

Final report

1. Project details

Project title	Smart Green Indoor Climate Manager
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Name of the funding scheme	EUDP
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Project partners	VELUX and Nilan
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2. Summary

2.1.1 English summary

The Smart Green Indoor Climate Manager (SGICM) project successfully developed and demonstrated an intelligent control system integrating VELUX roof windows and Nilan HVAC systems to optimize indoor climate and energy consumption in single-family houses.

The system combines wireless sensors (e.g. temperature, humidity, CO₂), a central gateway with Model Predictive Control (MPC) algorithms, cloud-based data platform, and tablet user interface. Two Danish demonstration houses tested the system over one year, comparing baseline and demonstration periods.

Key results include:

- **15-18% annual heating energy savings** (968-1,393 kWh), translating to 2,900-4,100 DKK annual cost reductions per household
- **Maintained excellent indoor environmental quality** with 95-100% of temperatures within comfort standards (EN 16798-1) and CO₂ levels consistently below 1,200 ppm through intelligent ventilation and automated window control (with exception of peaks)
- **Improved user comfort and health:** one family reported elimination of winter respiratory issues due to better humidity control

The automated system became seamlessly integrated into daily life, removing mental load while proactively ensuring healthy indoor climate - particularly through nighttime and daytime window operation when homes were unoccupied. Users appreciated the "fresh air" feeling and reduced stuffiness.

Technical achievements demonstrated successful cross-manufacturer interoperability and continuous operation for over one year. The project also increased user awareness of indoor environmental quality, leading to sustained behavioral changes (increased kitchen range hood use, discontinuation of bio-fireplaces).

Areas for future development include: user override functions for greater autonomy, enhanced summer cooling capabilities, adaptive learning algorithms that automatically adjust to building characteristics, and integration with energy tariffs for demand-response optimization.

The SGICM solution represents a viable smart investment delivering both economic savings and improved well-being for environmentally conscious homeowners.

2.1.2 Danish summary

Smart Green Indoor Climate Manager (SGICM) projektet udviklede og demonstrerede et intelligent styrings-system, der integrerer VELUX tagvinduer, Nilan ventilations-/varmesystemer for at optimere indeklime og energiforbrug i enfamiliehuse.

Systemet kombinerer trådløse sensorer (temperatur, fugtighed, CO₂), en central gateway med Model Predictive Control (MPC) algoritmer, en cloud-baseret dataplatform og tablet brugergrænseflade. Systemet blev testet i to danske demonstrationshuse i over et år og derpå sammenlignet med før og efter baseline-perioder.

Hovedresultater:

- **15-18% årlige varmebesparelser** (968-1,393 kWh), svarende til 2.900-4.100 DKK årlige omkostningsreduktioner per husstand
- **Opretholdelse af et fremragende indeklime** med 95-100% af temperaturer inden for komfortstandarder (EN 16798-1) og CO₂-niveauer konsekvent under 1.200 ppm gennem intelligent ventilation og automatisk vinduesåbning (med undtagelse af kortere peak-niveauer)
- **Forbedret brugerkomfort og sundhed:** én familie rapporterede eliminering af vinterhoste pga. bedre fugtighedskontrol

Det automatiserede system blev problemfrit integreret i hverdagen og fjernede mental belastning, mens det proaktivt sikrede sundt indeklime—især gennem natlig og daglig vinduesåbning, mens hjemmene var tomme. Brugere værdsatte følelsen af "frisk luft" og reduceret 'tung luft'.

Tekniske resultater demonstrerede tilfredsstillende interoperabilitet mellem forskellige produkter og kontinuerlig drift i over et år. Projektet øgede også brugernes bevidsthed om luftkvalitet, hvilket førte til varige adfærdændringer (øget brug af emhætte, ophør med biopejs).

Områder for videreudvikling omfatter: bruger-override funktioner for større autonomi, forbedret sommerafkøling, adaptive læringsalgoritmer der tilpasser sig bygningskarakteristika, og integration med energitariffer til fleksibel styring efter prissignaler.

