and energy operations of the electrified airport (Trainelli, Salucci, Riboldi, Rolando & Bigoni 2021). A Chinese study considers an electrified airport with solar production, battery storage, and hydrogen production (Xiang, Cai, Liu & Zhang 2021). To support the flow of electricity within the airport, this analysis proposes a direct current (DC) power network within the airport, as depicted in Figure 10.

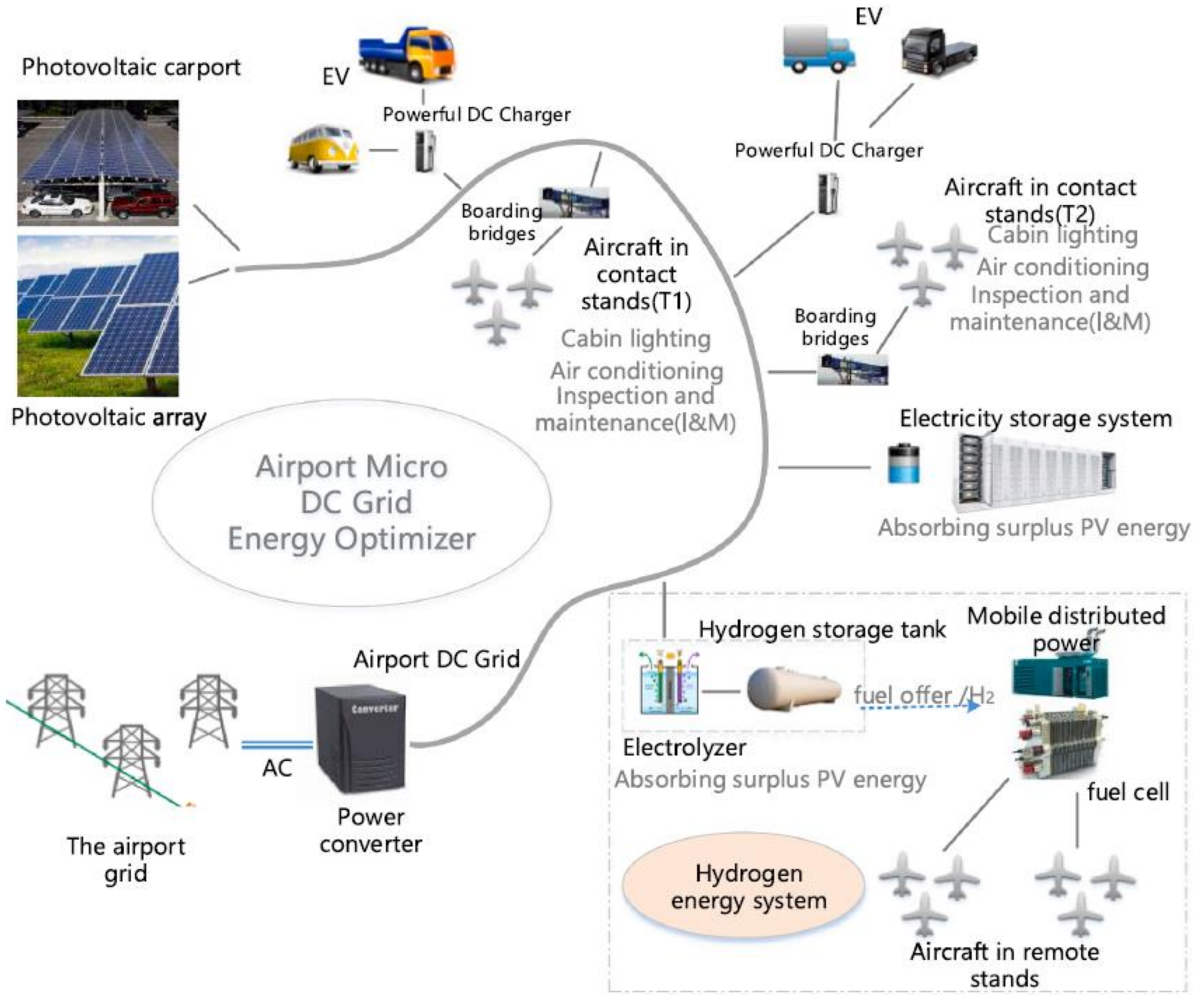

Figure 10: A schematic drawing of a hypothetical direct current (DC) airport microgrid, operating at 600 V DC, connecting major points of generation, load, and storage (Xiang, Cai, Liu & Zhang 2021).

