Master Thesis

MSc Energy for Smart Cities

Development and Analysis of Pathways for a Sustainable Housing Cooling Sector in Ljungby, Sweden, using Modular Participatory Backcasting

REPORT

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Review

This master thesis aims to design a pathway for the cooling sector in Ljungby, a town in south of Sweden, which would meet local stakeholders' needs and fulfil sustainability criteria. At the same time, the thesis makes an attempt to quantify future need for household cooling in Sweden, and test adaptability of Modular participatory backcasting to local conditions.

Context was analysed by mapping local stakeholders on an interest-power plane, and evaluating functions of the system, sustainability criteria, and growth drivers. Structure of the cooling system in 2035 and 2050 has been built around a stakeholder's vision of an *adapted and efficient cooling system supplemented by cooling demand reduction*, while its scale was assessed by using the United States as a proxy. A pathway and a short-term action plan for this desirable future vision have been created.

The thesis demonstrates the need to engage in strategic planning of the cooling sector early on, even in cold countries such as Sweden. At the same time, an argument can be made that resorting to qualitative approach – adopted due to limited data sources on household cooling in Europe and limited participation from local stakeholders due to pandemic restrictions – did not reduce the quality of analysis and presents a viable way of assessing the future vision of the system.

Contents

List of abbreviations

- AC Air conditioning
- BAU Business-as-usual
- CDD Cooling degree day(s)
- CHP Combined heat and power
- GHG Greenhouse gases
- DC District cooling
- LEAP Long-range energy alternative planning system
- mPB Modular participatory backcasting
- PB Participatory backcasting
- VC Vapor-compression

1. Introduction

Anthropogenic greenhouse gas (GHG) emissions are causing global temperatures to increase, which causes cooling demand to rise around the world. If and when actual use of cooling increases to meet this demand – something that depends on a multitude of other factors – it increases energy consumption, which in turn, in most cases, causes more GHG emissions.

Population in Europe, especially that in Scandinavia, historically did not feel the need to artificially cool down their households. However, as the demand starts to appear (or increase), together with increased availability of common vapor-compression systems, cooling sector becmes a significant user of energy. In addition, increase in electricity use for space cooling is threatening to endanger climate targets set by a range of international agreements and national plans, and peak demand for cooling during heatwaves presents a risk for stability of electrical grids.

Municipal government of Ljungby, a town in the south of Sweden, laid out ambitious energy and climate goals for the coming decades. At the same time while the energy-intensive sector of cooling is expected to grow, both GHG emissions and energy consumption are planned to decline. This master thesis aims to resolve this contradiction by estimating the future cooling load in Ljungby and creating a pathway for meeting household cooling demand in a sustainable way. Use of word *sustainability* in this case is not limited to mitigating negative effects on the environment but achieving sustainability in all aspects of the socio-technical system.

In order to achieve this goal, Modular participatory backcasting – a 13-step method developed for strategic planning of the heating and cooling sectors – was used. Relevant local stakeholders provided inputs for framing the problem and designing future visions for the sector. Two scenarios based on stakeholders' visions were created and then compared to the business-as-usual scenario. By combining the three, the final scenario was made and a pathway and short-term action plan for reaching this desirable future were designed.

Testing adaptability of Modular participatory backcasting to local conditions was another aim of the thesis, as despite the fact that the method was created for strategic planning of both heating and cooling sectors, case studies thus far have focused only on heating.

2. Theoretical background

2.1. Climate change and greenhouse gas emissions

As early as back in 1896, Swedish scientist and chemistry Nobel laureate Svante Arrhenius attempted to quantify the *greenhouse effect* of CO2 on the Earth's atmosphere (IVA, 2008). He, however, overestimated the capability of the oceans to absorb this gas, while at the same time underestimating the amount of CO2 caused by human activity – relating it mostly to large volcanic eruptions and ultimately downplaying the danger of anthropogenic climate change. Several decades later, Charles Keeling determined that the concentration of this molecule in the air is constantly increasing and the idea of global warming gained traction with the environmentalist movements in the 1970s. Nowadays, as the concentration of CO2 in the air reaches 410 ppm, with the highest previous (pre-industrial) concentration being 300 ppm reached around 300,000 years ago (NOAA, 2020), the issue feels more pressing than ever. Peak concentrations happen in (global north) winter, as the emissions from decaying greenery adds up with anthropogenic emissions, which creates a "ripple" effect in concentrations, forming the Keeling curve.

In late 2015, UNFCCC parties reached an agreement, thereafter known as the Paris accord, in the attempt to keep the global temperature increase "well below 2 degrees Celsius" by the end of the century, aiming to hopefully limit it to 1.5 degrees (UNFCCC, n.d.). Expressed in total emissions, it is estimated that emitting additional 1,000 Gt CO2 equivalent (adding to the 2,200 already emitted since the industrial revolution) would have the effect of raising the temperature by 2 degrees (Buck, 2019), making that the planet's *carbon budget.* The current rate of emission is 40 Gt of CO2, or 50 Gt of CO2 equivalent per annum (Buck, 2019), meaning that at current pace, the carbon budget would be spent within the next 20 years. More worrisome still, is that the rate of emissions continues to show a steady rate of increase (PBL, 2020), while the pathways towards reaching the goals mentioned above (limiting warming to 2 degrees Celsius) includes peak emissions by 2020, onset of negative emissions by 2030, and achieving net negative emissions sometime past 2070 (Buck, 2019). This scenario is represented in the McKinsey report as "Peak at 510 ppm, long-term stabilization at 450 degree Celsius" (McKinsey&Company, 2010).

These scenarios assume a relatively linear correlation between emissions and global temperature increase, i.e. the absence of significant natural feedback loops which may make the emissions, or the temperature increase exponentially, such as the release of methane stored in permafrost caused by increased temperatures in tundra or the shifts in large sea currents, respectively. These effects are known as *tipping points* and present a large danger to keeping climate change at bay. They represent points where linearity is broken and may cause large-scale, potentially irreversible effects for the environment. They are largely an unknown, as only by reaching a tipping point may we know there was one to begin with (Buck, 2019). Similar effects after certain points can happen in socio-technical systems as well, which will be discussed in the following sections.

Sweden is not exempt from climate change, both in terms changing weather patterns, as well as frequency and intensity of extreme weather events. The country has been 1.7 degrees warmer since the end of the 19th century (SVT, 2020). Disappearance of ice and snow surfaces (or shorter periods of their existence within in a year) due to increased temperatures decreases reflectivity for incoming solar radiation, further enhancing the warming up effect (SVT, 2020). In 2005, a cyclone called Gudrun ravaged south of Sweden (including Kronoberg county), as wind speeds of up to 42 meters per second felled four years' worth of harvesting volume in a few hours (Södra, 2020). In 2018 Sweden made the headlines again due to record high temperatures and forest fires. Despite being considered a cold country with low CO2 emissions per capita due to strict regulations and large forest area, mitigation and adaptation to global warming has been an increasingly important topic in Sweden, particularly in recent years.

2.2. Space cooling

2.2.1. Global warming and thermal comfort

Assuming that there was a need for space cooling in a certain place, any further increase of temperature requires a larger cooling sector to maintain the same level of thermal comfort. IPCC (2018) reports that the human-induced global warming is approximately 1 degree Celsius as of now, but 20-40% of world population live in regions which experienced warming of more than 1.5 degrees by 2015. The increase is larger over land than over the ocean (IPCC, 2018), further increasing thermal discomfort of land dwellers, i.e. human population. Aside from air temperature, air humidity is the other basic driver of cooling demand. Air temperature of 30 degrees Celsius feels like 31 degree when the relative air humidity is 50%, and 44 degrees when the humidity reaches 100% (IEA, 2018).

These two parameters go hand in hand, as the capacity of air to hold water increases with the increase in temperature.

Indoor thermal comfort is achieved through space cooling. The United States Environmental Protection Agency estimates that about 6% of energy for residential and 8% energy for commercial buildings in 2009 was used for space cooling (EPA, u.d.). According to the same agency, the total CO2 emissions linked to cooling are 210 (residential) and 150 (commercial) million metric tons per year, respectively (EPA, u.d.). In the EU, according to 2018 figures from Eurostat, 75% of heating and cooling is still generated from fossil fuels while only 19% is generated from renewable energy (European Commission, 2015). However, Jakubcionis and Carlsson (2017) claim that unlike the well covered and analyzed heating sector, the sector of space cooling is mostly overlooked, and little data is available on space cooling demand for EU countries. The authors further state that only 8 out of 28 member countries reported current space cooling demands in the Energy Efficiency Directive’s (EED) Article 14.

Since 1990, global emissions of carbon dioxide due to cooling have tripled to 1.13 Gt CO2 equivalent. The International Energy Agency reports “very confidently” that the “global demand for space cooling and the energy needed to provide it will continue to grow for decades to come” (IEA, 2018). In the Baseline Scenario for the future, IEA assumes that those who require cooling and can afford it will buy and use ACs, as well as that the private sector’s, and governments’ targets and plans will be reached – thus a “major shift” from BAU trends. Yet, this model predicts tripling of energy use for cooling between 2015 and 2050, driven mostly by the residential sector, upping the total CO2 emissions to over 2 Gt by the end year (IEA, 2018). The prevalence of different technical solutions and subsequently energy use and GHG emission vary greatly based on a multitude of factors, but the rising trend in cooling demand during summer months is linked to climate change and increases in temperature (European Commission, 2015). The GHG emissions caused by space cooling on one side, and the increased need for space cooling caused by global warming on the other side, are forming a vicious positive feedback loop.