SGICM-løsningen repræsenterer en energieffektiv investering, der leverer både økonomiske besparelser og forbedret livskvalitet for miljøbevidste boligejere.

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3. Project objectives

3.1 Objective

The objective is to develop, document and demonstrate a user-friendly intelligent control system for roof windows and HVAC systems (heating, ventilation, and air-conditioning) based on measured and experienced indoor climate. The system must ensure a healthy indoor climate with minimal consumption of fossil energy through energy efficiency and energy flexibility. The solution targets existing and new single-family houses (detached houses and semidetached houses) in the VELUX Group's and Nilan's current markets - Denmark, the Nordic countries and the EU. The focus is primarily on single-storey buildings, or with utilized roofs, and with roof windows and mechanical ventilation. In short, to achieve energy savings without compromising the indoor environmental quality.

3.2 Technology developed

The project developed an Integrated Climate Manager System and demonstrated it as a fully functional integrated prototype system comprising of:

- Wireless indoor climate sensors (e.g. temperature, humidity, CO₂)
- Central gateway with adaptive control algorithms
- Cloud data platform
- Tablet user interface
- Integration modules designed to facilitate interoperability among VELUX roof windows and blinds, Nilan ventilation and heating systems, as well as Wavin and Uponor heating solutions.

4. Project implementation

4.1 Project evolution

The figure below shows the timeline of the project. The figure is divided into two sections showcasing the steps in the development of the intelligent system itself and the touch points with the demonstration houses.

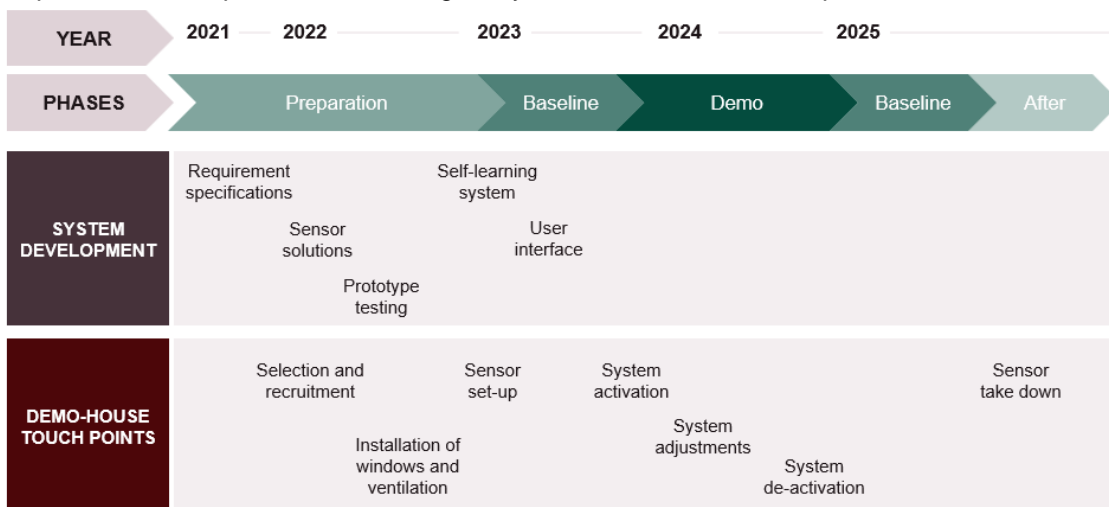


Figure 1: Project timeline

4.1.1 Milestones

The project implementation and achievements of planned milestones generally developed as foreseen with a few major diversions. As described in chapter 6.1 the initial scope of also testing in Europe was dropped due to difficulty of recruiting demo-houses outside Denmark. Secondly one of the three Danish demonstration houses dropped out, and finally the project was extended by an additional year to compensate for incomplete baseline data (due to an initial delay of the project start). Besides, the milestone 8.1 on developing a configuration tool for the demo house participants was dropped to focus the effort on the main objective. All other milestones were met and have resulted in the following results described in this report.

4.1.2 Risks and mitigation

The risks associated with conducting the project can be divided into technical and social risk.