4.1. Charging options for future electric aircraft

If electric aircraft are deployed in the future, charging them under current operational constraints could become a significant high-power load in a decarbonized airport. Several regional aircraft have been designed with battery capacities close to 1 MWh, and with an aircraft turnaround time of 30 minutes, charging powers exceeding 1 MW per aircraft would be expected (Smedberg, Nordberg & Oja 2021). Future improvements in battery technologies may permit larger electric aircraft and longer flights, which would increase the demand for ground power at airports. As an illustrative example, assuming a constant electricity consumption of 0.1 kWh/seat-km (Reimers 2018), 100-passenger plane flying 500 km would consume 5 MWh; to recharge its battery in a 30-minute turnaround, it would need 10 MW of charging power.

The cooling requirements of such a high-power charging system are worth noting here. The heat generated by a DC charging system is related to resistive heating in the charging system, which scales as the square of the charging current. Typical EV battery systems are designed for charging at 400 V DC, so a 1 MW charger would carry 2500 A of current. As EV manufacturers design battery packs capable of operating at 800 V, the current would halve. (Lovati 2022) Figure 11 shows that, with only passive cooling, the charging cable and connector would need to become increasingly massive to dissipate the heat generated during charging. Thus, an active charging solution (i.e., liquid cooling) is required for a megawatt charging system (MCS), which increases complexity, weight, and cost.

