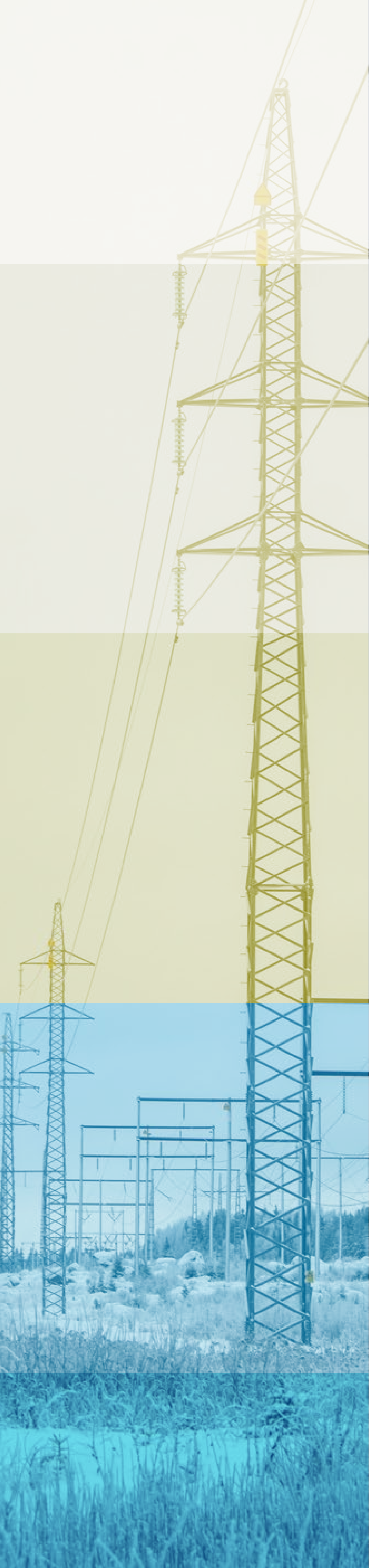

MISTRA
The Swedish Foundation for
Strategic Environmental Research

Background paper

The future energy landscape for Swedish industry and society

A selection of research challenges

November 2019

Authors:

Philipp Blechinger, Unit Head, Off-grid systems, Reiner Lemoine Institut

Mikael Hildén, Director, Finnish Environment Institute

Benjamin Smith, Senior advisor, Energy systems research, Norwegian Research Council

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The contents of this background paper are the responsibility of the authors.

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Contents

A Mistra programme on energy infrastructure would fill a gap

The Swedish government has set a goal of net zero national greenhouse gas emissions by 2045. Achieving this goal will require major changes throughout society and will have both direct and indirect consequences for Swedish industry.

Mistra's board has requested a proposal for a funding call[1] with a focus on 'the energy landscape for future industries and society in an environmental perspective'. This background report has been commissioned to guide the development of the call.

The report identifies six priority research areas and provides a brief overview of the current context in each research area. In addition, the report puts forward some ideas for a suitable scientific approach that the envisioned research programme[2] may employ.

The scope and character of the proposed funding call fills a gap in the current Swedish research landscape. The call is unique in offering longer-term funding than other funders, and through its inclusion of both the technological solutions and institutional changes required to transform the energy system. The majority of current research funding in Sweden tends to focus on either purely technological issues, or to a lesser extent, research questions that fall squarely in the field of social science. We envision a programme that more clearly recognises and addresses the links between different aspects of future energy system development pathways, drawing upon an array of research fields working together via inter- and transdisciplinary research.

The background report was co-authored by an external group of international experts. As part of the preparatory work for this report, Mistra organised a workshop on the theme "Powering tomorrows industry – energy infrastructure and the industrial landscape of tomorrow". The workshop took place in September 2019 and involved a number of representatives from relevant Swedish organisations. Moreover, Mistra's own staff contributed to the report.

1 Throughout this report we refer to Mistra's coming call for research, which we are proposing, as "the Call".

2 Throughout this report we refer to an envisioned programme successfully responding to Mistra's call for research as "the programme".

The programme should have a broad scope and a systemic approach

Aim

The overarching aim of Mistra's programme should be to support the transition to a more sustainable energy system achieving net zero national greenhouse gas emissions by 2045.

Specifically, the research should shed light on what will drive future energy infrastructure development and how to achieve the technical and institutional changes necessary to quickly reduce greenhouse gas emissions to very low levels, while meeting other societal objectives and constraints.

Scope

The research programme should address and recognise the multi-faceted character of the energy challenge. This requires a systemic view that can span the entire technological spectrum of the energy system from demand, through distribution of energy carriers, to energy conversion and supply. We believe that exploring drivers of demand of energy services, institutional aspects of innovation and similar non-technical aspects can add value compared with other research efforts in the area.

While a systems perspective is valuable, it is important to note that no research programme can address all relevant aspects. Prioritisation and a clear understanding of how the chosen scope fits into the wider system will be key, as will how the research can have real impact and accelerate the transformation of the energy system.

We suggest that issues directly related to land use and agriculture are excluded from the programme, as well as research, development and demonstration of hardware and other purely technical solutions.