Technical risks and mitigation:

- Problems occurring mainly due to interruptions of the data collection include:
 - Receiver driver was unstable: It initially needed manual restart after power outages which gave interruptions, this was solved by a smart-plug enabling restart remotely.
 - Sensors needing change of batteries: Initial battery swaps did not last sufficiently long due to swap to non-lithium-batteries – solved by swapping to lithium batteries again.
 - Weather station was temporarily down due to insufficient solar energy input.
 - IP-addresses were initially dynamic (changing), creating instability. This was solved by having static IP-addresses.
 - Nilan gateway initially did not connect to the MQTT-server/broker properly. This was solved by a Nilan sub-contractor.
- Delay of the baseline data gathering: This was solved by extension of the time frame
 - The above-mentioned problems with the data collection led to gaps in the baseline period.
 - Due to logistical reasons, it was only possible to install sensors in one house at a time leading to DK3 lacking a few months on the baseline period.
- Similar products launched by competitors: The last year we have seen a couple of similar systems emerge on the market, which should be deemed as competitors with the developed SGICM. This EUDP project, however, has ensured that VELUX and Nilan are among the leading part of the smart system market, with a competitive edge which includes roof windows.

Social risks and mitigation:

- Participant dropout: There was a risk that the recruited families would opt out of the project. We therefore recruited three houses, which ensured that we still had sufficient data even if one family was to leave the project. In the end, one of the families did drop out, but due to the preventive measure, there was still data enough, and the dropout did not jeopardize the whole project.
- Inability to accept loss of control: There was a risk that the families would not be able to give up control and allow the system to steer the indoor climate. Continuous requests to make adjustments to the system or in other ways influencing the indoor climate would have negatively affected our ability to compare data over time. We saw however that the families had only a limited number of requests for adjustments and besides that allowed the system to control the indoor climate.

- Significant changes in behaviour: Drastic changes in customer behaviour during the demonstration period or between the baseline and the demonstration could additionally have influenced the ability to make comparisons in data. However, the families did not change behaviour drastically, and the changes that were made were already implemented when the sensors were set up. We therefore did not have any difficulties comparing data from the baseline and the demonstration period.

4.2 Device/actuator overview

Product/Device	Device settings	Interface / protocol
VELUX windows	Window opening percentage	MQTT/iO Homecontrol
VELUX internal blinds	Blind opening percentage	MQTT/iO Homecontrol
VELUX external sun protection	External blind opening percentage	MQTT/iO Homecontrol
Nilan Hot Water	Temperature setpoint / On-Off control	MQTT/API
Nilan Heating system	Temperature setpoint / Heating mode	MQTT/API
Nilan Ventilation system	Airflow control / Ventilation level	MQTT/API

Table 1 Overview of the applied devices in the SGICM system.