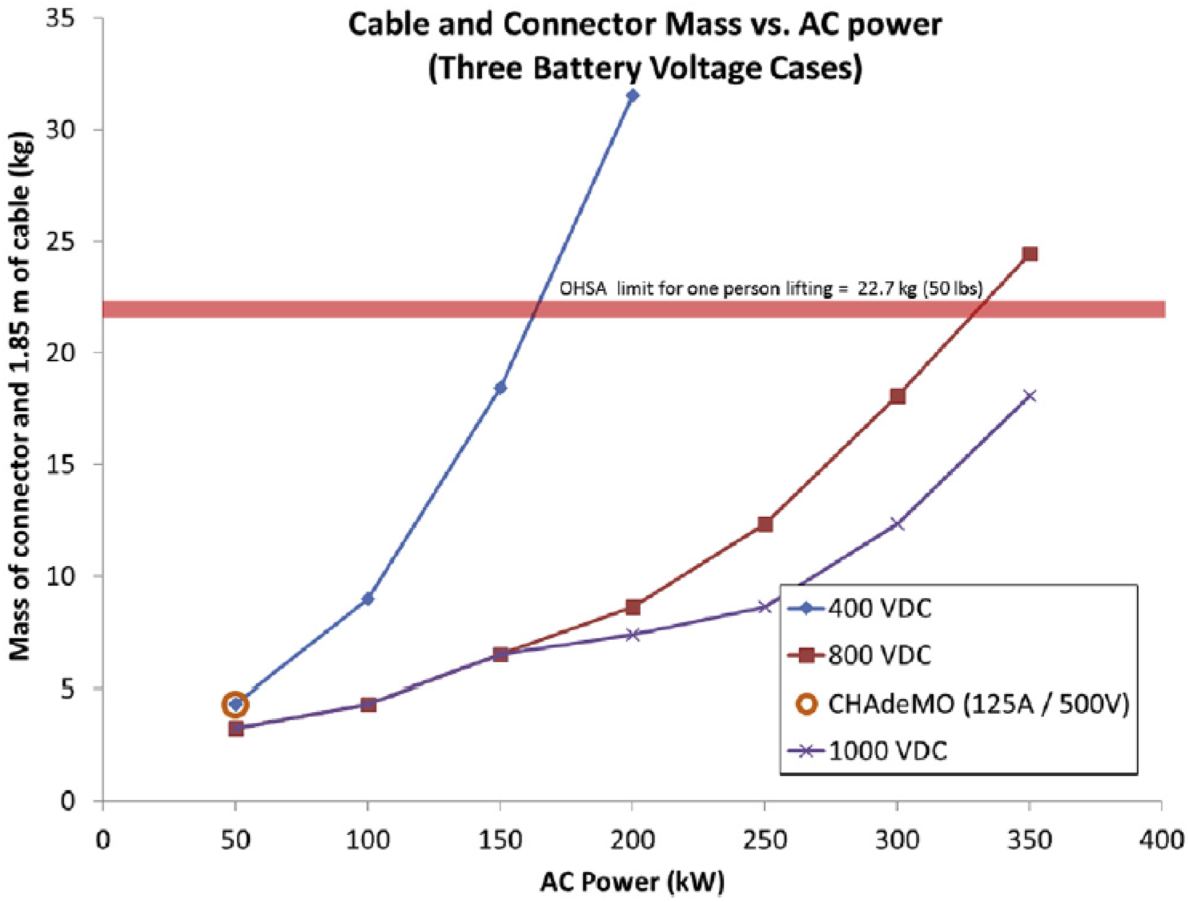

Figure 11: The mass of an uncooled charging connector and 1.85 m cable increases exponentially with charging power (Burnham et al. 2017). This study considered charging up to 350 kW, whereas electric aircraft are expected to require megawatt charging systems.

The cooling requirements of a megawatt charging system (MCS) mean that long-distance (i.e., more than 2 m) DC transmission of charging power may be cost-prohibitive. Shorter, dedicated high-voltage DC lines could be an option, though, in certain circumstances.

The way electric aircraft are charged affects both the transportation and energy systems at the airport. Figure 12 shows a schematic of four different charging options for electric aircraft. In these four options, numbered from top down as #1 to #4, power is alternately taken directly from the grid (#1, #3) or buffered via battery storage (#2, #4), and megawatt power is delivered to the aircraft either using fixed (#1, #2) or mobile (#3, #4) megawatt-class charging stations. In charging option #3 ("mobile MCS and transformer"), the mobile charging truck must have a connection to the grid, while the truck in option #4 carries its own energy storage devices (i.e., batteries).

Installing fixed charging stations at one or more gates simplifies the energy connection, but it limits the operations of electric aircraft to the use of the gate(s) equipped with these chargers. Installing more fixed chargers increases operational flexibility, but the significant cost of the chargers themselves is a deterrent to installing them at all gates[1].

[1] Although megawatt charging systems (MCS) are not yet commercially available, extrapolating cost estimates by the Interreg Deutschland Nederland project Electric Green Last Mile (eGLM) of the hardware and installation costs of chargers of different power outputs suggests that a MCS system could cost on the order of a half million euros (eGLM data, as reported in Nationale Agenda Laadinfrastructuur, 2023, p. 11).