Introducing six linked priority research themes

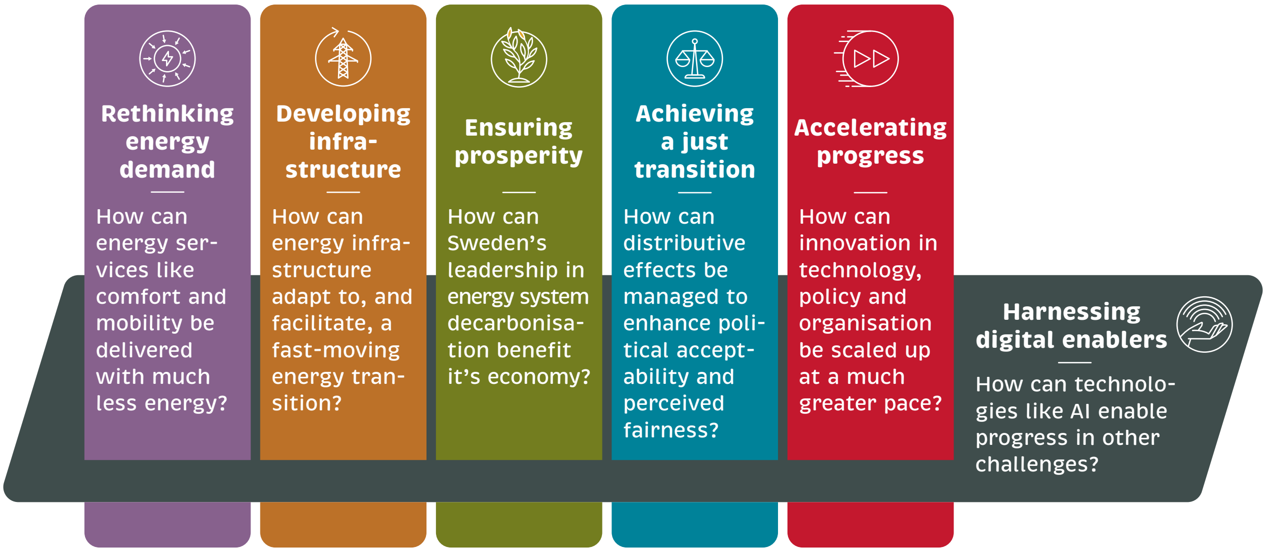

FIGURE 1. Proposed research themes and examples of potential research questions.

There are many ways to structure research around the Swedish energy transition and the role of infrastructure in it. We propose six interconnected research themes that together represent a wide array of research challenges, reflecting the complexity of the task at hand (figure 1).

1. **Rethinking energy demand** looks at drivers for energy demand, and how energy services such as indoor comfort or mobility can be delivered with much less energy than today. In a long-term perspective, even issues such as what forms citizens' preferences are relevant.
2. **Developing infrastructure** is based on the premise that any future pathway will require large investments in infrastructure, and that there is a strong path dependence in all investment strategies. Energy infrastructure can thus be both a facilitator and a barrier in the energy transition
3. **Ensuring prosperity** recognises that the energy transition will need to go hand in hand with continued prosperity of the Swedish society. Identifying and leveraging co-benefits of a cleaner energy system will thus facilitate and accelerate the transition.
4. **Achieving a just transition** broadens the traditional techno-economic focus on efficiency, to include aspects of justice and perceived fairness. There is a growing recognition that these factors will central for the feasibility of any meaningful political action.
5. **Accelerating progress** takes a broad view on actions and institutions that can incentivise and accelerate the transition to a more sustainable energy system, including the role of different actors and how policy can be designed and implemented.
6. **Harnessing digital enablers** focuses on the new possibilities created by the ongoing revolution in computing power, data analysis and connectivity. These technologies and methods hold great promise, and much of the potential remains untapped.

The research themes are described in more detail in the section below. In order to provide additional guidance, each section contains a list of example research challenges for the respective research theme. Due to the interconnected and overlapping nature of these six themes, certain research challenges are mentioned in multiple themes. These lists are by no means exhaustive and we do not expect any research programme to address all, or even a majority, of these illustrative challenges.

A scientific approach that matches the character of the challenge is required

The research themes are all coupled, and there are benefits of addressing the linkages between them as well as research questions within each theme. Depending on the chosen scientific approach, the size and composition of a consortium, and the available resources, it may be appropriate to be more – or less – comprehensive in the scope of a research proposal.

The research challenges will require a combination of social science and technology-oriented research. Many potential research questions have clear economic and other societal dimensions but cannot be fully answered without a good understanding of the technological aspects of the energy system itself. Thus, a research team that has both social scientists and energy technology experts will likely stand a better chance of success than one with a narrower set of competencies.

We also expect that the research programme would benefit from tying some research to a framework of scenario modelling and analysis. While this may not form the majority of the work or be at the centre of the programme, it can serve as a way to organise the research questions, facilitate the internal coherence and strengthen the impact of the results.

Considering the urgency of the energy challenge, it is critical that the research programme is relevant to actors and organisations that may transform the results into concrete action in the short to mid-term. Therefore, involving such stakeholders in the work would be beneficial. However, some important research questions do not easily lend themselves to, for instance, industry involvement or co-funding. Thus, the suitable type and level of engagement with stakeholders will depend on the chosen character and scope of the research.

Research theme 1
Rethinking energy demand

Energy demand is the crucial input parameter for determining the future energy supply. Reducing demand for energy, in particular peak demand, would make it easier to achieve the Swedish energy- and climate policy targets. Moreover, the drivers and patterns of demand will influence how a sustainable energy system could be developed and achieved.

Finding ways to realise and leverage the opportunities of reduced and changing patterns of energy demand is the core challenge of this research theme.

Current context

Energy demand can be broadly defined as electricity, heat and fuel consumption in buildings, transport, industry and agriculture. These facilitate energy services, such as comfort from space heating, mobility, and the production of goods.

Energy intensive industries play an important role in the Swedish economy today and have been instrumental in building the economic base for the current economy. Swedish energy prices, in particular for electricity, have long been lower and more stable than in most other OECD countries, forming an important competitive advantage for the industry.