Quantifying cooling demand is traditionally done by expressing it in cooling degree-days (CDD) (IEA, 2018). CDD measure how warm a given location is, by comparing the mean of the high and low outdoor temperatures recorded each day to a set standard temperature (T_{base}), i.e. 18 ºC in Europe (IEA, 2018), or

$$CDD = \sum_{i=1}^{365} \left(\frac{T_{i,max} + T_{i,min}}{2} - T_{base}\right)^{+} \quad (1)$$

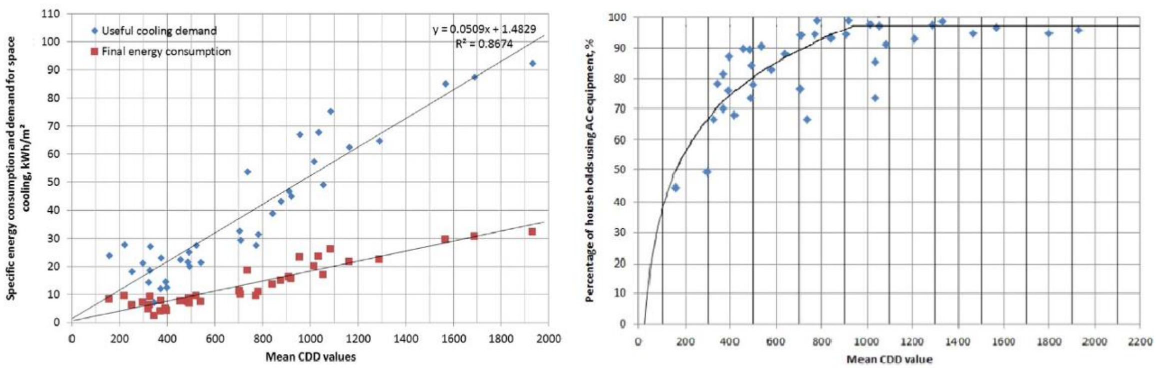
When the outside temperature reaches 18 degrees Celsius, people begin to consider cooling the building, instead of heating it (Investopedia, 2019). Jakubcionis and Carlsson (2017) studied the correlation between specific residential cooling demand ($Q_{cooling}$) and CDD for particular locality in the US and found that the linear regression expressed by the formula

$$Q_{cooling} = 0.051 \times CDD + 1.483 \left[\frac{kWh}{m^2 a}\right] \quad (2)$$

describes "almost 87% of all identified response variable variations" (Figure 1a). As for the extent to which this cooling demand is met, the same authors described that this correlation is "non-linear until at approximately 920 CDD" and can be described with the formula

$$PNT = 26.33 \times ln(CDD) - 81.69 \quad (3)$$

where PNT is the household AC equipment penetration rate. At this point (920 CDD), full penetration of AC equipment is reached (Figure 1b). Limitations of these assumptions, both those presented by Jakubcionis and Carlsson and those regarding the specific case of Ljungby (and Sweden), are analyzed in the Discussion section of this thesis.



(a) Cooling demand versus CDD (b) AC penetration versus CDD

Figure 1. Dependency of specific cooling demand and AC equipment penetration rate on CDD for different localities in the US, adapted from Jakubcionis and Carlsson (2017).

CDD fluctuate over time with the weather and surges in CDD can lead to permanent shifts in the cooling load. IEA estimates that the rising average temperatures as a result of climate change will lead to a “significant” increase in CDD in certain areas, including northern Europe. For the EU as a whole, this increase will be 17.5% between 2016 and 2050 – from 292 to 343 CDD.

2.2.2. Other drivers of space cooling

Population growth and urbanization are also important drivers of cooling demand. Larger population requires more indoor housing and commercial space to satisfy its everyday needs, which (all other things being equal) directly increases the cooling load and subsequently the required energy. UN estimates that the current world population of 7.7 billion would increase to 9.7 billion by 2050 and 10.9 billion by 2100 (UNDESA, 2019). The increase in Europe is expected to be much smaller, rising from 1.11 billion, peaking at 1.14 billion in 2050, and then slowly decreasing to 1.12 billion by the end of the century (UNDESA, 2019). Thus, population increase may not present a considerable cooling load driver on the continent as a whole, but the increase could be considerably high in certain places such as Ljungby, which plan on significantly increasing their number of inhabitants. Urbanization, resulting mainly from rural-urban migration, will also drive the cooling demand upwards (IEA, 2018). There are several secondary reasons for this, such as economic and lifestyle differences between urban and countryside populations, but the main one is the *heat island effec*t (Figure 2.). Greater density of electric appliances (heat generators), buildings (heat capacitors), cities being less reflective than the countryside, and lower rate of evaporation due to large concrete areas (IEA, 2018) are all causing this effect.

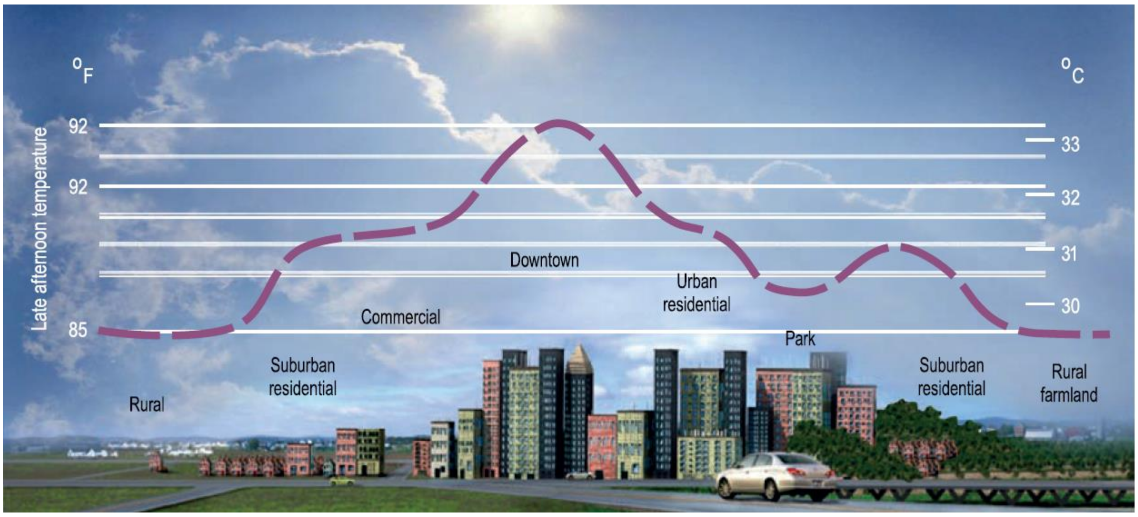


Figure 2. Heat island effect.

The increasing cooling demand is largely unmet in certain regions of the world, as a multitude of factors, such as the degree of electrification and economic status, also play a significant role in using space cooling. For instance, only 4% of households in India possess AC equipment (IEA, 2018), despite it being one of the highest temperatures and humidity regions in the world. On the other hand, 98.8% of households in private apartments in Singapore own an AC device, while 60% of electricity consumption of non-residential buildings is caused by air conditioning (Happle et al., 2017). All other things being equal, an increase in income in the hottest countries causes an increase in AC demand (IEA, 2018).

In rich, warm countries, where in the majority of households and businesses AC had already been installed and is being used, the *gradual* increase in cooling load will come mainly from the gradual increase in CDD, caused by the warming climate (in case of lack of other major drivers such as population surge). Accordingly, the IEA (2018) report states that the US had an increase of only 1% of electricity demand for cooling between 1990 and 2016. Poor, colder regions would witness the same kind of CDD increase and would also see hardly any increase in cooling load as a consequence, due to limiting economic factors.

The remaining two categories of countries are the ones interesting for analysis, as socio-technical systems, just like the natural ones, might have their “tipping points”. One such point with regards to space cooling is related to poor, warm countries, as “when income increases past a certain threshold, households start supplementing or even replacing electric fans with ACs” (IEA, 2018). Thus, economic prosperity will likely be the key driver of what the IEA expects to be “rapid growth” of AC demand in developing countries. The tipping point in rich cold countries may get crossed as rising outdoors air temperatures causes a drastic increase in installed cooling capacity. It has been reported that a series of heatwaves in France in 2015 led to periodic surges in sales in ACs in several regions, which caused a permanent increase in cooling loads during regular summers – consumers started using newly-bought ACs in the same weather conditions where an electric fan would earlier suffice (IEA, 2018). Thus, a gradual increase in CDD in Sweden may cause a disproportionally large increase in cooling load in the future.

2.2.3. Total energy demand and peak load

The total (mostly electrical) energy demand for cooling is not a dramatic issue at present, as cooling in the EU uses a fairly small share of total final energy (European Commission, 2015). However, it may prove crucial for strategic planning of the future, mainly due to two reasons – climate targets and grid stability. On one hand, cooling is a small sector, but one which will undoubtedly grow in the near future. At the same time, the sector must "sharply reduce its energy consumption and cut its use of fossil fuels" in order to fulfil the EU's climate and energy goals (IEA, 2018). In other words, even if the overall cooling demand remains the same, which will hardly be the case, structural changes should be sought with respect to the efficiency and the primary energy mix used to power the sector. When it comes to demand spikes, space cooling accounted for around 14% of peak demand in 2016, averaged for all countries (IEA, 2018). Most households in Singapore turn on their air-conditioning between 9pm and 11pm, and off between 6am and 8pm (Happle et al., 2017). On the other hand, IEA reports that cooling demand in California starts at 7am and lasts until 17pm in winter and until 21pm in summer (IEA, 2018). Planning around when the cooling demand occurs – both in terms of seasonality as well as time of day – is another thing to keep in mind, as maintaining and operating electricity capacity to meet the peak cooling demand is very expensive (IEA, 2018).

2.2.4. Indoor cooling in Sweden

Sweden has historically pioneered different heating solutions and their large-scale applications. More than 50% of heat in buildings is delivered through district heating and the country has the highest share of renewables for heating in the EU (SEI, 2017). However, the topic of space cooling has come to focus in recent years as well, due to changing climate. This topic is not unrelated to that of space heating, both in terms of issues, as well as solutions. The strong heating focus in design and construction of buildings in Sweden, done with the intention of lowering heat losses, also obstructs heat flows in warm summer days, increasing the demand for cooling (Werner, 2017). On the solution side, the established expertise of district heating kickstarted the deployment of district cooling solutions, with the first system implement in Västerås in 1992. Nowadays, district cooling systems in Sweden deliver 3.6 PJ of cold per year in 40 urban areas, with the annual expansion rate of 8% since 2000 (Werner, 2017). The capacity of DC systems in Stockholm ranges from 3 MW on the lower end, all the way up to 228 MW for the ones supplying the central areas of city (Logstor, n.d.).

Due to rising demand for space cooling, in the absence of large-scale solutions (such as district heating) in less densely populated areas, and with little economic obstacles, crossing an “AC tipping point” could sharply and irreversibly increase electricity consumption, endangering different climate targets and the stability of electrical grids. The particular case of Ljungby will be addressed in the following section.

2.3. Ljungby, Sweden

This master thesis is done in cooperation with Ljungby kommun (Ljungby municipal government). The call for the thesis project named “Climate change scenarios” was open for different approaches, with the intention of designing climate change mitigation and adaptation strategies for different socio-technical systems in the town. Following is the preview of relevant information about the town itself and the climate and energy goals and targets set by the municipal government.