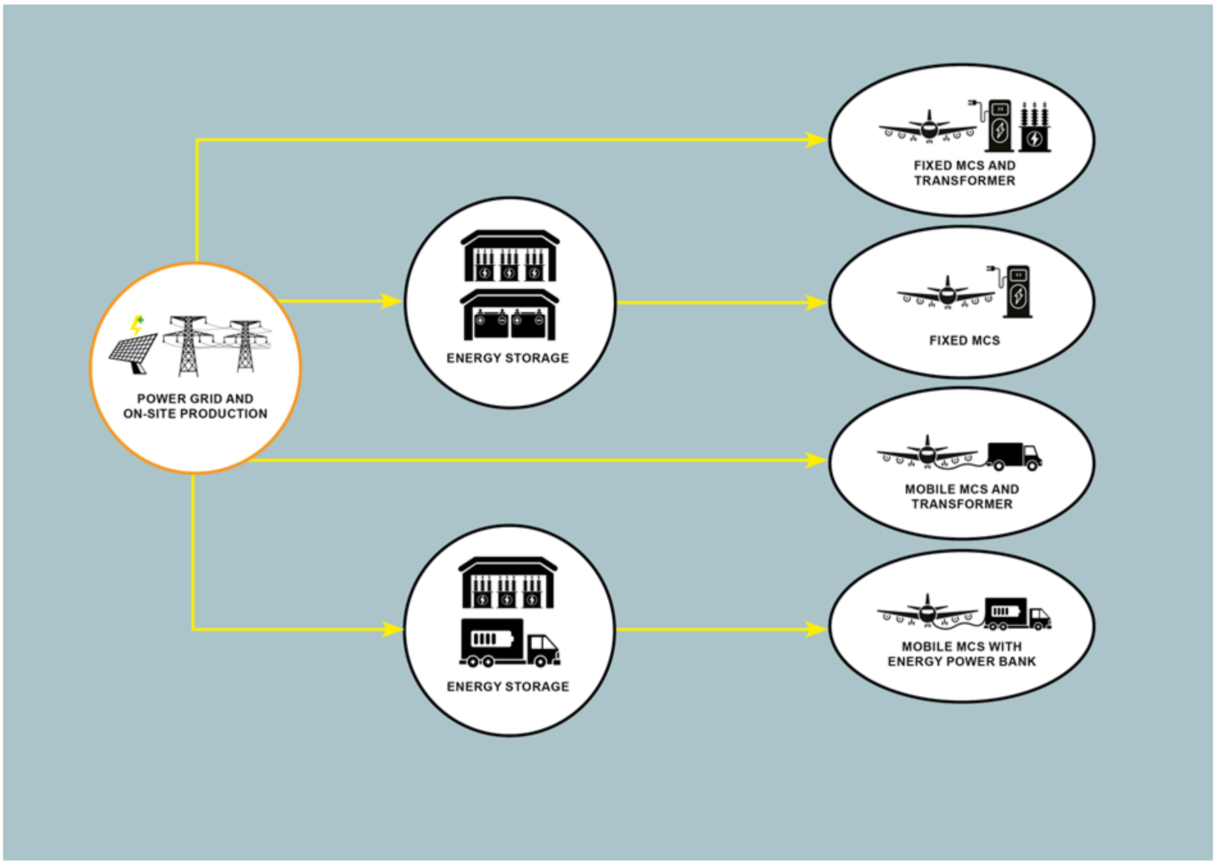

Figure 12: A schematic representation of four different charging configurations for electric aircraft at an airport. MCS stands for megawatt charging system. Arrows represent electric power lines in the local airport network. (Source: VTI, based on earlier draft by Swedavia, working material from the FAACE project.)

Installing the MCS hardware on a mobile platform (i.e., a truck) provides more flexibility for the transport operations of the airport, since the charging station can be driven to the aircraft. In Figure 12, the bottom two options show megawatt charging systems (MCSs) mounted on trucks. Both trucks would also need an active-cooled charging point, including coolant, pumps, and heat exchanger. The upper truck (option #3) pulls power from the local airport grid and converts it with onboard transformer/rectifiers, while the lower truck uses onboard batteries to supply the electrical energy (and power) to the (discharged) aircraft. Mobile aircraft charging options are assumed to cost more than their stationary equivalents, but they provide scalability and operational flexibility to the transportation operations of the airport.

A fifth charging option, not shown in this figure, would be an aircraft with the possibility to have its battery physically removed and replaced during aircraft turnaround (i.e., within 30 minutes). This battery swapping option would be similar to option #4 in Figure 12, where the discharged batteries removed from the aircraft would later be charged in a grid-connected energy storage facility.