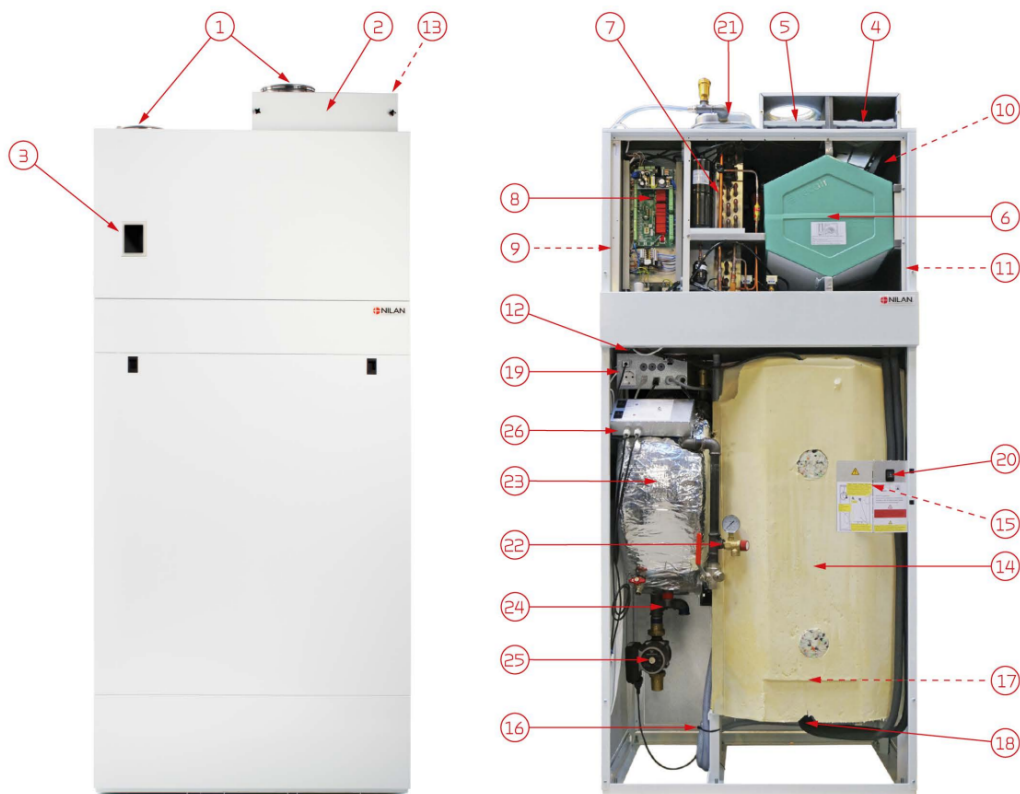


Figure 2: The ventilation heat pump unit installed in both houses. Nr. 6 is the heat recovery (counter flow), nr. 7 is the heat pump, nr. 9 is ventilator and nr. 23 a buffer tank 50L

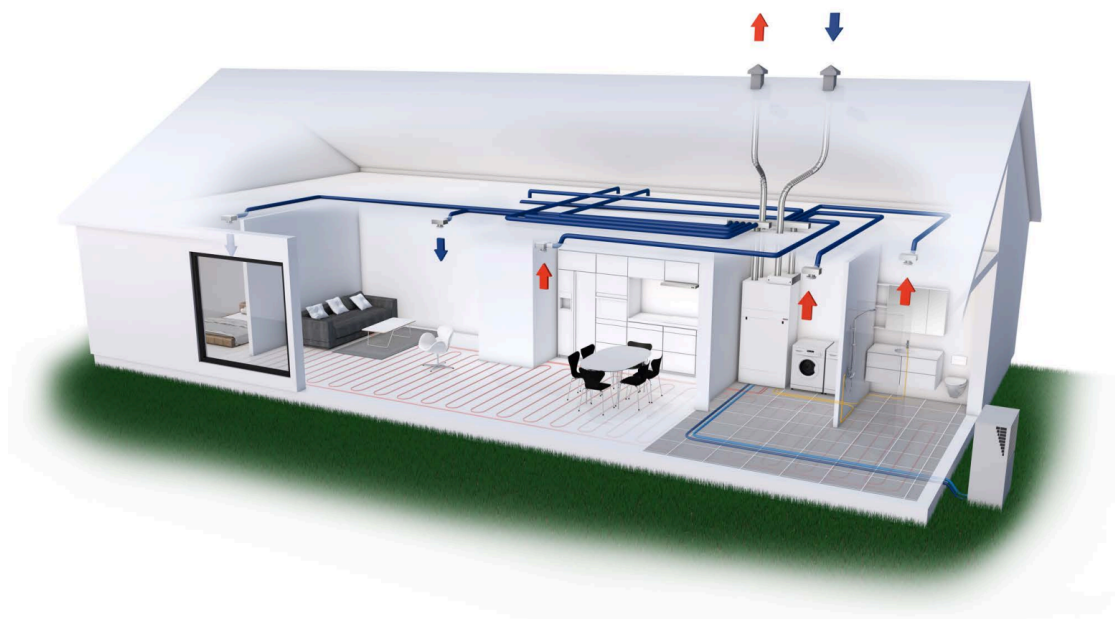


Figure 3: Overview of the general design of the ventilation/heating system w. heat recovery



Figure 4: The VELUX roof windows applied in the demo houses, with automatic/smart opening and blinds

4.3 Sensor overview

From the project start, the team had a goal of collecting as much data as possible given the unique opportunity of collecting data from a modern built house with living residents. The philosophy adopted was a “better safe than sorry” mentality even though a fraction of the collected data would eventually end up being used.