2.3.1. Local climate, population, and energy sector

Ljungby lies in the south Sweden (Latitude: 56° 49' 59.66" N Longitude: 13° 56' 26.95" E). With respect to the Köppen-Geiger climate classification, climate in Kronoberg county is “temperate, no dry season, warm summer”, or “Cfb” type. According to publicly available data (BizEE, n.d.), the average number of CDD in the last three years for Ljungby was 190. This number varies greatly from year to year, as heatwaves in 2018 caused the CDD for this year to be 297, while 2020 was relatively cool with only 121 CDD (Figure 3). The demand for cooling starts by mid-April and ceases by late September, with peaks usually occurring from June to August. The number of CDD in Ljungby is expected to increase with further global warming. Different global scenarios predict different effects for Kronoberg region by the year 2100 but forecasting temperature increase is more reliable for mid-century. Results of both “optimistic” and “pessimistic” climate change models by Eklund et al. (2015) predict temperature increase of between 1.5 and 2.0 ºC in summer months in Kronoberg region between 2021 and 2050 (the same two models show very different values for century-end).

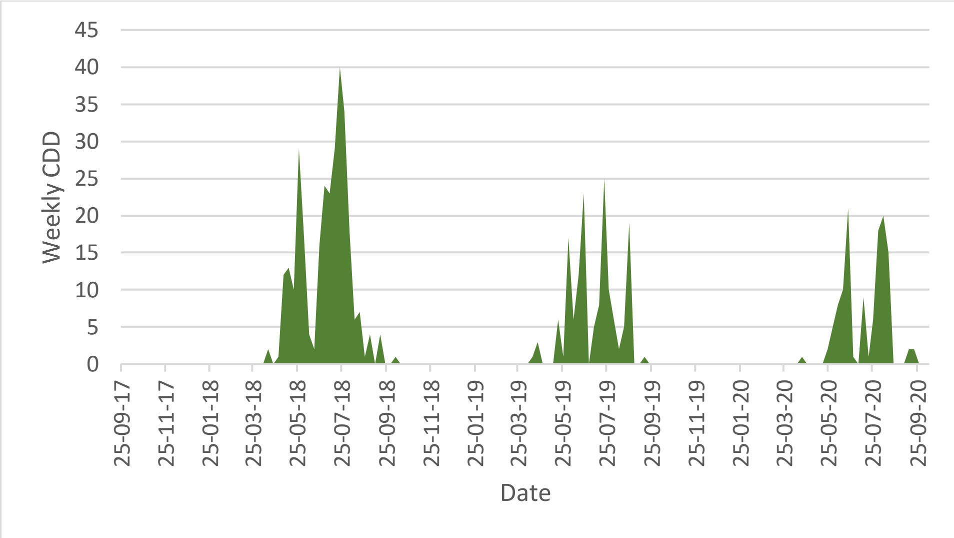


Figure 3. Cooling degree days in Ljungby with 18 ºC base.

Ljungby has 28,521 inhabitants – 16,094 or 56.4% living in central Ljungby (urban population) and 12,427 or 43.6% rural. There are 12,471 households in Ljungby as of 2019 (SCB, n.d.). Useful floor space and the number of households of each given size are given in Table 1. For comparison, the estimated average living space per person in Sweden is 42 m^2 (SCB, n.d.).

Table 1. Household useful floor space and inventory in Ljungby.

Floor space [m^2]	0-50	51-80	81-110	111-140	141-170	171+
Avg. floor space [m^2]	25	65	95	125	155	185*
Size of inventory	849	3563	2793	2734	1562	970

Table adapted from the SCB website. * denotes extrapolation based on arithmetic progression.

In 2016, total energy consumption in Ljungby was 1,060 GWh, out of which 318 GWh (or 30%) was electricity (Ljungby kommun, 2018). 44% of total energy was from renewable resources, an uptake from 38% in 2016 and estimated total CO2 emissions were around 150,000 tons (Ljungby kommun, 2018). Ljungby energi, the local energy company, operates a hydropower plant (yearly output of around 8.5 GWh) and a CHP plant used mainly for supplying district heating, but also producing 21.5 GWh of electrical energy annually (Ljungby energi, n.d.). Ljungby energi is by far the largest local producer of electricity. The local CHP plant is run on communal waste, which is considered to be 60% fossil fuels, and peat, which IPCC since 2006 classifies as “a fuel between fossil and renewables” (Green, n.d.). A small amount of electrical energy is gained from solar PV (Ljungby energi, n.d.) as an average rooftop in Ljungby can produce around 125 kWh/m^{2}a. The municipal Plan (addressed in the following section) states that "15-20% or around 50-70 GWh" is produced locally – in 2016 this was around 30 GWh electricity and 20 GWh heat (Ljungby kommun, 2018). The rest is imported from other regions of Sweden.

2.3.2. Climate and Energy Plan

The municipality government published a Climate and Energy Plan (Plan) which includes six focus areas – emissions, renewable energy, energy efficiency, transport, consumption, and security of supply – and targets for each, reaching until year 2050 (Ljungby kommun, 2018). Targets of most importance with respect to strategic planning of the cooling sector are:

1. Emissions (goal 1)
    a. Net emissions from Ljungby should be zero by 2045; compared to the year 2005, a reduction of 63% by 2030 and a reduction of 70% by 2035 is expected.
2. Renewable energy (goal 2)
    a. By the year 2045, the municipality should be free of fossil fuels – all energy should be renewable.
3. Energy efficiency (goal 3)
    a. Compared to 2005, energy efficiency in Ljungby should be 50% higher by the year 2030.
4. Security of supply (goal 6)
    a. Renewable energy production should cover "important societal needs" by 2035.
    b. By 2050, Ljungby should contribute to Kronoberg county being a net exporter of energy.

Ensuring that Ljungby reaches the goals set by the Plan would require significant strategic planning and implementation monitoring by the municipal government. The former is the main reason for opening a call for the Climate Change Scenarios master thesis. However, developing a plan for a green and sustainable transition of a system is only the first step towards reaching the end goal, in particular in circumstances when the transition would have to involve many different stakeholders' actions. A method which could ensure mutual agreement of all involved parties in the process of long-term planning of socio-technical systems is needed. The following section would describe how Modular participatory backcasting fits in this scenario.

3. Methodology

3.1. Backcasting

Backcasting is used for long-term strategic planning for sustainability transitions of socio-technical systems (Zivkovic et al, 2016). It is an approach which consists of creation of a desirable future vision, followed by creation of a pathway on how that future can be achieved (Damsø et al., 2014). Karl Dreborg (1996) argues that backcasting is best applied on “long-term complex issues, involving many aspects of society as well as technological innovations and change”, and also in cases when dominant trends are a part of the problem, and longtime horizons allow alternative futures to develop (Quist, 2013). In addition, backcasting provides stakeholders with a better understanding of possible gains and side effects of a future vision (Quist, 2013).

Backcasting focuses on the problem, rather than current trends and present conditions (Dreborg, 1996). This distinguishes it from the other two methods for scenario creation (Figure 4.), as described by Quist (2013):

- Exploratory studies focus on what *could* happen. This method investigates all possible ways in which a socio-economic system could evolve in the future, with the result being a set of different futures (*scenario cone*) with different likelihoods of occurring, reflecting uncertainty and different perspectives.
- Forecasting asks the question what *will* happen and is about likely futures. The results are often surprise-free futures and BAU scenarios which reflect dominant trends at the moment of analysis. In a sense, the forecasted future is the most probable one from the scope covered by exploratory studies.
- Backcasting relates to the normative question what *should* happen. These type of scenarios are also referred to as normative scenarios, or future visions.

The approach was developed in the 1970s and early 1980s, as common practices of the time, when it came to energy forecasting, emphasized large-scale electricity production and nuclear power, and assumed a strong growth of energy demand (Quist, 2013). The situation with GHG emissions in the 21st century is a similar one – BAU scenarios would result in futures of global warming of multiples of that agreed on by the Paris accord.

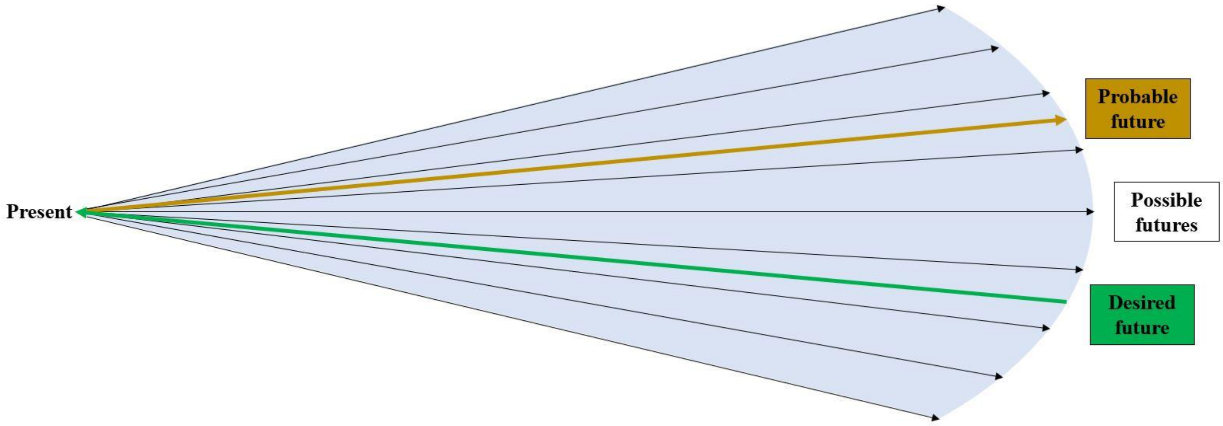


Figure 4. Scenario cone. Note that the *Desired future* arrow is pointing backwards, which is what *Backcasting* is named after.

3.2. Modular participatory backcasting

The particular sub-category of backcasting used in this paper is Modular participatory backcasting (mPB), developed by Kateryna Pereverza in her PhD thesis "Steering sustainability transitions? Modular participatory backcasting for strategic planning in the heating and cooling sector", defended at KTH, Stockholm in 2019 (Pereverza, 2019). The approach used in Ljungby was inspired by Paper 1 and 2 of the thesis, in which the intention was to:

1. Develop a strategic planning framework for the heating and cooling sector based on PB and examine its adaptability to local contexts, and
2. Develop methods for scenario development, selection and analysis to allow for co-informing between modelling and participatory process with PB-based strategic planning.