The system complexity, mass, and hazardous operational environment of all airside MCS charging options may provide a role for specialized, autonomous, airport service vehicles for the mobile charging options in Figure 12. This potential is being explored in a new Trafikverket (TRV) project, called “Flexible and automated aircraft charging via energy storage at airports (FAACE)” (Trafikverket 2023).

4.2. Managing power flows in a grid-connected airport microgrid

As an electrified airport increases its electricity consumption and integrates production and storage, it is natural to think of the airport as its own semi-independent (grid-connected) micro-grid. Like the distribution network of an urban area, which may incorporate electricity generation and storage to manage the power flows within its network, an airport-as-energy-hub could do the same; this is consistent with the previous analogy of an airport's energy consumption being like that of a city's.

Besides reducing cost, treating an airport as a micro-grid can also improve the airport's resilience. This was shown in a recent paper, in which an airport conceived as a grid-connected micro-grid demonstrates greater resilience (i.e., the ability to continue to serve critical airport loads during a grid outage) compared with other standalone or hybrid electricity topologies (Masrur, Sharifi, Islam, Hossain & Senjyu 2021). Other work considers the resilience of an electrified airport micro-grid with electric aircraft and EVs in a parking lot, in which the scheduling of charging of both aircraft and EVs can impact both resilience of the airport energy system and its operating costs (Guo, Zhang, Zhang & Zhang 2022; Guo, Li, Taylor & Zhang 2023). The airport uses its own electricity storage to help balance the surrounding transmission grid (aviation-to-grid, A2G). Technology and operational considerations include charging scheduling (i.e., smart charging, V1G), vehicle-to-grid (V2G), and battery swapping.

Coordinating airport operations, including aircraft charging, and storage to capture these cost and resilience benefits requires a different kind of coordination of the airport's transportation operations. While traditional non-electric airports centrally coordinate aircraft operations to ensure smooth transportation operations, this coordination can generally consider energy prices to be fixed over the timeframe of the coordination decisions (e.g., a day). In an electrified airport, energy prices can change by an order of magnitude over the course of a day, so transportation operations and energy operations need to be considered together.

There is no single obvious transition pathway from coordinating the transportation hub activities of an airport to joint coordination of an energy-transport hub, but two possibilities emerge. First, existing airport authorities could extend their domain of responsibility to include energy hub operations. This would likely require enhancements and significant modifications to the knowledge, tools, and regulations that exist today for managing an airport's transport operations. This would result in a top-down coordination of energy operations: charging, storage operations, and investment decisions about new generation and storage capacity. This would have the advantage of management simplicity, as it would simply extend existing lines of management and coordination to the energy domain.

The other option is to leave the management of the airport transport hub activities largely the way it is, but to create a new market mechanism, a local electricity market (LEM), for managing the energy hub operations (Sousa et al. 2019; Tushar, Saha, Yuen, Smith & Poor 2020). A LEM functions as a market-based price-mediated coordination mechanism between generation, storage, and demand for electricity. Although these markets have been discussed for off-grid and residential applications, applying a LEM in an airport context would likely represent a novel application (Bjarghov et al. 2021).

Operating an LEM at an airport would require the development of new management tools and operating procedures, and the benefits are unknown. Still an emerging concept, there is no consensus within the LEM literature for how an LEM should be established. Mengelkamp, Staudt, Gärttner, and Weinhardt (2017) describe the operation of a hypothetical LEM consisting of interconnected residential customers and prosumers (i.e., residential consumers with rooftop solar) under two different market designs (decentralized peer-to-peer and closed order book auction) and two different types of market participants (random bidder and intelligent bidder). Although not an airport, this analysis represented a grid-connected LEM with significant electricity generating capacity and no load shifting (e.g., moving electricity consumption from one hour to another), which is similar to the operational constraints of an electrified airport in the future. Faia, Soares, Ali Fotouhi Ghazvini, Franco, and Vale (2021) conclude that an LEM may be centrally optimized up to a certain size of the market, but that above a certain number of LEM agents a decentralized peer-to-peer (P2P) market structure is more efficient. In this study, a system with 90 residential agents, each of which independently control generation and shiftable load (i.e., EVs with smart charging), is better optimized under a P2P market structure. This finding may have implications for airports, which might have a limited number of potential LEM agents so a central control may work well without the overhead of constructing and operating a P2P market mechanism.