The link between energy demand and economic growth shows sign of decoupling in the Swedish economy, but globally the demand for energy is still rising along with demand for energy services. Breaking this trend would provide many benefits, including making it easier to reach climate and energy policy targets.

Recent research[3] on low energy demand pathways towards 1.5 °C has questioned assumptions on future energy demand growth, pointing to the potential of digitalisation in providing services with significantly less energy. Moreover, there is a rich literature on the links between energy use, economic prosperity and subjective well-being that suggest that the coupling may not be as strong as historic data indicate.

Action related to energy efficiency is needed in at least four dimensions:

- Improving efficiency of existing technologies and activities
- Developing and deploying new and more efficient technologies
- Reducing energy demand in absolute terms and maximising the utility obtained from each unit of energy
- Increasing the flexibility of energy demand

The necessity of such a four-pronged approach can be illustrated in transportation. There, improving fuel efficiency is likely the easiest way to reduce energy demand and emissions in the short term. Moving to more energy efficient modes of transport and scaling new vehicle technologies is vital to get further progress, while pro-

3 Grubler et al. (2018), A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nature Energy 3 (6): 517-525.

cesses such as urban planning, transport infrastructure investments or even lifestyle changes will influence the underlying demand for transport services over the long term. Flexibility can be achieved via flexible charging of electric vehicles and access to alternative fuels such as hydrogen.

Potential research challenges

Maximising subjective well-being and personal utility while reducing energy demand. Research indicates that activities that maximise subjective well-being for individuals do not necessarily demand a lot of energy. That suggests that there is an untapped potential in this regard, but realising that potential is challenging. It is likely to require a combination of cultural change, new institutional structures and suitable economic incentives. Interdisciplinary studies of practices and perceived utility can provide new insight into how such changes can be achieved and upscaled.

Facilitating the energy transition through reduced energy demand. Sweden has a relatively clean supply of electricity and heat. Thus, reducing energy demand may not have a significant direct effect on national Swedish emissions. However, indirect effects may be significant, for instance through exporting clean electricity that substitutes carbon-intensive electricity in other countries and freeing up renewable resources for use in other sectors.

Managing potential trade-offs between reducing overall energy demand and other issues, such as higher peaks in energy demand. Electrifying transport and industry offer significant opportunities to reduce energy demand and emissions in those sectors. At the same time, the patterns and drivers of demand will change, which will create new challenges and opportunities. Mapping and comparing different pathways can shed light on the trade-offs between strategies, for example highly electrified scenarios vs. power to X scenarios.

Identifying and realising the potential for energy efficiency improvement in the Swedish economy in various scenarios. Research on energy efficiency has shown that there are numerous untapped opportunities, and significant effort has been put into understanding how to unlock this potential. Low energy prices play an important part, but oft-cited reasons also include information asymmetries and principal-agent problems. Understanding the current state of play and which actions could accelerate progress would be valuable. This can include both institutional aspects and technological, such as opportunities that new sensor and optimisation technologies offer.

Understanding the character and drivers of demand. This includes both technical issues, such as methods to adjust and control energy demand from industrial activities, automated process and appliances, as well as consumer behaviour. Efforts to harness behaviour change for energy efficiency have so far yielded mixed results. On the other hand, emerging trends in consumer preferences and behavioural norms, such as 'flight shame' and the rising interest in plant-based alternatives to animal-based foods, can offer insights on the potential role of behaviour. The potential for future shifts in consumer preferences and how that would influence energy demand is little understood.

Research theme 2
Developing Infrastructure

The guiding challenge for this research theme is how existing and new energy infrastructure can be planned and implemented to facilitate the transition towards a net zero emission energy system in Sweden.

The potential speed of the energy transition depends greatly on existing energy infrastructure such as power and heat generation assets or transmission and distribution grids. These represent substantial investments with expected lifetimes that often far exceed the time available to avoid the worst consequences of climate change. There are challenges related to stranded assets and how to develop entirely new infrastructure in all parts of the energy system, not just in electricity.

Despite an inevitable path dependency of the current system, decarbonising the energy system will require substantial changes to infrastructure. Sector-coupling, decentralisation, increased flexibility and digitalisation will be key trends going forward. Complicating this further is the challenge of how to finance necessary large and long-term infrastructure investments in time, adapt them to changing demand patterns and whether society will accept them.

Current context

The current Swedish electricity infrastructure is largely centralised and mostly decarbonised. Electricity generation is predominantly based on large-scale hydro, nuclear, wind, waste-to-energy, and bioenergy, complemented by district heating grids. There is significant domestic and cross-border transmission capacity. Despite this, there are already challenges related to investment in grid infrastructure, with insufficient grid capacity available to meet industry needs in some parts of the country.

Swedish energy infrastructure is connected to and strongly influenced by broader European energy infrastructure. European energy trends that will impact Sweden include, for example:

- Agreement on GHG emission reduction targets for both the European emission trading system and country-specific targets for effort sharing sectors outside the scheme.
- An ambition to transition from large-scale coal, gas and nuclear towards a system with large shares of distributed and variable energy generation such as wind and solar.
- An ambition of greatly increased interconnection and cross-border electricity trade.

Put together, the energy transition puts new and large demands on energy infrastructure across the economy both in Europe and in Sweden. Notably:

- Flexibility must be increased to handle greater variability in both supply, such as wind and solar, and demand, such as electrification of transport and heat.
- Sector-coupling is necessary to decarbonise demand sectors and will entail deep integration of electricity, district heat and transport infrastructure.
- Decentralisation, due to new renewable energy and flexibility, must be managed.
- Digitalisation will be a key enabler in realising these changes.

Development of infrastructure is far from solely a technical or economic question, nor is it constrained to the electricity system. In transport, the chicken-and-egg problem in charging infrastructure versus vehicle deployment is still a challenge, another example of developing a new system for production and distribution of clean hydrogen for use in vehicles and industry.