The original research done as a part of Pereverza's PhD thesis has been conducted on the heating sectors in Bila Tserkva, Ukraine (case study 1) and Niš, Serbia (case study 2). The method is applied in Ljungby in a somewhat different context, as:

- The socio-technical system analyzed in Ljungby is the cooling system, unlike the heating system in Bila Tserkva and Niš
- There are numerous references in Pereverza's paper to her study being done in developing countries, which cannot be said for Sweden
- Ljungby is several times smaller (in terms of the number of inhabitants) than the two cities analyzed as a part of Pereverza's thesis, etc.

The two defining characteristics of the mPB approach are, as the name says, modularity and its participatory nature. While modularity "enables for a more flexible design and a higher level of detail and specification of system performance", participation of relevant stakeholders "in contextualization of visions of a future system and in making strategic choices" increases robustness in transition pathways, due to stakeholders' diverse perspectives and knowledge about the system. (Pereverza, 2019). With respect to modularity, the process consists of 13 steps, each having specific inputs and goals, with the outputs serving as inputs for further steps in the process (See Appendix A).

Stakeholder participation was achieved initially through storytelling by a municipal government officer, then through a round of questionnaires, and at the end through online interviews. The Climate and Energy Plan of Ljungby presents a kind of a future vision which the municipality hopes to achieve in the following decades, and it served as a framework for further work in the backcasting process. Different parts of the document present a description of the current situation, drivers, criteria, etc., which are all steps in the mPB approach. Resemblances of stakeholder analysis, as well as solutions are also present in the Plan. The document by no means contains enough information to be the sole input for the backcasting process, but instead serves as an excellent starting point for the analysis. Additional information has been sought through literature studies, multiple rounds of interviews with different stakeholders, data requested directly from relevant organizations and companies, etc. All these served as inputs for steps 1-8.

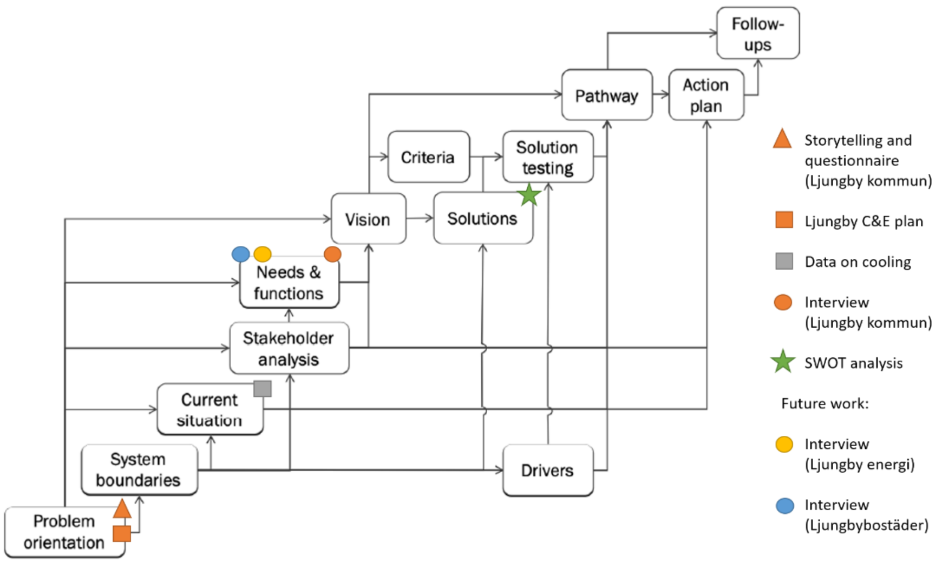


Figure 5. Steps in the mPB analysis with stakeholder inputs.

Step 9 compares three scenarios/solutions – two corresponding to stakeholders' visions (step 6), and a BAU scenario – using SWOT analysis. The final scenario, which is either selected from the original ones or is a mix of them, is then further elaborated in step 10. Steps 11-13 present long- and short-term timelines, action plans, and division of responsibilities in order to reach the final scenario.

Figure 5. describes the order of steps in the mPB process conducted for this master thesis, as well as the first time certain information has been used as an input for a particular step. Due to the nature of mPB – every step has particular inputs from previous steps and results in inputs for the following ones – explaining them in-depth at this time would be tedious and would make it hard to corelate with the actual work done. Thus, the methodology section only gives a brief overview of the steps of mPB, and these will be discussed in detail sections 4 and 5.

4. Contextualization (mPB steps 1-8)

In this paper, the 13 steps of the mPB analysis are split in two large parts. Contextualization, which includes steps 1-8, can be considered as a part of both theoretical background and results. The purpose of these eight steps is to design scenarios/soulutions for the future of the socio-technical system based on the information provided by the stakeholders (among other sources) to the researcher. Results, or steps 9-13, are done by the researcher based on previously collected data and then communicated back to the local stakeholders.

4.1. Problem orientation

The initial step towards framing the problem was pinpointing the exact issue in Ljungby to be solved, both in terms of its climate adaptation and/or mitigation potential, as well as selecting one the local stakeholders have different views on. On my first visit to Ljungby it was conveyed to me that the future of the cooling system is one such an issue – according to Tobias Wagner, there had been lack of agreement between local stakeholders if "central cooling should be used in the future", or if it is too expensive and complicated to plan for and implement. Keeping in mind the average lifetime of and average building which this kind of system would supply (several decades) and the capacity range of DC systems in Stockholm (3-228 MW), this is an issue whose solutions would affect the local energy system greatly and do so for a long time. As such, strategic planning of space cooling in Ljungby is just the kind of an issue where mPB is frequently and successfully used.

In order to find out more about the particular differences in opinions regarding the future of the cooling system and the local context, a questionnaire (see Appendix B) has been designed and sent to two municipal officials – T. Wagner, in charge of technical systems and emergency situations, and H. Svahnström, municipal's environmental strategist. Questions covered different topics included in the first 5 steps of mPB and were designed with the intention of being answered broadly. Avoiding focusing questions at this point in the process allows the stakeholders to share what for them are the most pressing concerns without hinting at particular ones, and helps to steer further work by acquiring potentially crucial information which an "outsider" could be unaware of. Answers regarding particular steps in mPB will be discussed in this section (in the appropriate subsection), while full answers are presented in Appendix B. The questionnaire is not the only form of communication with local stakeholders – storytelling (during the visit to Ljungby) and direct correspondence (mostly via email) also served as data sources for problem orientation.

According to T. Wagner, the initial point of conflict were different opinions on CAPEX and OPEX of different cooling solutions. It is not only the size of the investment that was disputed, something that could be resolved by doing cost benefit analysis, but also who would be making it. In case of the cooling system resorting on private AC units, the (comparatively low) initial investment would be done by private individuals who would later pay (comparatively higher) operational costs, almost cutting the local energy company out of the equation. On the other hand, the high initial investment for a system reliant on district cooling would be done by a company, but the system would later present a steady source of income. Degree of utilization (capacity factor) presents another dilemma for the local stakeholders. Local district heating companies charge by the amount of heat delivered, which is a profitable model for a cold country such as Sweden, but the requirement for space cooling is considerably lower than that for heating.

Another major consideration are the targets presented in the Plan. H. Svahnstöm conveyed her worries that "using energy for space cooling" might endanger reaching the goal of reducing energy consumption by 50% by 2030. This view is opposing both the hands-off AC approach, as well as the central cooling approach, suggesting that the solution should be sought in other kinds of solutions.

4.2. System boundaries

There are several types of boundaries which need to be set in order continue onward with the analysis. Temporal boundary is set to 2050, as this is the last year for majority of targets in the municipal climate and energy Plan and studying the effect of cooling sector on reaching those targets would be of interest. Another reason for setting the boundary to 2050 is the nature of cooling load with respect to (rising) CDD which implies that there is only a limited time to lay foundations for development of this socio-technical system before the BAU regime settles in.

The spatial boundary is set to Ljungby municipal borders. This may seem redundant to note at first, but it implies a few important details for further consideration. Firstly, any energy disbalances in

Ljungby are considered to be compensated by import/export, as currently is the case. Altering the gap between production and consumption of energy caused by the proposed future cooling solution will be evaluated not only with respect to energy efficiency, but also with respect to the goal in the Plan of being a net exporter of energy by 2050. Secondly, setting this boundary implies that estimations of GHG emissions will be territorial-based (also known as production-based). In other words, increase in secondary energy (electricity) imported from outside Ljungby municipal borders would not affect total emissions of the system. This approach in GHG emissions is in line with the methodology which the local government currently uses, as it was conveyed in the interview with H. Svahnström.

With respect to technical components, different types of cooling solutions have been taken into account – household VC AC equipment and centralized solutions like district cooling. Other sorts of technologies for reducing cooling demand (artificial and natural shading, building insulation, etc.) and energy generation technologies (solar panels) have also been considered as a part of the process. As for the social components, end users of household space cooling (i.e. residents of Ljungby), service providers, and government entities (legislators, strategists, etc.) have been considered. The most important sectorial component to note is that this thesis will focus on *household* cooling solutions. This decision has been made due to lack of data on cooling demand in other sectors, as well as the unpredictable effects the 2020 pandemic will have on office space demand and occupancy in the future.

4.3. Current situation

The situation as of 2020 in Ljungby regarding cooling sector is in early stages of its development. This is the case to the extent that very little data is available regarding how widespread space cooling is, what technologies are used and ultimately what is its effect on the power grid and the environment. This is in line with the observations of Jakubcionis and Carlsson stated earlier, that there is a notable lack of space cooling data in the EU. None the less, some estimations on the current situation can be made.

Author's impression based on living in Sweden was that very few households have AC units – a claim which I made in my master thesis proposal and a claim Ljungby official disagreed with. I was told that AC is "more prevalent than it appears in the text". The impression of local stakeholders is that mini split units are "quite common in households outside city center (…) that do not have district heating heat pumps", while the ones that are connected to district heating network "might also have packaged portable units" (Figure 6).

Figure 6. Two most common household indoor cooling solutions according to local stakeholders.

Numerical estimation can be made using formulae (2) and (3). In order to do so, estimating total indoor housing space in Ljungby needs to be done first. Based on the housing statistics in the municipality given in 2.3.1. – by multiplying the number of households in each category by the average area of the household in each category – the total housing area in Ljungby is estimated to 1,281,000 m^2. This equates to slightly less than 45 m^2 per capita, which is a bit more than what SCB reports to be the average for Sweden (42 m^2). This is an expected result as the country average is driven down by lack of space in large cities, which is stated in the quoted article. Based on this area, using (2), the total annual residential cooling demand is estimated to be 14.32 GWh for an average year – ranging from 22.38 GWh/a for 2018 (relatively warm summer) to 9.12 GWh/a for 2020 (relatively cold summer). AC equipment penetration can be estimated using (3). Using the three-year average value for CDD of 190, penetration rate of 56% has been calculated.