5. Areas for future research

The airport as an energy hub requires a shift in perspective, from seeing the airport as primarily a transportation hub that only consumes energy to viewing the airport as managing its dual roles in the broader transport and energy systems. While techno-economic considerations surrounding the viability and implications of electric flight remain, many other technical and cost questions affect only the transport or energy systems, but not both (e.g., cost and performance characteristics of MCS, scheduling and routing in an electrified aviation system). While these questions are critical for operating an electrified airport, the challenges are not solely those of the airports themselves.

Some of the most interesting research questions in this context are, therefore, those that affect the transition of airports themselves to electric operation and supporting electrified flight, and those that span both the energy and transport domains. These questions tend to be operational, systemic, and economic. Given the uncertainty in aviation decarbonization technologies, solutions should be technology-neutral, which favors research that facilitates information, organization, and planning, though technology demonstrations may also yield valuable insights. In compiling this concept review, the lack of published research around several such questions stood out:

1. How might aviation operations (e.g., flight scheduling, gate assignment, flight turnaround, cargo warehousing, grid connectivity, generating capacity investments) evolve as the airport takes on a more central role in the energy system?
    a. Can the airport's role in both transport and energy systems be represented in a quantitative mathematical model (i.e., a cost-optimizing model, assuming static demands, or a profit-maximizing model assuming dynamic demands, or a multi-objective model)? Which boundary conditions must be assumed, and what happens if they are violated?
    b. Under which set of future conditions, if any, would it add strategic value to reduce aviation service levels at an airport intentionally in the interest of enhancing the energy system (or vice versa), for example, during a power outage, during a recurring low travel demand season, or systematically over time if an airport's aviation demand decreases?
    c. How might these trade-offs and opportunities differ from airport to airport and how might the solution space evolve over time as aviation decarbonizes? How does tighter integration with the surrounding community's energy system affect these trade-offs? Does a smaller airport play a greater or lesser role in the regional energy system?
    d. What are the observable signs or metrics that indicate when an airport could gain incremental value by shifting investment or operational capital toward or away from the energy system or the transport system?
2. Which energy investments would be most economic for an airport?
    a. Given the uncertainty in demand for electricity at airports as they decarbonize, and the uncertainties in future technology cost and performance characteristics, which near-term investments (or operational changes) are the most robust to these uncertainties? For example, would investing in solar panels (or battery storage) create more, or less, economic value to the airport if capital cost declines resulted in dramatic increases in solar generation (or battery storage) within the rest of the energy system? What might this do to energy price variations or the value of grid ancillary services?
    b. Are there any specific investments (or operational changes) that might preserve an airport's option value for the future, even if their expected returns are not among the highest today? For example, would investment in a mobile electric aircraft charger justify the expected higher costs compared with a stationary charger?