The plan was to gather as much data as possible and later boil it down - through data analysis and laboratory testing - to the most essential parameters needed to run the developed control system.

4.3.1 Sensor plan

Prior to the start of the baseline period a sensor plan was laid out and executed. This section highlights the most essential for context. Besides the sensors listed in Table 2, each house had a pair of Lindab Ultralink

installed for measuring the inlet and outlet air flow. In houses with floor heating (DK1 and DK2) the existing thermostats and control valves were used.

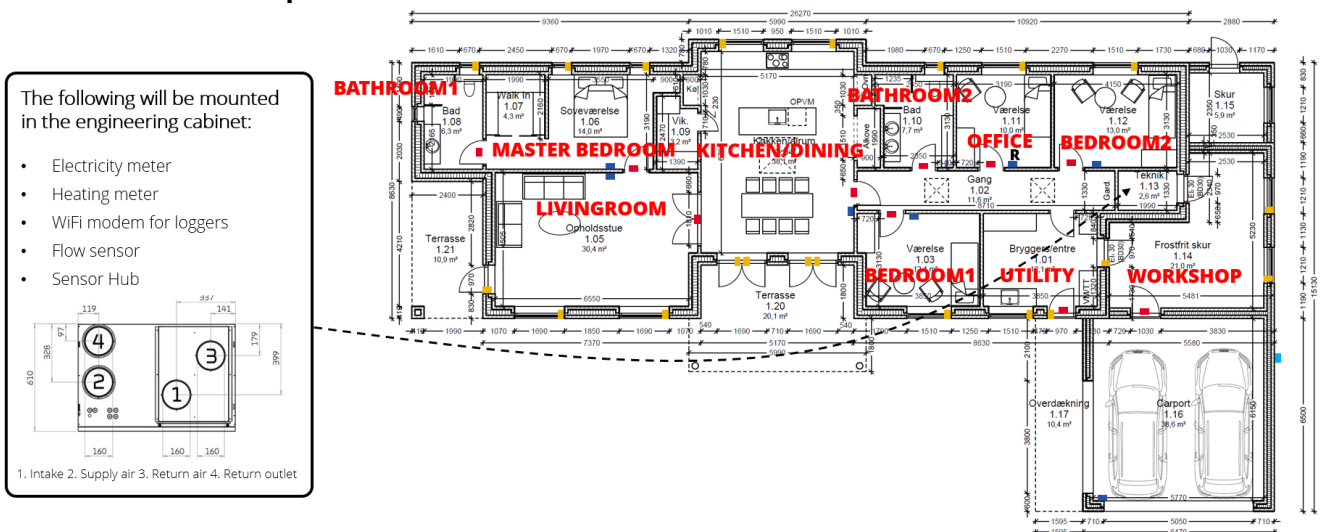
Sensor	DK1	DK2	DK3
Aeotec MultiSensor 6	10	10	9
Airthings View Plus	10	9	9
Airthings Wave Plus	1	2	1
Fibaro Door/Window Sensor 2	21	20	14
Airthings Hub	1	1	1
Power meter	2	2	2
WiFi Modem	1	1	1
Weather station	1	1	1
CO ₂ sensor in Ventilation unit	1	1	1
RH sensor in ventilation unit	1	1	1

Table 2: Number of sensors installed in each house.



Figure 5: The main types of sensors with color coding, to view their placement on the sensor plans of the demo houses.