4.4. Stakeholder analysis

The purpose of this step is to identify and assess which individuals or organizations can influence or can be influenced by the issue at hand. This is best done by "ranking" them according to two criteria – *interest* and *power*. High interest – high power stakeholders (i.e. *players*) are key for the further process of designing solutions, while low interest – low power stakeholders (i.e. *bystanders*) can be disregarded. The remaining two groups – *subjects* (low power – high interest) and *context setters* (low interest – high power) each have their roles to play with respect to their position in the interest-power plane. In order to properly map stakeholders on the plane (Figure 7), question 3 in the Questionnaire inquired about local stakeholders' interest and power. Each of the mentioned stakeholders is analyzed further in this subsection.

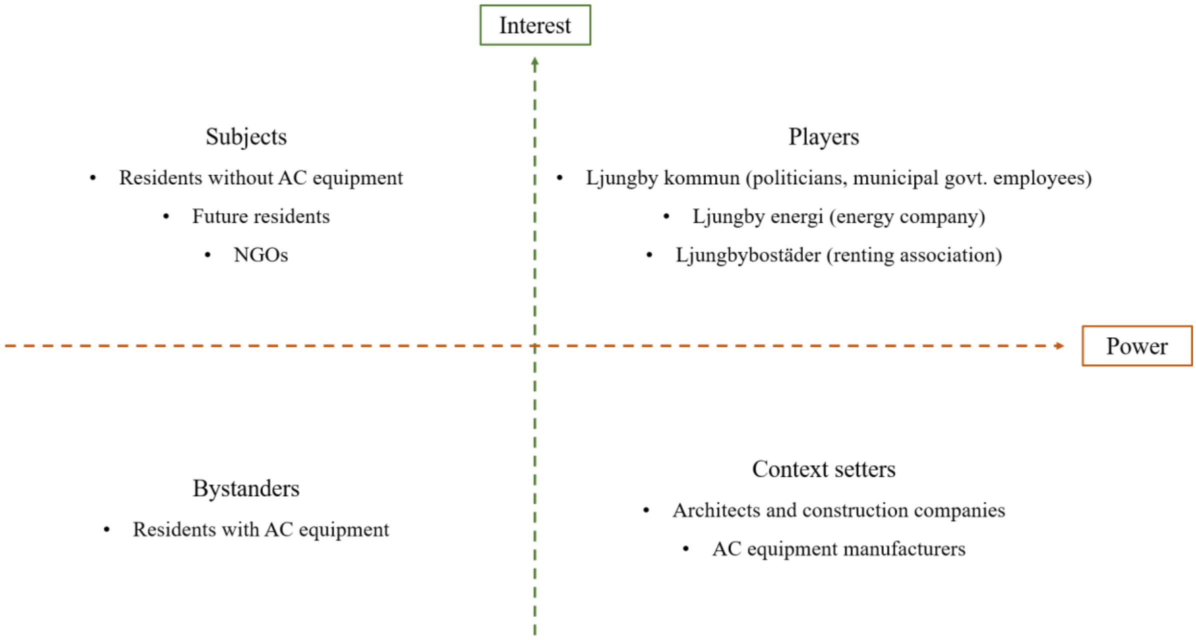


Figure 7. Interest-power plane for local stakeholders.

Players (high interest – high power):

- Ljungby kommun includes both politicians and non-political municipal government employees (strategists, engineers, etc.). Their interest in solving the issue lies primarily in making sure that the additional energy consumption for space cooling does not endanger reaching different targets set by their own Plan. Secondarily, solving such issues is the mandate of the local government and the job of government employees, making political and productivity goals additionally motivating.

  In terms of power, both interviewees designated politicians as high-power stakeholders. One reason is that "funding for municipal infrastructure is decided by the politicians". Additionally, politicians are "making a huge impact by being brave and making what is prioritized". An interesting observation by an interviewee – which is in line with remarks from the IEA report regarding the role of government, but outside the (spatial) boundaries of this analysis – is that the politicians on the "national level can decide national standards in a way that would force everyone to do the same".

- Another high interest – high power stakeholder is Ljungby energi, the local energy company. In order to put their role in perspective, it is important to note that the company is publicly owned but competes on the free market. According to H. Svahnstöm "the Plan and corresponding action plan applies for the entire municipality organization including the municipal companies", thus Ljungby energi is obliged to act and plan accordingly. Another factor for making Energi a high interest stakeholder in solving the space cooling issue is profitability – different solutions would mean different revenue streams for the company, as they supply Ljungby with electricity, but would also be the entity in charge of implementing large-scale solutions such as district cooling.

  This is also where their high power comes from – any solution based on stakeholder consensus would be indirectly (electricity for increased AC load) or directly (building and operating district cooling network) implemented by Ljungby energi. The company is the main "tool" of the local government to materialize its plans, making them unavoidable in the mPB process.

- Ljungbybostäder is the local renting association. It is in its interest to provide comfort for its members (rentees/residents), including thermal comfort. Additionally, terms of renting their properties in the future depends on cost structure of living in specific housing, which includes air conditioning bills. Renters' associations in Sweden in general have high power, as they are in charge of planning, installing, operating and maintaining infrastructure in their housing units. T. Wagner included them in the list of stakeholders with most power in his Questionnaire answers.

The three players in development of cooling system in Ljungby are both interested in the outcome of the process and unavoidable in seeing it implemented, but for three different reasons. While the municipal government is a sustainability-driven player, Ljungby energi's primary interest is profitability, and the local renter association is mainly concerned with the topic of comfort. This distinction will be additionally explored in following subsections.

Subjects (high interest – low power):

- Future residents and current residents without AC equipment are the ones that would be the most affected by the design of the space cooling solution in Ljungby. Despite their interest to have the cheapest, most comfortable solution in the future, their options are currently limited to installing personal AC equipment, making their power low. It is the three players' actions which could provide them with more space cooling options in the future.

- There are several NGOs mentioned in municipal Climate and Energy Plan that are cooperating with the government in order to secure reaching the targets, but they mostly serve as a counsel-giving stakeholder, as the executive power still lies with governmental entities.

Context setters (low interest – high power):

- Urban planning, architectural design and the choice of building materials directly affect indoor cooling demand. Estimations on energy use for cooling made in 2.2.1. are based on the assumption that similar building standards which exist in the US and Europe are respected – an assumption which, if untrue, would greatly affect the results.

- As reported by the IEA, efficiency of AC equipment available on the market varies greatly, which directly affects the amount of energy required to achieve the same level of thermal comfort. By producing cheaper, less efficient units, manufacturers effectively transfer a part of initial investment to operational costs, which may financially be good or bad depending on the context, but unavoidably causes higher electricity consumption (thus higher primary energy consumption and GHG emissions).

Bystanders (low interest – low power):

- Residents of Ljungby who have already installed personal AC units have nothing to gain or lose, nor much power to influence the direction in which the local cooling system as a whole will head. In a sense they do influence the energy system by consuming electricity to ensure thermal comfort, but this effect is most likely to remain constant in the future.

4.5. Needs and functions

The primary need for the cooling system is to provide *thermal comfort*. No final solution would differ in this regard, so on its own this is not an important distinction between different scenarios. What is of importance for analysis is quantifying how large cooling demand is, and to what extent it is met. Formulae presented in 2.2.1. are the main tools used in this master thesis to quantify both cooling demand and load. The limitations of this approach will be analyzed in the Discussion section. The other important aspect is *how* this demand is met, which is what actually distinguishes different approaches and ultimately what needs and functions will be met.

Important function which both surveyed stakeholders emphasized is the need for the cooling system to *operate during heatwaves*. This answer could be interpreted as Sweden being a cold country which needs cooling only on certain summer days. This is true to some extent, as this hypothesis relies on end users resorting to installed space cooling solutions only when outdoor temperature exceeds a certain threshold. However, as it was discussed in section 2.2.2., installing AC equipment might irreversibly increase energy use for cooling even when the objective cooling demand is not as high – a kind of a direct rebound effect. Exactly this could be the alternative interpretation of the above statement – that Ljungby municipal officials are worried that increasing cooling capacity may skyrocket energy use throughout summer and that the solution should be such that it is used only when necessary.

What this answer also implies, is that during these heatwaves, cooling systems would run at full capacity. As a consequence, *grid stability* might be endangered, but only if the system is heavily reliant on electricity. Ensuring that this does not happen is another thing that the solution needs to strive towards. On a similar note, *resilience* has been mentioned by Tobias in survey answers as a need presented for the system. He further explained that self-powered households and local production of energy in Ljungby would ensure resilience on both micro and macro levels.

4.6. Vision

Vision defines and clarifies a desirable future for the given system. Question 6 in the survey was designed with the intention of hearing what the local stakeholders' vision for the cooling system in Ljungby. The (slightly modified) answers are the following:

Vision 1 (Hanna): Adapted and efficient cooling system that is focused on the most needed areas and includes other options for minimizing cooling load.

Vision 2 (Tobias): Central cooling system that is robust, resilient, cost-effective, and cooling in the heatwaves of the future.

These visions present the basis for mPB step 9 – Solutions, which is where a more thorough description of what each of them would include, as well as their upsides and downsides, will be laid out. Alongside these two, a BAU scenario (or hands-off approach) will be discussed.

4.7. Criteria

As the very name of the master thesis implies, *sustainability* is the most important criterion to be addressed. In recent years sustainability has been increasingly more often associated with environmental sustainability and more particularly reduction in GHG emissions. While this is certainly an important aspect of designing any energy-demanding socio-technical system, the word sustainability in this case should be perceived more broadly – a feature of the system which ensures that in the long term its future growth would fulfill stakeholders' needs and stay within certain criteria. For Ljungby municipal government this would mean that the system which will be meeting the expected increase in cooling demand should help, or at least not endanger, reaching targets set by the Plan. Thus, broadly speaking, the municipal Climate and Energy Plan is a list of criteria for the future cooling system. The goals which are the most likely to be affected and/or constrained by the future cooling solution have been laid out in section 2.3. These include keeping GHG emissions at minimum, using renewable energy sources, ensuring high efficiency, and security of supply of energy.