The energy transition in Europe has slowed down as the number of systemic conflicts increases. There is also a need to question the meaningfulness of paradigms and regulations of the conventional energy system and, if necessary, to replace them with new regulations that meet the requirements of a net zero emission energy system.

Research on technology diffusion[4] points to higher learning rates in "granular" technologies such as solar panels, batteries or LED bulbs. These technologies are easier to experiment with because they are modular, mass-produced and rapidly deployed with low risk. This contrasts with slower learning rates and more gradual cost reductions for "lumpy", customised technologies such as grid infrastructure, CCS, or electric roads. Decarbonising the energy system will rely both on granular and lumpy technologies. How lumpy investments can be accelerated to avoid creating bottlenecks in the energy transition is a major challenge.

A broad spectrum of research attempts to support the development of energy infrastructure. Energy system modelling and scenarios play a central role in this research. Key elements of infrastructure planning are computer-based models and simulations to understand the needed infrastructural changes, investments and technical challenges. Analyses of transitions to very low emission energy systems are typically based on techno-economic optimisations at different spatial and temporal resolutions, seeking the lowest cost solution from a system perspective. Currently, the modelling of the electricity system is well understood in technical terms and various scenarios exist for 100% renewable energy supply systems. However, research gaps exist on more comprehensive transformation pathways, sector-coupling and inclusion of social aspects into energy system models. A further challenge is accessibility and transparency, highlighting the importance of modelling with open source tools and the use of open data.

Potential research challenges

Understanding infrastructure needs driven by increased interplay between different parts of the energy system. For example, deployment of renewable power generation, transport and storage technologies will affect each other and needs to be analysed from a systemic point of view. More research is needed on the potential for flexibility between power and heat generation, transport, storage and demand, and what implications this have for infrastructure. Also, the requirements for a future grid supporting decentralised and flexible power supply need to be analysed. This may include decentralised supply scenarios and their alignment with

4 Healey, S. (2015). Separating Economies of Scale and Learning Effects in Technology Cost Improvements. IR-15-009. IIASA, Laxenburg, Austria.

local demand, looking specifically at the role of electrical islands and of prosumers (households and industry). This leads eventually to the question of the physical characteristics of a future electricity/energy system with zero emissions.

Designing policies and markets for infrastructure investment. The long lifetimes, high capital costs and complex permitting processes often associated with infrastructure investment make them particularly sensitive to policy uncertainty and political risk. Interaction between technological development, economics and policies need to be considered in decision making. Moreover, modelling of the future energy system can be made more actionable if it is combined with insights on the type of policies that are needed to support the transition. Examples include new forms of regulation for natural monopolies such as energy grids, allowing for greater innovation and opening certain aspects of the market for competition, such as storage. New market designs for energy services at different geographic and temporal scales that incentivise flexibility and market structures that allow trade and clearing prices for zero marginal costs electricity supply systems. This can be complemented by more inclusive forms of infrastructure planning and ownership that overcome political and social acceptance barriers.

Realising the potential of sector-coupling. Infrastructure planning needs to consider future developments in demand of all sectors and the different linkages of those. Thus, infrastructure development of electricity, heat and transport cannot be seen as standalone activities but must be coupled. This requires a detailed understanding of future demand scenarios and the linkages between the sectors. For instance, sharing infrastructure needed for large scale carbon capture and storage in Sweden between many firms and across is likely necessary in order to bring down the specific cost to reasonable levels. Research supporting such synergies is lacking. Other key focus areas include the role of CHPs, hydrogen, renewable methane, transport electrification and demand side management.

Facilitating innovation in infrastructure through local and regional case studies. An accelerated transformation does not only require scenarios on the transformation pathway and long-term goals, but also specific examples on implementation of new technologies. Again, a systemic view is preferred to test the possibility of implementing future technologies, but solutions have to be implemented and not only be described from a macro perspective. Here, locally adapted solutions can help showcasing the decarbonized energy system infrastructure of the future. In pilot cases it can be tested how a smart and sector-coupled grid can be implemented on a local scale or how stakeholders can be involved in the implementation of new infrastructure.

Research theme 3
Ensuring prosperity

A transition to a net zero emission energy system will also mean a transition of the economy. While this involves high upfront costs, these can be more than offset by a multitude of potential benefits. A prosperous energy transition will rely on these benefits being realised, for example through:

- Innovation to enhance the competitiveness of Swedish products and services in the global market, thereby securing export revenues and domestic employment.
- Utilising natural, economic and human resources efficiently, thereby reducing costs.
- Leveraging the non-climate co-benefits of low-carbon solutions and reducing side effects, thereby maximising well-being.

Current context

A hallmark of the energy transition, and a factor in its tardiness in responding to the climate challenge, is the high upfront cost. This is accentuated by the fact that many low-carbon technologies have higher capital costs and lower operating costs relative to fossil alternatives. Examples of these costs for a country like Sweden include:

- Subsidies for low-carbon technologies until they reach parity with fossil fuel-based technologies.
- Well-being impacts through reduced consumption of high-carbon products and services.
- Stranded assets, both physical and human.

A successful transition should result in these costs being offset by savings, with examples including:

- Efficiency improvements.
- Avoided impacts from climate change, assuming a global energy system transition.

Beyond minimising costs and maximising savings, countries have the option of pursuing several additional potential benefits, which could be the difference between a successful energy transition, and a prosperous one. These potential benefits include for example:

- Export revenues and domestic employment opportunities from the provision of low-carbon products and services.
- Increased well-being from the realisation of non-climate co-benefits and reduction of side-effects from low-carbon solutions.