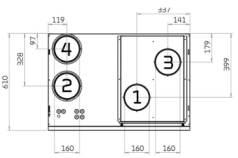
4.3.1.1 DK1 sensor plan



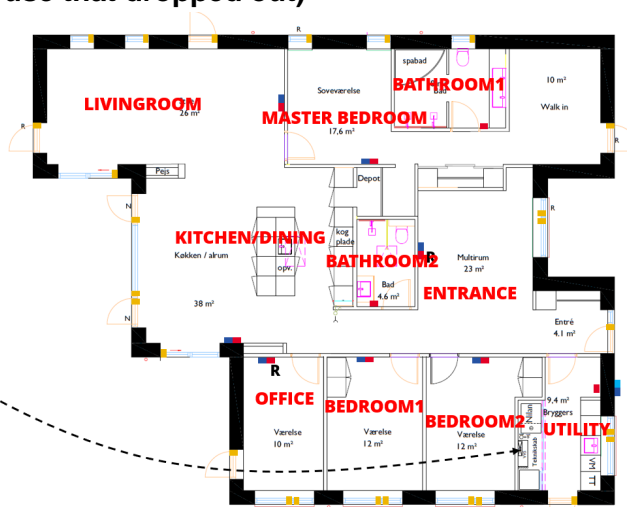
4.3.1.2 DK2 sensor plan (the house that dropped out)

The following will be mounted in the engineering cabinet:

- Electricity meter
- Heating meter
- WiFi modem for loggers
- Flow sensor
- Sensor Hub



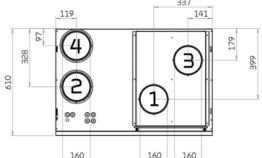
1. Intake 2. Supply air 3. Return air 4. Return outlet



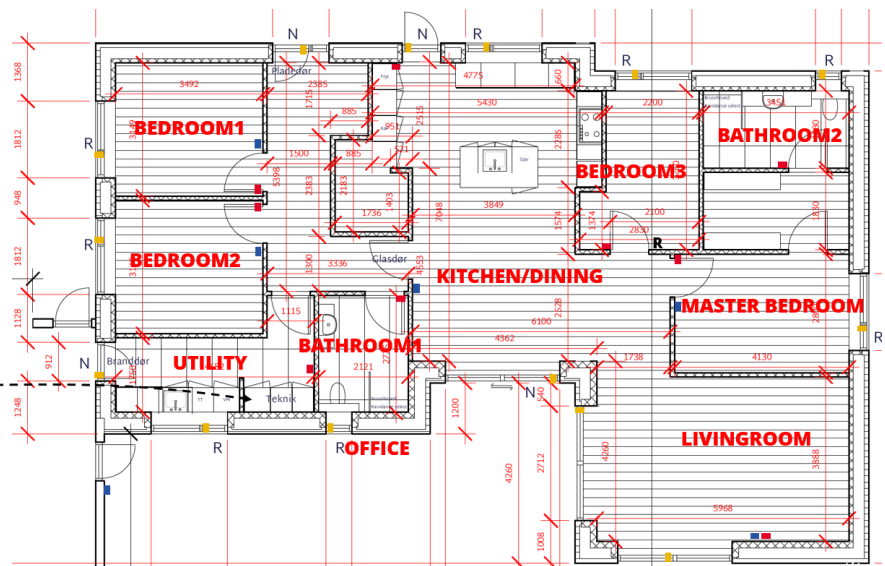
4.3.1.3 DK3 sensor plan

The following will be mounted in the engineering cabinet:

- Electricity meter
- Heating meter
- WiFi modem for loggers
- Flow sensor
- Sensor Hub



1. Intake 2. Supply air 3. Return air 4. Return outlet



4.4 Data acquisition architecture

The fundamental data architecture was to install a local computing unit in the house acting as a local (Node-red) gateway, which was interfacing with all the smart sensors, the VELUX windows and the Nilan HVAC unit. The local gateway was connected to a server in the cloud over the internet.