As it was conveyed to me during the interview with H. Svahnström, the only primary source of energy which is considered to be a (60%) fossil fuel is municipal waste, which is incinerated at the local CHP plant. Aside from that, the only production-based GH-emitting primary source of energy used for electricity generation is peat. Remaining emissions come from other sectors (transportation, food, etc.), while the rest of electricity is generated from renewables – by hydropower plants and to a small extent by PV panels – or it is imported, thus causing no territorial-based emissions. In short, even a cooling sector which would be completely reliant on electricity as the secondary source of energy would be quite "renewable" with respect to the primary energy source, which at the same time means low GHG emissions. This means that goals 1 and 2 are as significant for further analysis as goals 3 and 4.

It can be concluded that the two most important criteria for the cooling system as far as Ljungby municipality (targets) is concerned are *energy efficiency* and *security of supply*. It is however hard to quantify these criteria as the mPB methodology suggest should be done – an energy-intensive sector which is expected to boom in the coming years should strive towards these two goals. Hanna pointed out during the interview that the emphasis should be placed on efficiency and rational use, while "some electricity would definitely need to be used for this purpose".

Finally, the criterion of CAPEX and OPEX, their size and who makes it – the criterion which sparked the discussion between local stakeholders in the first place – will also be considered. Termal comfort of end users and consumer choice will also be addressed as a criterion. As the participatory aspect of this project did not cover profit- and comfort-driven stakeholders due to organizational and time limitations, better assessment on their needs and criteria will be had after those interviews, which are planned for future work.

4.8. Drivers

As discussed in section 2.2., the main reason for the need to plan the future of Ljungby's cooling system – the main driver – is temperature increase. This driver is not particular for the municipality, as outdoor temperature is the main driver of cooling demand in almost all places around the world. What is different in Ljungby, and to large extent for entire Scandinavia, is that historically there was never a need for space cooling, so the potential for growth and subsequent disruption of energy systems is quite large. This is especially true when having in mind that there are no economic obstacles for meeting cooling demand like in some other, warmer places.

Jakubcionis and Carlsson (2017) described the linear rate of increase of specific cooling demand (Equation 2), and logarithmic rate penetration rate of AC equipment in households (Equation 3), both as a function of increase in CDD in a particular locality. When the formula for cooling demand is multiplied by AC penetration rate (i.e. the rate at which this demand is met), total cooling load, which is now an exponential function of CDD, is obtained. Furthermore, when equation 3 is solved for CDD, it gives zero penetration rate up until 22 CDD and 67% penetration rate for 283 CDD, which is slightly less than what Ljungby had in 2018. This illustrates the need to plan cooling systems as soon as demand appears, as the sharpest increase in cooling load happens in the 22-283 CDD interval. This explains the sudden, permanent cooling capacity increase in France during heat waves.

Using the combination of the abovementioned two formulae and data for temperature increase by Eklund et al. (2015), cooling load for Ljungby for the next 30 years can be calculated. Firstly, CDD data has been obtained by decreasing base value (instead of increasing summer temperature) to 18 ºC for 2020, 17 ºC for 2035, and 16 ºC for 2050, according to predicted levels of warming. Next, specific residential cooling demand (*Qcooling*) and AC equipment penetration rate (*PNT*) have been calculated using formulae (2) and (3), respectively. By multiplying the two results, Specific cooling load (Q_{load}) has been obtained. The increase in total household area needs to be calculated (estimated) separately, in order to get total cooling load.

Table 2. Cooling data for increase in temperature in Ljungby, Sweden.

Year	2020	2035	2050
CDD	190	240	304
$Q_{cooling}$ [kWh/m^{2}a]	11.17	13.72	16.99
PNT [%]	56.5	62.6	68.8
Q_{load} [kWh/m^{2}a]	6.31	8.59	11.69

Additional to the macro increase in CDD in Ljungby, local temperature inequalities should also be addressed when it comes to cooling demand. In questionnaire answer 6, Hanna mentioned “other options for minimizing the need for cooling systems (include) using green and blue areas in our city planning”. Later in the interview she expanded on this, saying that green areas represent parts of Ljungby with abundant greenery, while blue areas are the ones around the river. What they have in common is that daily temperatures spikes are not as high as in the rest of Ljungby (hereafter named “red area”), and outdoor temperature lowers more quickly after peaking around noon. The cause for this thermal inequality lies in spatial planning, as red areas tend to have large concrete parking areas and little greenery (Figure 8). The heat island effect is not limited to the area – it also affects the surrounding neighborhoods.

Figure 8. Areal view of Ljungby with one of “red areas”.

Another major space cooling driver present in Ljungby is the planned population increase, reported in the Plan and reiterated in correspondence with the Hanna and Tobias. By 2035, the municipality intends to increase its population from the current 28,521 to 35,000. This presents a 23% increase compared to 2019, or 1.4% increase every consecutive year (i.e. compared to the year before) for 15 years in a row. Assuming the same distribution of household size as today – which was reported in 2.3.1. – the expected total useful household area to support total population in Ljungby in 2035 would be 1,573,000 m^2. Assuming the same total population increase until 2050 brings total area to 1,864,000 m^2. All other things being equal (even if outdoor temperatures remained constant), population increase would present a considerable driver of cooling load (and energy demand in general).

5. Results (mPB steps 9-13)

This section will lay out mPB steps 9-13 – solutions (scenarios) based on stakeholder feedback obtained in previous steps, selection of the final scenario and its testing, and creation of a pathway, action plan, and follow-ups in order to implement it.

5.1. Solutions

Based on visions laid out by the interviewed stakeholders, two different scenarios for the future of cooling system in Ljungby have been created and compared to the BAU scenario. As it was discussed in section 4.7., the main criteria for evaluating the scenarios are energy efficiency, security of supply, comfort and cost. Due to the inability to quantify specific targets for these criteria (only general strivings), and in the absence of quantifiable targets, the comparison was made in qualitative terms, using SWOT analysis.

5.1.1. BAU Scenario

The BAU scenario describes what would happen if local stakeholders assumed a hands-off approach to strategic planning of the sector. Due to lack of alternatives, households which would require space cooling would resort to common AC equipment (small-scale VC cooling systems), which would become the cornerstone of the future system.

Table 3. SWOT analysis of the BAU scenario.

Strengths	Weaknesses
• Requires the least amount of planning • No direct investment on behalf of the government or municipal companies • High end user control and personalization	• Cooling load entirely covered by electricity, large rise in demand • Risk of grid destabilization at peak loads • Lowest COP (least energy efficient)
Opportunities	**Threats**
• Good synergy with solar PV	• Spike in penetration rate (actual cooling load) due to heatwaves • Energy efficiency depends on manufacturers and consumer choices

5.1.2. Vision 1 – Adapted and efficient cooling system supplemented by cooling demand reduction

Stakeholder Vision 1 describes a system which focuses on using different technical solutions based on location properties and local cooling demand, and at the same time resorts to shading for reducing cooling load. Hotspots in Ljungby with larger cooling demand (red areas) would be connected to the town's district cooling grid, while the cooler areas would install common household equipment.

Table 4. SWOT analysis of Hanna's vision.

Strengths	Weaknesses
• Reduced cooling demand • Pairing technology and demand optimizes for energy efficiency • Allows for consumer choices	• Hard to implement district cooling in existing (red) areas
Opportunities	**Threats**
• Reviewing strategies and solutions along the way, enforcing more successful ones	• Shading and PV panel clash

5.1.2. Vision 2 – Robust, resilient, and cost-effective central cooling

Stakeholder Vision 2 is a system based on central cooling, which is supposed to cover the entire cooling demand in urban areas.

Table 5. SWOT analysis of Tobias' vision.

Strengths	Weaknesses
• High energy efficiency • Utilizing thermal properties of river reduces electricity use to minimum • Fast-track to ensuring security of supply • Complementary with district heating	• Possible to implement only in urban areas • Huge initial investment • Low capacity factor • Offers no consumer choices
Opportunities	**Threats**
• Long-term profitability for Ljungby energi	• Housing price increase • Fragility of centralized systems

5.2. Final solution testing

Based on the qualitative comparison of different scenarios presented to Ljungby kommun officials, the final solution has been designed. It is based on *Vision 1 – Adapted and efficient cooling system supplemented by cooling demand reduction*, with a few adaptations.

Drawing from the BAU scenario – the synergy between AC equipment and solar panels should be exploited where possible. Forming a kind of “solar cooling” solution in this way would benefit the cooling system more than shading, which is why it should have the priority, while shading will be primarily used in district cooling areas. Ljungby already has a goal of mandating installment of PV capacities in future households which are large energy consumers. Instead, the aim should be correlating production and demand (achieving solar cooling).

Drawing from *Vision 2*, and in order to tackle the weakness of the selected solution (district heating hard to implement in existing areas), district cooling could be expanded to include new non-red neighborhoods as well. In case future red areas had neighboring blue areas, the two could be connected to the same district cooling system, with the DC plant build at the river to utilize its thermal properties. In this way, initial investment per unit of cooling would be reduced – by both economies of scale of a larger system and by building DC infrastructure in both existing and new areas – while simultaneously increasing energy efficiency and reducing dependency on electricity (thus contributing to security of supply) by utilizing cooling energy from the river.

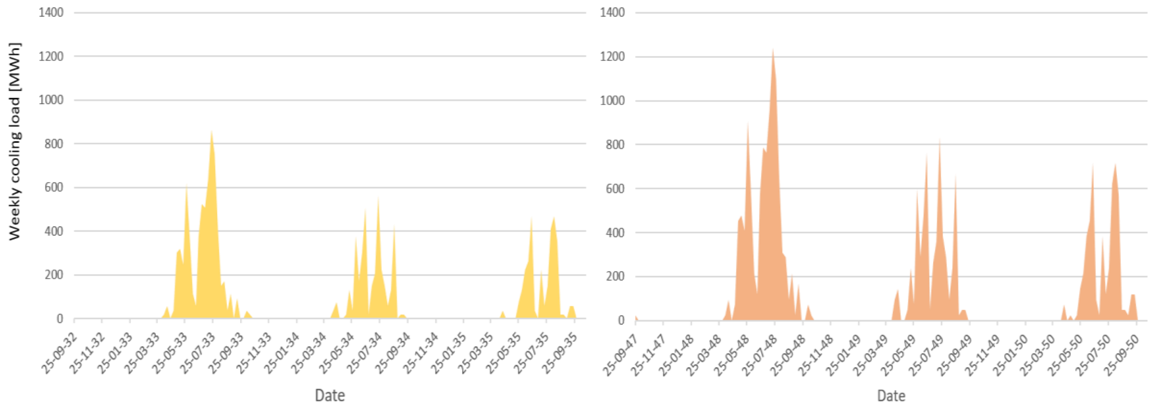


Figure 9. Weekly cooling load in 2033-2035 (left) and 2048-2050 (right) based on temperature and population increase.