International experiences with energy transitions so far have revealed the difficulty in achieving these potential benefits. While both German solar subsidies and Norwegian electric vehicle tax breaks have led to impressive technology diffusion, success in fostering and sustaining domestic industries has been more varied.

This is not to say it is not possible to reap these benefits with imported hardware. Learning from technology leadership can give a competitive edge in software solutions such as new business models and value chains.

The aforementioned cases have also raised questions about co-benefits and side effects. German solar subsidies have negatively impacted the affordability of energy, and the electrification of the Norwegian vehicle fleet has mildly increased driving distances with implications for road congestion. This underlines the importance of assessing low-carbon technologies against a range of societal goals, not only emission reductions.

A suite of crucial but nascent technologies offer new opportunities for Sweden to realise these potential benefits, including low-carbon trucking, as well as metals and chemicals production. There is however a knowledge gap relating to how an energy transition can be managed to not only achieve emission reductions at lowest cost, but also to maximise co-benefits and facilitate the growth of domestic industries with internationally competitive low-carbon products and services.

An important strand of research on this topic is that of sustainability transitions[5], which analyses the process of socio-technical systems change, for example through competition between incumbent and new actors. This, alongside other strands of research, can shed light on the framework conditions and industrial dynamics needed to foster emerging clean energy industries. A broader, related field looks at the role of government, through for example science, technology and innovation policy, in fostering innovation during a transition. A concept from this field with significant traction is that of mission-orientated innovation policy and the entrepreneurial state[6].

Potential research challenges

- **Translating the cost of technology leadership into a first-mover advantage.**
  The significant business opportunities in the global energy transition are most relevant where they intersect with existing Swedish industrial competencies. More insight is needed on how existing competencies can be leveraged to not only reduce Swedish emissions, but also achieve international competitiveness in the technologies related to those emission reductions. An important related question is that of the respective roles of energy, climate, industrial and innovation policy and the potential for their greater alignment.

- **Identifying business opportunities in the increasingly integrated European electricity market.**
  With greater shares of variable renewables in the EU and increasing market integration, Sweden has an opportunity to ramp up its provision of energy and flexibility services to the continent. It is however unclear to what extend Sweden should be a net exporter of energy and/or flexibility, and how this aligns with the goal of net zero emissions. Key questions include: How the buildout of wind power and interconnectors will affect the competitiveness of Swedish energy intensive industry; Who will finance the interconnectors; and How the costs and benefits will be distributed between system operators, producers and consumers.

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5 Markard, J., Raven, R., Truffer, B. (2012). Sustainability transitions: an emerging field of research and its prospects, Res. Policy, 41 (6) 2012, pp. 955-967

6 Kattel, R. & Mazzucato, M. (2018). Mission-oriented innovation policy and dynamic capabilities in the public sector. Industial and Corporate Change. 27. 787-801. 10.1093/icc/dty032

- **Understanding the competitiveness of the Swedish energy sector in the future information economy.**

  It is unclear how the energy transition and the incumbent energy sector will be impacted by the increasing value of personal data and the central role of multinational technology giants in the market for digital services. A better understanding is needed of the potential for the integration of energy services with, and learning from, other markets such as entertainment, communication, mobility or security services.

- **Harnessing the vast untapped flexibility potential in the current energy system.**

  The energy system is currently dimensioned for peak capacity. Achieving more flexibility and reducing this peak could result is massive savings in deferred infrastructure investments. There is a need to determine what the appropriate mechanisms are to incentivise flexibility to a much greater extent than today. Examples of more specific questions are: Finding the optimal balance between consumer intervention and automation; Increasing the accessibility of flexibility provision, for example by integrating flexibility services into consumer purchases of other services or energy-consuming appliances; and Understanding the potential of aggregators for flexibility and how should they be regulated.

- **The role of fiscal incentives and revenues under a successful transition.**

  Fuel taxes currently fulfil the dual purpose of disincentivising carbon-intensive activities and generating fiscal revenues. A successful transition to for example electric vehicles and carbon-free heating will lead to falling fiscal revenues. There is a need for guidance on how the collection of taxes should be modified to maintain the fiscal income while at the same time encouraging the transition process.

- **Transition strategies to better leverage the co-benefits of low-carbon technologies.**

  Examples include better local air quality, energy security, energy savings, and personal comfort and safety. Policies need to be designed to not only maximise co-benefits, but also to mitigate the rebound effects and negative side effects of low-carbon solutions. Examples include greater demand for energy and mobility services due to low operation costs of low-carbon technologies.

Research theme 4
Achieving a just transition

Research has suggested that distributional effects and perceived fairness may be equally, if not more, important than total societal costs for the possibility to transform the energy system.

A just and fair transition means that the transition and its consequences do not create unacceptable hardship for individual citizens, nor at a system level for different actors such as industries and businesses, civil society and other organisations. A key societal challenge is that a transition to net zero carbon energy system requires regulation that will create winners and losers, both amongst individual citizens and amongst firms. This raises questions on how to create policy mixes that can, if needed, compensate for unacceptable losses.

Because active interventions to achieve a transition in the energy infrastructure will affect numerous actors, accountability and transparency are crucial for transitions to be perceived as just.

Current context

One of the key challenges in achieving energy transitions is to identify and progress on pathways that are perceived to be legitimate, fair and just. At the Conference of the Parties of the UNFCCC in Katowice 2018 many countries signed the 'Just transition Declaration', which states:

> ***"Considering the social aspect of the transition towards a low-carbon economy is crucial for gaining social approval for the changes taking place. Public policies to reduce emissions will face social resistance and significant political risks for the governments implementing them if they are not accompanied by social security programmes for workers whose jobs will be lost or transformed. For these reasons, the issue of fair transition is a vital issue for governments, social partners and civil society organisations."***[7]

The concept of fairness has long featured in discussions of climate change mitigation. Examples include fairness in burden-sharing amongst developed and developing countries, or questions of fairness towards future generations.