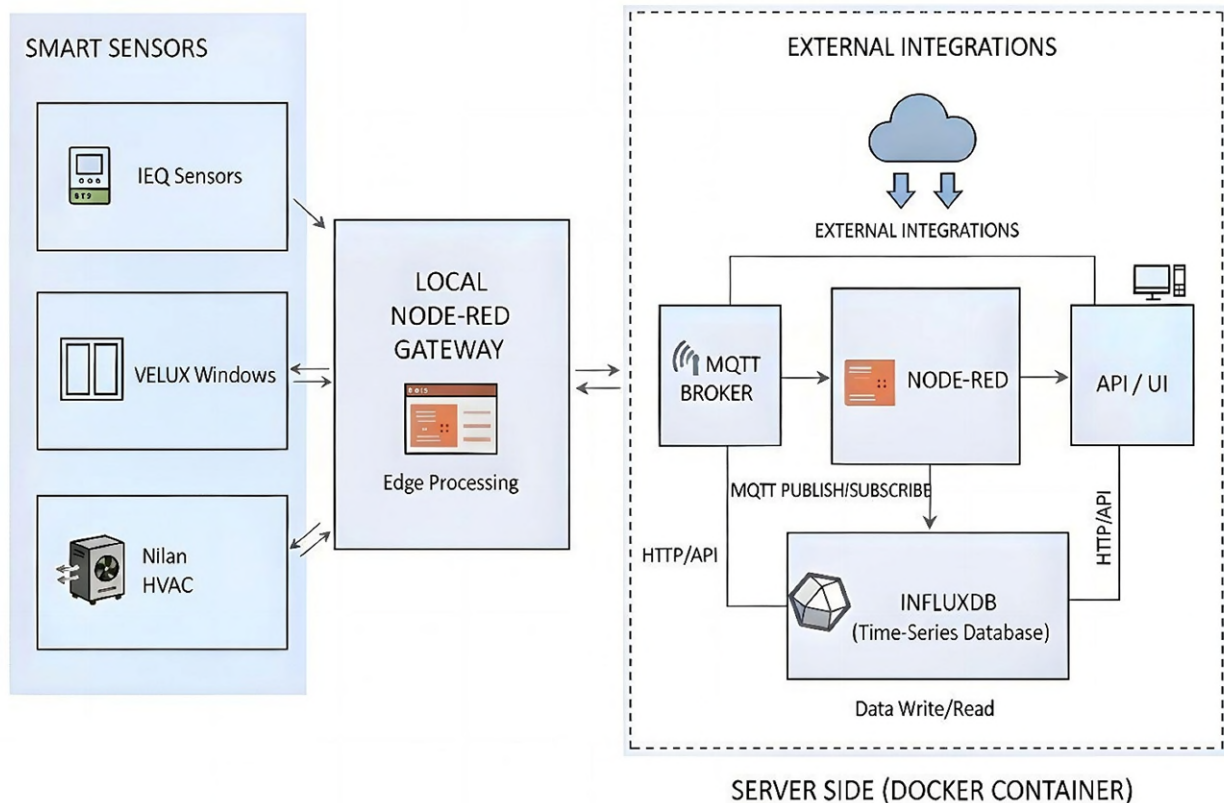


Figure 6: Simplified data acquisition architecture.

Local gateway (raspberry pi):

- **Indoor environmental quality (IEQ) sensors** (see p. 4.3.1 for complete list)
- **VELUX windows** two-way communication through a KLG300 gateway
- **Nilan unit** two-way communication through their own gateway unit

Server (docker container):

- **Node-red** acting as a central hub for all the data from the houses as well as collecting data from external API's
- **MQTT broker** acting as a "highway" for all the data.
- **InfluxDB database** for datalogging the data.
- **API** for extracting data from the database. Useful for sharing of data between the partners.
- **User Interface** for continuous monitoring of the data. Made for the teams internal use and not the families.

A raspberry pi was installed in each house functioning as a local gateway. The raspberry pi was running a local installation of node-red with the purpose of interfacing with the different protocols by the various chosen

sensors. Alongside collecting data from the sensors, it would interface with the VELUX and Nilan gateways to keep all data flowing through this central local hub.

The local gateway (raspberry pi) was connected to the internet through an LTE 4G modem. As the project had several houses to manage along with data from cloud API's like weather forecasts, electricity prices etc., a cloud-based node-red server was set up to function as an online gateway. This gateway would host the MQTT-broker, collect data from external API's and send all the data to an InfluxDB timeseries database. An UI was also developed in node-red for easy monitoring of the collected data.