Section 4.8. quantifies specific household cooling load (which the described cooling solution needs to accommodate) based on predicted temperature and population (household area) increase in Ljungby. In 2035 total load will be 13.5 GWh, while in 2050 cooling load will be 21.8 GWh. Figure 9 shows that weekly peak cooling loads will be reaching 500-800 MWh, and 700-1200 MWh, respectively, depending on how warm a particular summer is. Let us assume that in 2050, 43.6% households remain rural, and resort to vapor-compression systems for space cooling. At the same time, one half of urban households (the remaining 56.4%) uses VC systems, while the other half is connected to district cooling grid. However, DC system is also cooling red areas, so it takes 60% of total urban cooling load. Figure 10 shows an estimation on what technologies will deliver what part of cooling in a hypothetical heatwave-week in 2050 (left), and electricity used by the cooling system during such a week (right), assuming COP of 2.5 and 3.85 for VC and DC systems, respectively. Note that shading is not accounted for on Figure 10, as quantifying its effect would be too arbitrary at this point.

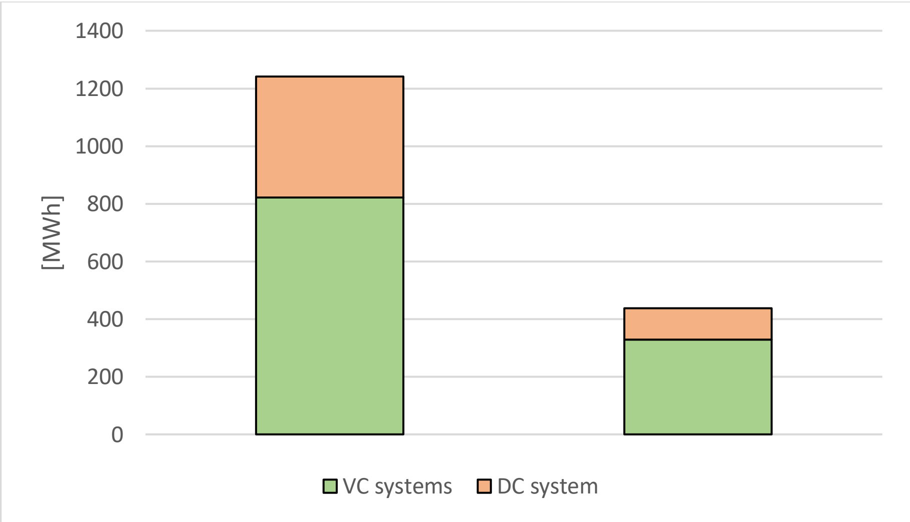


Figure 10. Cooling load (left) and electricity consumption (right) of the two dominant systems technologies during a 2050 heatwave.

Development of a pathway and action plan to reach the desired state of the cooling system (described in this section) by 2050 will be laid out in the following sections.

5.3. Pathway

The pathway consists of a chain of changes, that are required in order to achieve the aforementioned vision. Arrows above the timeline represent actions suggested by the municipal Plan that can be related to the future cooling system (green) and targets presented in the Plan (orange) which were already discussed in section 2.3.2. Underneath the timeline are actions required to be taken by Ljungby kommun (orange), Ljungbybostäder (blue), and Ljungby energi (yellow), in order for the cooling system to operate as was envisioned in the previous section.

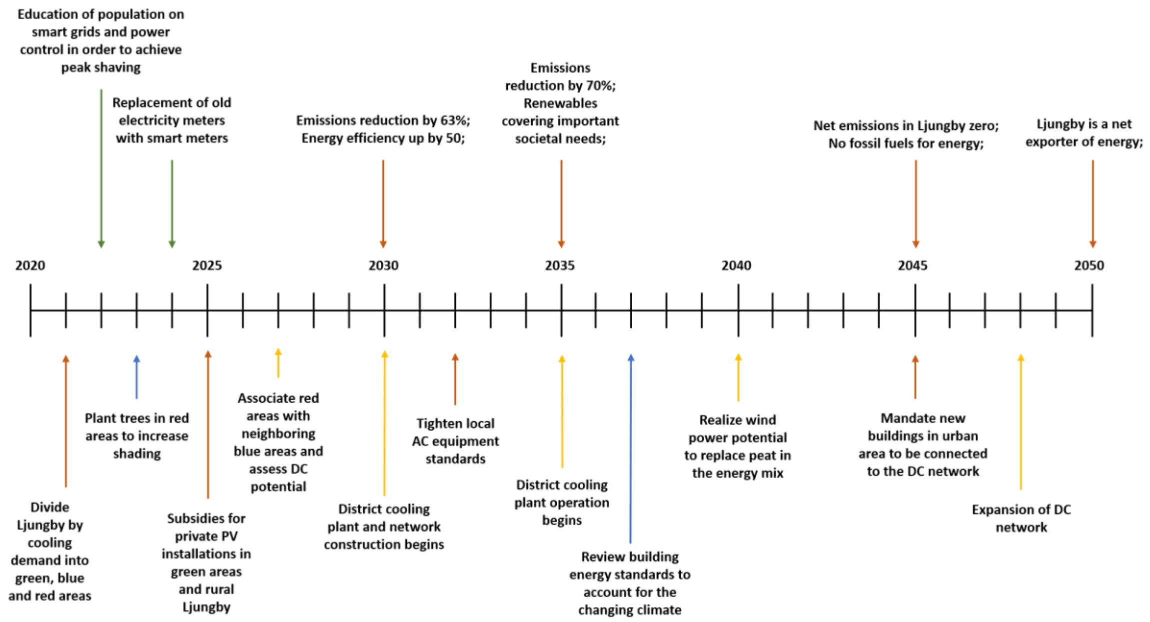


Figure 11. Pathway towards the selected vision.

The pathway is, of course, subject to reviewing, as stakeholders might encounter hardships that are at this time unaccounted for, or perhaps even find some steps easier to implement and do so sooner than expected. However, the order of steps should not change dramatically as, for example, planning and building a district cooling network is considerably harder than planting trees for shading. This variety in scale of actions also illustrates why the selected vision/scenario is superior to the other two it was compared to – by combining short- and medium-term goals related to PV installations and energy standards, and long-term plans regarding DC network and changing energy mix, it is possible to keep pace with the increasing cooling demand all the way from 2020 to 2050. Relying on central cooling would be impossible in the near future, while small-scale solutions wouldn't enable Ljungby to reach the ambitious targets set by the Plan on the long run.

5.4. Action plan

Action plan outlines the short-term (usually next few years) steps needed for setting the socio-technical system on the right path for the future. As discussed previously, most of these steps in the case of cooling in Ljungby are related to VC systems, shading and zoning.

Table 6. Short-term action plan.

Short-term goal	Action step	Stakeholder	Start date	End date
Zoning	Create an outdoor and indoor thermal map of Ljungby	Ljungby energi, Ljungbybostäder	December 2020	November 2021
	Split existing neighborhoods into green, blue, and red areas	Ljungby kommun, Urban planning department	December 2022	January 2022
Greenery	Determine planting positions based on shading potential, absence of PV panels, available space, type of area, etc.	Solar engineers, Ljungby kommun	February 2022	March 2022
	Planting trees in the appropriate season	Municipal gardening department	April 2022	June 2022
PV expansion	Determining a good model for solar PV subsidization	Ljungby kommun, Ljungby energi, Ljungbybostäder	December 2020	March 2021
	Onset of subsidization in rural areas and popularization	Ljungby energi, Ljungby kommun	April 2021	x
	Onset of subsidization in urban green areas	Ljungby energi, Ljungby kommun Ljungbybostäder	February 2022	x

All immediate actions depend on zoning (color-coding) neighborhoods in Ljungby, which is supposed to be done after thermal mapping. Such a mapping would require a year to cover all seasons, and all other actions would have to wait until then. If such a map already exists, all deadlines could be moved by a year sooner.

5.5. Follow-ups

Initial monitoring of implementation would be done by the stakeholder in charge of specific action from the Action plan. Ljungby kommun would act as a coordinator between different stakeholders involved in each step. It would be helpful for all actors involved in the process to adopt internal documents stating deadlines, and employees in charge of tracking deadlines and coordinating actions.

6. Discussion

The absence of reported cooling data in the EU on one hand, and lack of stakeholders' mutual interactions and their limited participation on the other hand, made the author of this thesis rely more heavily on qualitative approach to analysis and comparison of solutions in section 5.1. than originally intended. However, SWOT analysis has proven quite useful in locating strong and weak spots of different solutions and how they fit in the context of Ljungby. This information could have gotten obscured by results of a quantitative analysis. In addition to lack of data, vagueness of climate goals of Ljungby also steered the analysis towards qualitative methods. Through interaction with local stakeholders I was told that several goals which I thought were crucial for framing the problem were either "intended to represent strivings", that "different assessments of current status gave widely different results" or that "the aggregate effect of other sectors isn't known well enough to set tangible targets for the emerging cooling sector". As a consequence of all this, the results laid out in section 5 tend to be descriptive, rather than particular.

It is the opinion of the author of this thesis that:

a) The contribution made toward designing the future of cooling system in Ljungby – one which would meet stakeholders' needs and stay within sustainability criteria – is significant, because there hasn't been enough thought regarding this growing sector before, and
b) Despite providing mostly descriptive results, the urgency to engage in strategic planning of the local cooling sector due to exponential rate of increase of cooling loads in locations with CDD levels close to those in Ljungby, has been clearly described.

In the light of discussion on lack of quantitative results, it is also important to mention limitations of the two formulae introduced by Jakubcionis and Carlsson (2017), which were used extensively in this thesis. Firstly, while the two authors claim that the "building codes in USA and Europe are on comparable levels", they themselves note that "actual buildings are not always conforming to the requirements and there might be significant differences between regions". This is especially true for Sweden, as it was mentioned earlier that "strong heating focus in design and construction of buildings in Sweden (…) obstructs heat flows in warm summer days, increasing the demand for cooling". Another point made by the authors is that "space cooling demand is heavily influenced by occupant behavior", which should also be taken into account. Lastly, the fit based on which the formulae were derived in the paper has only one locality with CDD comparable to the three-year average for

Ljungby (160 and 190 CDD). However, there are many data points for the 300-400 CDD range, which makes long-term forecasts done in this thesis more reliable.