This theme focusses on the perception of fairness by actors within the political jurisdiction of Sweden – voters, businesses, civil society – and its role in facilitating or blocking policies for the energy transition. This can be divided into:

- Procedural: does everyone get a fair say, is the process of identifying and agreeing on transition pathways inclusive and transparent?
- Distributive: are the actual real world economic, environmental and social consequences of the steps in the transition perceived as fair and equitable?

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7 *https://cop24.gov.pl/presidency/initiatives/just-transition-declaration/*

- Retributive: are those who do not want to follow agreed rules coerced to do so and are there mechanisms for punishing those who break the rules?

Fairness and justice are value-laden concepts but can also be approached analytically. Research striving at creating the knowledge base for transitions therefore needs to tackle questions that affect how transitions are perceived. The processes of identifying and agreeing upon goals for and steps towards the transitions can be developed and assessed to ensure that they are open, inclusive and perceived as fair. The research on the fairness and justice of deep decarbonisation paths need to be focused on the measures and actions that are examined in other parts of the programme.

Policy actions to achieve transitions towards deep decarbonisation will have consequences for individual citizens and enterprises and groups of actors. The impacts will be seen in areas well beyond the typical example of loss or transformation of jobs, e.g. the distribution of income, costs of commodities and services and wellbeing. Policy actions are likely to expose vulnerable groups to hardship. Carbon pricing typically manifests as a form of flat taxation and may even be experienced as regressive taxation if economically advantaged groups in society are able to avoid the tax by transitioning to low-carbon technologies. The electrification of personal transport offers an example, where policies might include carbon taxation on fuel and road pricing differentiated by vehicle emission intensity. Vulnerable groups are left paying these taxes while economically advantaged groups can avoid them by switching to – likely subsidised – electric vehicles. Pareto optimal solutions at the level of individual citizens are not likely to be possible in the long-term without active interventions beyond energy policies, through for example social security or regional policy.

For enterprises the consequences of an energy transition are reflected in e.g. business opportunities, profits and competitiveness, including potential windfall gains. By affecting the use and distribution of natural resources and raw material there may be environmental impacts and cross sector impacts as illustrated by the food-energy-water nexus. Fairness with respect to the impacts and compensations for adverse consequences will affect the acceptability of relevant polices and actions.

Thus, policies need to be developed in such a way that unacceptable consequences can be avoided. Incumbents can, however, use potential consequences as arguments against the transition towards decarbonisation and thereby slow down the processes at a national, EU and international level.

Not even the best efforts to plan and advance transitions are likely to achieve undisputable fairness. Therefore, it is essential that all interventions by the public sector are transparent and fulfil high accountability standards. A practice of systematic and transparent evaluations will be needed to maintain trust in the interventions actions that aim at advancing transitions. Such research-based evaluations can address the merit and worth of individual policies or policy mixes, their side effects and the ability to alleviate undesirable consequences.

Potential research challenges

An important challenge is to create pricing mechanisms and policies that ensure access to energy at affordable prices for all groups in society. The costs of energy, and in particular the volatility of energy prices during peak demand are important as potential drivers in an energy transition, but may also become a matter of equity. The cost of energy is also a matter in creating a level playing field for certain business sectors and individual businesses. The change of energy costs during transitions in household expenditures and in the cost structure of businesses, are therefore relevant.

Steps/criteria need to be identified for just and fair pathways towards energy transitions. Analyses of how transition pathways and actions can fulfil criteria of inclusiveness and participation can create the base for identifying actions that ensure transparency and accountability. Empirical economic, social and environmental evaluations of policies and actions aiming at transitions provide a base for learning and upscaling of transitions.

Co-creation approaches in identifying and designing pathways can be seen as a way to ensure just and acceptable energy transitions. Co-creation potentially opens up new processes for knowledge generation that may include joint fact finding, transition arenas, and other participatory processes at different level of governance.

The role of the public sector in enabling just and fair transitions may be critical. Policies may reduce the risks of adverse consequences for individual actors or groups of actors/citizens. This may have implications for the design and use of policies and policy instruments in ensuring fair and just transitions and questions of policy coherence become important. Questions of distributive and retributive justice will need to be addressed. The existence and practical design of non-energy policies that compensate vulnerable groups impacted by policies for the energy transition will be important.

A successful energy transition has significant implication for current fiscal policies that are based on taxing the use of fossil energy sources. A switch away from fossil fuel will remove part of the fiscal base. In 2018 Sweden collected 77 Billion SEK based on energy and nearly 50 Billion SEK were collected from fuel and carbon dioxide taxes.[8] There is thus a need to examine how fiscal policies should be developed to compensate for the future loss of current taxation income.

A just transition needs to navigate existing power structures, path dependencies and incumbents. It is relevant to explore and understand why societal actors strive to hinder transitions and how the opposition against transition operates. The barriers to desirable transitions need be examined and the factors affecting them identified.

8 Totala miljöskatter i Sverige 1993-2018. *https://www.scb.se/hitta-statistik/statistik-efter-amne/miljo/miljoekonomi-och-hallbar-utveckling/miljorakenskaper/pong/tabell-och-diagram/miljoskatter/totala-miljoskatter-i-sverige/*

Research theme 5
Accelerating progress

In order to avoid the worst effects of climate change, let alone keep within a carbon budget corresponding to the Paris agreement, it is urgent to accelerate the transition towards deep decarbonisation.