3. Which options for fast charging future electric aircraft are most cost effective, and which are most robust to future uncertainties in the growth of electric aviation? (The FAACE project mentioned earlier will attempt to address aspects of this question.)
    a. Can deployment of aviation MCS systems at airports hasten the advent of electric flight? If so, is it more economically efficient to provide economic support to all airports for this or to invest in a few MCS systems at targeted airports? How would the system evolve differently in the two cases?
    b. What are the total system costs and differential effects on aircraft, the airport grid, batteries, and other system components from stationary MCS, mobile MCS, battery-buffered and non-buffered operation?
4. What is the potential for hydrogen and other carbon-free fuels production at airports, either for internal consumption or for trade? Under which conditions (cost, market development, pipeline infrastructure, emerging industry, etc.), assuming they hold both within and without the airport, would fuel production at airports be encouraged/discouraged in the future?
5. How much potential is there in A2G?
    a. Can the airport authority manage the energy loads within the airport (e.g., V1G, load shifting)? Can it encourage two-way charging of connected loads (V2G)? Which use cases are most/least amenable to management, and how can they be encouraged?
    b. How far out into the surrounding community's expected future power demands should an airport consider when planning its own energy system investments? What are the advantages and risks of collaborating with adjacent energy system actors on, e.g., future demand scenarios, disaster planning and management, grid operations, investment planning?
    c. What potential errors are introduced by assuming that the off-airport energy and transport systems do not change or react to changes at the airport? For example, could the electricity tariff structure (or connection costs, energy prices, net load profiles, etc.) change in the future?
    d. What errors could be introduced by assuming too-optimistic assumptions about behavior changes outside the airport (e.g., airport charger use by non-airport vehicles, depot charging by airport-affiliated fleets, reluctance of agents to participate in managing loads or V2G)?
6. How does managing the power network of an airport as an energy hub differ from that of any other distribution network (i.e., a grid-connected micro-grid)?
    a. How do the loads differ, how does the potential for generation differ, how does storage differ, and how does the connection to the grid differ, if at all? How much influence, if any, do existing airport grid operators have over any of the above energy components?
    b. Can a LEM be created within an airport? What tools and processes would need to be developed, and what would the startup costs be? How much participation could one expect from airport users? Would it be more, or less, efficient than central management of the airport grid? What conditions might affect this over the short and long term?
7. Which regulatory and/or standards barriers discourage an airport from creating more societal value in its dual roles in the energy and transport systems?
    a. Which existing airport regulations (i.e., EU, Swedish national, regional, or municipal) could affect an airport as an energy hub in the future?

b. Which existing energy regulations would an airport become subject to if it became an energy hub?
c. Which standards are lacking and would need to be defined to coordinate energy sector and transportation sector agents in a decarbonized aviation future?
d. Are there any new regulations that should be enacted to facilitate the emergence of new actors and business models? For example, if the airport authority owns the local airport network, how can they prepare to serve loads on adjacent networks, either directly (e.g., via transmission lines) or indirectly (e.g., by offering EV charging stations for EVs that would otherwise charge elsewhere)?
e. Given the uncertainty around the pace of technology change and the global energy transition, which of the regulatory and standards changes are most important to make in the short-, medium-, and long term?

6. Conclusions

Airports, like maritime ports, are already hubs in the intermodal transportation system. As transport decarbonizes, they have similar opportunities to become energy hubs as well. The shift away from petroleum-based aviation fuels toward emission-free aviation, including electric aviation for short-haul flights, is likely to increase the demand for electric energy and, more importantly, power at airports. Electrifying airport operations means, among other things, that ground vehicles will likely become electric. Independently, vehicles coming to the airports for passengers (i.e., cars, buses), freight and service vehicles (light- and heavy-duty trucks), will also likely become electric, and they may need to charge at the airport. Satisfying the total demand for electrified operations and vehicle charging at an airport will increase its power demand; this makes it a more significant node in the energy system but does not make it an energy hub.

The increased cost for this electricity demand (i.e., increased transformer capacity, greater cost for peak power) creates incentives for the airport to manage its net load. Airports are already investing in renewable generation, but they may supplement this with electric storage and demand management. An airport electricity network with possibility for electricity generation, storage, and demand management makes an airport an energy hub in a decarbonized future.

To maximize the advantages of the airport energy hub, an airport would seek to simultaneously optimize its transport operations and its energy operations. Airport authorities are used to managing transport operations across a variety of disparate actors for the transport network's benefit, from aircraft to ground operations to passenger and freight handling to terminal services. Similar cooperation on the generation, storage and use of energy could also help manage the net airport load, which may reduce airport operating costs and may also support the off-airport energy system as well.

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