It is however important to note that a potential error in Jakubcionis' and Carlsson's formulae or their misinterpretation does not change stakeholders' visions, the three compared solutions, or the choice of the final solution. This is due to the fact that up until step 5.2. no quantitative data has been communicated back to the stakeholders.

7. Conclusion

Modular participatory backcasting fit well in the description of the problem which was addressed in this thesis – a vaguely defined long-term sustainability issue which different stakeholders have different views on. However, applying mPB has been made extremely hard due to the pandemic and the associated restrictions. The aim of the method is to supply local stakeholders with quantitative and qualitative data based on their descriptions of a particular issue and their preferred approaches, and then design a solution through dialog and round tables. Quarantines, lockdowns and overnight normalization of online meetings made this last part – having important stakeholders “together at one table” – impossible, which undoubtedly affected (in a negative way) the development of this master thesis. This was particularly true for mPB steps that required brainstorming.

The process of designing the solution for cooling system is Ljungby was inspired by the mPB approach used in the process of designing the heating system in Bila Tserkva and Niš, as discussed earlier on multiple occasions. Pereverza designed the method to be used in both heating and cooling sectors, and while the two socio-technical systems may have a lot in common, there is a fundamental difference between the two – maturity. Most cities in the EU have had district heating systems for decades and the data on the topic is abundant, which is not the case for space cooling. On one hand this presents and amazing opportunity to design innovative solutions with huge impact, as technological regimes have not yet locked in. On the other hand, a lot of estimations must be made based on limited data sources, which makes the process more difficult and increases its uncertainty.

8. Future work

Due to organizational and time constrains brought on by world events in 2020, it was impossible to expand the participatory aspect of the process on to profit-driven (Ljungby energi) and comfort-driven (Ljungbybostäder) stakeholders. However, doing this has already been agreed with thesis coordinators in Ljungby kommun, and this will be done in the near future. As a result, mPB steps 5-13 will be repeated with additional stakeholder input included.

There is additional work to be done on the input provided *to* the stakeholders as well, mainly related to finding more literature sources on space cooling demand, efficiency, limitations of different technologies, etc. Obtaining enough of this data and simulating scenarios in a software such as LEAP would enable comparing the scenarios quantitatively, not only qualitatively, which would undoubtedly contribute to the quality of the whole mPB analysis.

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10. Appendix

Appendix A – Steps of the mPB method applied in the project

Color code:

INPUTS - only mentioned the first time they appear;
REQUIRED ACTIONS
OUTPUTS

1. **Problem orientation;**
    a. Ljungby Climate and energy plan
    b. Inputs from the questionnaire and storytelling
    c. Initial problem formulations
        i. Different views by different stakeholders;
        ii. Ambitious climate and energy goals set by the Plan;
    d. A common understanding of the problem among all participants
        i. Formulation and specification of a problem to be addressed;
        ii. Identification of key challenges;
2. **System boundaries;**
    a. A defined sociotechnical system that will serve as the point of departure for the study
        i. Spatial boundaries (especially with regards to emissions);
        ii. Temporal (2035-2050);
        iii. Sectorial (cooling);
        iv. Social components;
        v. Technical components;
3. **Current situation;**
    a. Data on the cooling sector in Ljungby
    b. Analysis of the current state of a sociotechnical system and its relevant features
        i. Current cooling system
            1. Type of technology (AC units, central/district cooling, etc.);
            2. Energy consumption;
            3. Identification of subsectors (difference between private and public?);
        ii. Identifying key problems, weaknesses and strengths;
    c. Data for creating the business as usual scenario (BAU)
4. **Stakeholder analysis;**
    a. Defining actors that can affect, or can be affected by, the problem
        i. Categorizing stakeholders by identifying the main motive
            1. Sustainability-driven
            2. Profit-driven
            3. Comfort-driven
        ii. Mapping stakeholders on the interest-power plane;

    iii. Identifying potential conflicts and common interests for future consensus-building;

5. **Needs and functions;**
    a. Inputs from stakeholder interviews
    b. Exploration of current and future system functions and societal needs to be fulfilled
        i. Profitability, sustainability, comfort, and anything else that the interviewed stakeholders consider relevant;
6. **Vision;**
    a. Creation of a desirable future vision
        i. Keywords that describe the desirable future;
        ii. Grouping keywords in a “slogan”;
    b. Desirable future vision
        i. A concise but inspiring future vision, e.g. **Stockholm for everyone** – the City of Stockholm should be a socially, financially, ecologically and democratically sustainable municipality by 2040.
7. **Criteria;**
    a. Criteria that specify the vision
        i. Generating ideas for criteria
        ii. Prioritizing criteria and defining measurement methods for each (tickable or preferably quantifiable)
8. **Drivers;**
    a. Identification of external forces that could impact the system
        i. Population increase, changes in weather patterns, energy prices, etc.
        ii. Assessing drivers based on impact and uncertainty
    b. Key uncertainties (high impact, high uncertainty)
    c. Drivers (high impact, low uncertainty)
    d. Data for modelling final energy demand
        i. Energy consumption for cooling
        ii. Structure of the final energy supply
        iii. Final energy demand by (sub-)sector
        iv. Annual specific energy consumption for cooling
9. **Solutions;**
    a. Turning visions into scenarios.
    b. SWOT analysis.
    c. Final scenario.
10. **Final solution testing;**
    a. Combined final scenario (from 9)
    b. Testing the final scenario based on criteria.
11. **Pathway;**
    a. Creation of milestones and timeline by which they are achievable
12. **Action plan;**
    a. Elaboration of pathway
    b. Action plan
        i. Specific tasks

ii. Deadlines
iii. Responsibilities

13. Follow-ups.

a. Plan for initial monitoring of implementation

Appendix B – Stakeholder questionnaire

Following are the six questions and answers from the questionnaire. It consists of two parts – the first one focuses on the Plan of the municipality, while the other half focuses on cooling system and solutions. Answers given by Hanna Svahnström are given in red, while the answers given bz Tobias Wagner are in blue.

PART I

1. In what ways are Klimat- och Energiplan goals affecting your organization's future activities? Does Ljungby energi have a similar (energy- and climate-related, long-term) plan, and how is it related to the municipal government's Plan?

The focus will be on implementing the actions from the climate- and energy plan and action plan and to organize how we work with these issues and inspire the organization to further develop how we can minimize our climate emissions and use energy more efficiently so that we will continue in developing actions towards the long term targets. Also, for me and the municipal executive administration there are some specific actions that we shall implement, and we have a focus also on increasing cooperation with the civil society.

Mainly related to Ljungby energi. But for the technical services department it is very guiding in how we build and, to some extent, renovate our buildings. It is that plan that we refer to for the "extra cost" of solar cells on roof and so forth.

2. What do you think are the main obstacles towards reaching the municipal goals, especially the ones regarding "emissions", "renewables", and "energy efficiency"?

Main obstacles and possibilities lie within cooperation both internally and externally. Also, there is a need for the politicians to clearly prioritize these issues, which means both request results from the organization and the municipal companies and to provide resources when needed. Mainly I think that if the politicians (and local civil society) do not request and expect results this will not be prioritized as much.

Funding. Initially it costs, especially since we do more than we technically need to. Our facilities department (part of technical services) is underfunded and has been for long. Since we have higher demands on our own buildings, they cost more. And this is often questioned "why is the municipality so expensive" and so forth.

3. Who (i.e. which stakeholder) do you think has the most power when it comes to ensuring that the goals set by the plan are reached? Why? Who feels the most motivated to do it?

Difficult question. I think that in different aspects different stakeholders have the most power. We as citizens have some power in how we vote, both politically and where we choose to spend our money. But the larger companies and the politicians have the possibility of making a huge impact by being brave and making clear that this is prioritized. Most motivated would probably be youths in general but locally most initiatives and commitments has been shown from older people and parents.

Politicians and landlords. When it comes to the municipal infrastructure, funding is decided by our politicians. In addition, the national level can decide national standards in a way that would force everyone to do the same. Landlords when it pertains to their infrastructure.

When it comes to motivation, I think it varies greatly. An interesting thought lately is how this all connects to resilience and even the total defense doctrine. If each house is selfpowered, there is no use for an enemy to destroy the main power cables. It won't give any effect. So by going for renewables, being less dependent on oil (using locally produced HVO, ethanol etc) could become a national security matter.

PART II

4. In your experience, how widespread is air-conditioning in Ljungby in the following types of buildings? What type of cooling system, including electric fans, is most popular in each (please refer to the attached PDF for the most common types of AC)?

No idea actually. I haven't looked around with those glasses on.

a. Single-household residential buildings (private houses)

Basically, I would guess quite common in households outside city center I would assume. That is a lot of households that do not have district heating have heat pumps. (mini split units)

Some that have district heating might also have packaged portable units.

b. Multi-household residential buildings

Probably not many.

c. Office buildings

Some of the new might have but I would say that most does not. They have district heating.

d. Commercial properties (shops and similar)

Probably not that many but have no real info or insight.

5. Imagine that in the near future a larger number of households decided to install a certain type of AC system. How do you think this would affect the goals set by the municipality's Plan? How would it affect Ljungby energi's operations?

I think this might increase the electricity use and this increase might be offset by an increase in energy efficiency in general. Still it might have a negative impact on our overall efficiency target.

It would also mean that we have households that are more prepared for future heatwaves.

It would be interesting to investigate the need and efficiency of a district cooling system rather than a large number of households, in the areas where we have district heating today, investing in mini split units. That would be interesting for Ljungby Energy to explore.

I think it would help us reach the goal. But a big issue is the transportation, AC is only part of it so it would contribute but not all the way.

When it pertains to Ljungby energi, I’d imagine it causing a heavier grid load meaning potentially expansion of cables etc. But I am out of my depth here.

6. It is the year 2035. An engineering student is coming to Ljungby for the first time. How would you, in one or two sentences, like to be able to describe the cooling system in Ljungby at that time? Please feel free to use any combination of adjectives and descriptions you like, e.g. *My car is a blue, electric Volvo, has space for 4 passengers and a small trunk, and can reach 200 km without charging.*

I would hope that we have a cooling system that is adapted so that we have cooling where it is needed the most and that we have an efficient system. We have also used other options for minimizing the need for cooling systems, such as using green and blue areas in our city planning etc.

I’d like a central cooling system that is robust, resilient, cost-effective and cooling in the heatwaves of the future.