Current estimates of the limits of the global carbon budget[9] are being rapidly approached. Industrialised countries such as Sweden are expected to be among the front runners in reducing greenhouse gas emissions to zero. No exact blueprint exists for how the transition can be achieved, and despite ambitious national targets, no government or region has to date enacted economy-wide carbon pricing at a level sufficient to incentivise a timely transition. Thus, there is a need for a multitude of actions, such as policies, pilots and other measures, throughout different sectors of society. These can be learned from, scaled up, and thereby help to speed up the transition. A single action can be a catalyst for systemic change and hence the potential for upscaling should be explicitly considered in exploring, initiating and evaluating them.

Current context

In Sweden the heat and power sector has progressed towards decarbonisation, but there is a growing need to identify and implement action that can rapidly decarbonise challenging demand sectors such as transport. Both technology and policy experimentation and learning will be crucial. Despite encouraging cost reductions and deployment in certain technologies such as solar PV, wind, LED, and electric vehicles, the majority of necessary technologies for fulfilling the ambition of the Paris Agreement are far from on track.[10] While the situation is bleak, it also provides opportunities for break-through innovations and socio-technological transitions.

Sweden and other countries spend significant RDI-resources on supporting technological developments that are hoped to facilitate the transitions towards deep decarbonisation. In 2018 public energy RD&D budgets in Sweden were 149 billion USD (PPP), ranking 11th in terms of energy RD&D per unit of GDP (in 2017), ahead of Germany and Denmark, behind Norway and Finland.[11]

No single technology will be able to fulfil deep decarbonisation. The systemic transition that is needed will involve several technological changes that modify the way energy is produced and used. Such technological changes depend on and contribute to wider social, economic and cultural transitions[12]. Decarbonization of energy systems is not a technological issue alone, but needs to be seen as transdisciplinary challenge looking at economic, political, and social factors.

9 *https://public.wmo.int/en/resources/bulletin/annual-global-carbon-budget*

10 IEA Tracking Clean Energy Progress *https://www.iea.org/tcep/*

11 *https://www.iea.org/statistics/rdd/*

12 *https://www.eea.europa.eu/publications/sustainability-transitions-policy-and-practice*

The acceleration of desirable transitions in energy production and consumption requires actions on many different levels as socio-technical transitions depend on many institutional, technological, cultural and social factors. The emergence of innovations and their upscaling are complex processes. Research that supports the acceleration of transitions can therefore explore many different aspects of the transition from the evaluation of particular policies to the analyses of change in practice through different new technologies.

RDI-support can provide a base for niche management that nurtures innovations accelerating transitions in the energy system, but in addition existing path dependencies may need to be broken for transitions to materialise on a societal scale. Such systemic acceleration requires coherence across policies. For example, fiscal policies, policies for public procurement and innovation policies need to act in concert.

One important challenge is accelerating transitions is the recognition and management of uncertainties. Uncertainties pertain to the emerging technologies, the policy instruments used to accelerate the transitions, including side effects, and the wider context such as the global 'landscape' within which transitions take place. For example, the transitions in the field of transport may follow many parallel tracks from electric vehicles to biofuels and changes in the transport system itself.

Potential research challenges

A key challenge for Sweden is to identify the main drivers, solutions and barriers to a transition towards a net zero energy system in order to accelerate the transition by creating suitable technical, economic, political, and social conditions.

This question can be addressed from many different perspectives.

One way of achieving deep decarbonisation is to accelerate the progress towards a 100% renewable energy market. Its feasibility needs to be explored and acceleration can be achieved by designing appropriate rules for the electricity market that facilitate rapid addition of high levels of renewable energy in the system. The increasing share of intermittent energy and the decentralisation of production in the form of prosumers in both power and heat will challenge current markets. Market rules that encourage new entrants while at the same time maintain stability will need to be explored.

New solutions for energy production and control of energy system need to be showcased in real world laboratories. Many interesting experimental solutions exist, but in order to contribute to a transition they need to be tested and showcased in situations which are closer to real world conditions. Such operational testing will create the base for learning and more rapid upscaling.

Cities need to be encouraged to provide leadership and that can be leveraged for wider transition. Cities often have the political will and economic muscle to decarbonise at a faster rate than states. There are many examples of cities facilitating, demonstrating and testing novels solutions for decarbonisation and several networks have emerged among cities that act as front runners. Examples of solutions with city leadership are decarbonisation of the energy use in buildings, waste-to-energy with CCS, and low-carbon mobility. It is unclear however how these front-runners can contribute to wider decarbonisation at the national, European or global level, beyond being examples of progress.

Public procurement needs to be used as an important instrument in accelerating transitions towards deep decarbonisation. Public procurement is often seen as a potentially powerful driver for change, but current practices of public procurement are often conservative and maintain rather than disrupt existing energy systems. A major challenge is the identification of the necessary conditions for public procurement to become an action and driver that can accelerate transitions.

Constraints created by international politics, regulation and competition need to be overcome in developing and testing novel solutions that accelerate transitions. Radical solutions for advancing transitions towards deep decarbonisation may at least initially need 'protected niches' for testing and development. The upscaling from niche to mainstream needs to be enhanced without breaking rules on state aid and free trade, or the rules have to be modified.

Policies need to be designed to allow for the uncertainties in the transition. The acceleration of the transition to deep decarbonisation also increases risks of (partial) failure, when initially promising solutions fail to deliver. There are numerous sources of uncertainties that may turn into risks and failures, but also new opportunities. This requires flexibility at the level of policies and also technology neutrality in policies and measures striving to accelerate transitions. At the same time the acceleration may be dependent on a stable policy environment that supports particular solutions. These conflicting demands on policy need to be reconciled. A systematic evaluation of the policies and measures put in place to achieve and accelerate transitions is required to support policy learning.

Research theme 6
Harnessing digital enablers

Current trends towards greater volumes of data, better interconnectivity and enhanced methods to analyse and utilise data could revolutionise the way the energy system works.

Technologies exemplifying these trends, such as artificial intelligence, machine learning and automation, can function as digital enablers for progress in the five research themes outlined earlier in this report.

This final and cross-cutting research theme looks at where these digital enablers can make the most impact in facilitating and accelerating the energy transition, and how they can be harnessed.

Current context

Digitalisation in the energy sector is nothing new per se, but the rate and scale of digitalisation have experienced a step change in recent years, with further acceleration expected going forward. However, as digital technologies are playing an ever more important role in organising energy, energy is becoming ever more complicated to organise.

The future energy system is likely far more complex, granular and interconnected than today's. Examples include greater shares of distributed variable generation from wind and solar; deeper sector-coupling between electricity, heat and transport; and the proliferation of distributed flexibility resources such as smart appliances and electric vehicles.

Furthermore, societies and economies are becoming increasingly reliant on stable access to energy and digital services. The economic and societal costs of even momentary disruptions to these services are huge and mounting. While a more digitalised and interconnected energy system can be more resilient to disruption, it also exacerbates other challenges such as cyber security.

Research on digital enablers spans a broad range. An example from the computer science end of the spectrum is research on the dynamics of Complex systems – interactions of vast numbers of individual components and the emergence of collective behaviours. Here the energy system can be considered alongside other complex systems, such as the brain. A related field is Complex Adaptive Systems, referring to systems reorganising themselves to solve complex problems, with Neural Networks being a central example.

An example from the social science end of the spectrum is more applied research on how digital enablers can reach their full potential. Examples include issues around interoperability and standardisation, or issues relating to the secure and ethical treatment of personal data generated by consumers.

This theme deals with *Harnessing digital enablers* as a cross-cutting research challenge. This is due to its potentially decisive role in achieving urgently needed progress in the five preceding challenges:

- **Demand for energy** services can be better predicted and met more efficiently, for example through AI-based control of space heating, or by transitioning from physical to digital products and services.
- **Infrastructure development** costs can be greatly reduced through automated integration of variable renewables, predictive maintenance, or through deferred grid investments facilitated by automated peak shaving or peer-to-peer energy trading.
- A more **prosperous transition** is possible with significant cost reductions from digitalisation, as well as new opportunities for innovation and business development emerging from the integration of IT and energy sectors.
- Digital technologies can contribute to a **just transition** by increasing the accessibility of energy services such as mobility, or through fairer fiscal measures such as GPS-based congestion pricing instead of toll stations.
- The **transition can be accelerated** with digital technologies which can be rolled out and upgraded at much greater speed than hardware. Shared mobility can lead to higher utilisation rates and faster diffusion of more efficient technology.

Potential research challenges

- **Mapping of digital enablers and their applications.**
  Stakeholders in the energy system lack a clear understanding of how and where digital technologies can add value, artificial intelligence, distributed ledgers / block chain, machine learning and internet of things. This acts as a barrier for uptake, which could be mitigated by better mapping, for example through meta analyses.
- **Applying artificial intelligence (AI) across the energy system.**
  In the energy sector, AI-based systems have proven powerful in order to optimise systems, improve forecasts for demand and variable renewables, and control autonomous vehicles. Most applications are still narrow, reflected in the term Artificial Narrow Intelligence, as opposed to Artificial General Intelligence (AGI), which is used to describe AI with similar problem-solving capabilities to the human mind. How can AI be applied to broader energy system issues?
- **Enabling local markets for electricity and flexibility.**
  Significant potential for flexibility, energy efficiency, and deferred grid investments could be tapped through more geographically granular markets. Digital technologies, such as distributed ledgers / block chain technologies have been implemented in a number of pilot projects for peer-to-peer trading. There is however a knowledge gap relating to how digital technologies can facilitate a broader implementation of local markets, and how they can be seamlessly integrated with wholesale markets.
- **The role of active consumers in a digital energy system.**
  Harnessing distributed generation and flexibility will require a more active role for consumers. Relying on behaviour change has not proven to be a viable strategy for activating significant shares of the consumer base. Strategies utilising AI and automation, informed by insights from psychology, can play a key role in facilitating active consumers and minimising reliance on behaviour change.

- **Energy demand from data centres.**
  Many digital technologies, most notably cryptocurrencies, have significant data processing needs and inherent energy consumption. Data volumes are set to increase massively, which will entail huge energy consumption from data centres. Data centres require high energy security and often result in large and inflexible loads in the energy system. How can digital technologies be made more energy efficient and how can data centres contribute to flexibility in the electricity grid?
- **Modelling and managing uncertainty in energy system analysis.**
  Developments in data accessibility and processing power have enabled far greater detail in energy system modelling. One area on particular importance to analyses of future energy systems is uncertainty. Stochastic modelling enables the incorporation of uncertain factors such as weather data for variable renewables or policy developments. A key question going forward is how digital technologies can contribute to analysing the potential for not only known unknowns such as weather or policy, but unknown unknowns such as technology breakthroughs.
- **Data analysis, prediction and control.**
  Recent advances in algorithms from machine learning open up possibilities to design power system controls with the capability to learn and update their own control actions. For this type of multi-stage decision optimisation, deep reinforcement learning is a natural framework. There are many opportunities for theoretical machine learning research to contribute power system management and planning.
- **Data management.**
  A massive amount of data will be gathered from sensors, smart meters and IoT devices. A challenging question is how to archive and share such data, and how to maintain privacy and social acceptance for continuous monitoring of activities.

MISTRA

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