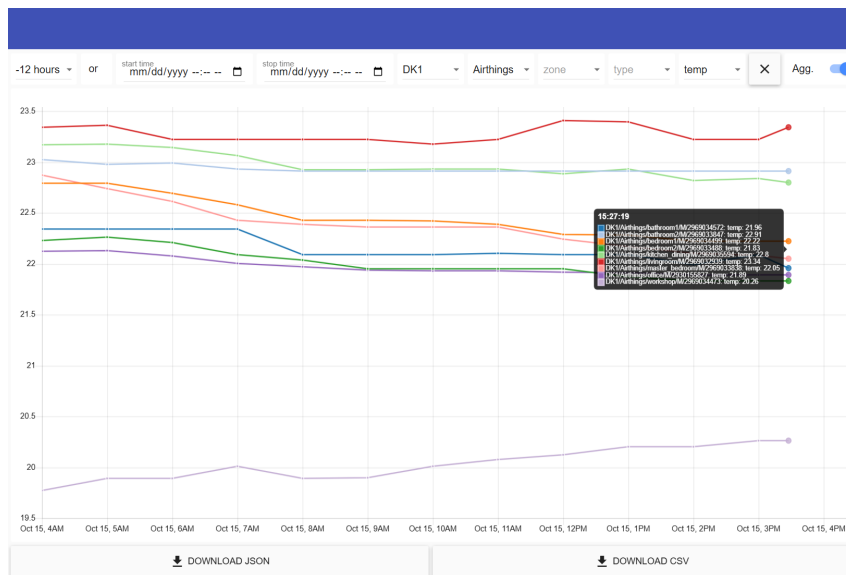


Figure 7: Online data monitoring tool developed in the project providing easy access to all the collected data

4.4.1 MQTT hierarchy

Managing several hundred different data points across several houses provided a challenge in the way the datalogging was handled to make the data easily retrievable. The solution chosen was to send each data point over MQTT making use of the built-in hierarchy structure to construct a unique identifying name.

function/house-id/sensor/zone/type

Figure 8: MQTT hierarchy

Explanation of keywords in the hierarchy referring to Figure 8:

1. **function** describes the function of the data. The most notable keyword here is “data” which means the data will be saved in the database. Other keywords available are “alert”, “mon” and “set”. Which in respective order are used to send alert (i.e low battery), monitoring realtime data not getting data-logged and set new setpoints.
2. **house-id** is the identifying keyword for the house the sensor is located at. In this project “DK1”, “DK2 or “DK3”.
3. **sensor** is the name of the physical sensor e.g “Airthings” or “ultralink” ect.
4. **zone** refers the zone of the house the sensor is located at according to the naming on the sensor plan (see 4.3.2) e.g “Bathroom1” or “Masterbedroom”

- 5. **type** indicates what type of data it is. “M” for measured by physical sensors, “SP” for setpoint (necessary because actuating sensors like VELUX windows or floor heating valves have both a measured value and a setpoint value) and “forecast” external forecasts like weather services or day a head electricity price.

All the data starting with the keyword “data” was datalogged into an influxDB timeseries database with each level of the mqtt topic added as a tag. This approach made it easy to retrieve data simply by filtering the different tags in the query. See Figure Figure 9 as an example.

data/DK1/ultralink/utility/M

Figure 9: Example MQTT topic of the measured value of an Ultralink located in the utility room of house DK1

4.4.2 API

A simple application programming interface was developed for easy retrieval of data and sharing data between the partners of the project without exposing the database directly. The API was a standard REST API allowing to query data from the database by providing timespan and filter tags.

Below is an example of a URL query to request data from the last 7 days on the Airthings sensor located in the kitchen in house DK1.

URL/data?start=-7d&house_id=DK1&sensor=Airthings&zone=kitchen

4.5 Development of the control algorithm

Different control strategies were discussed, and it was decided that the control algorithm with the highest potential was an MPC controller standing for Model Predictive Control.

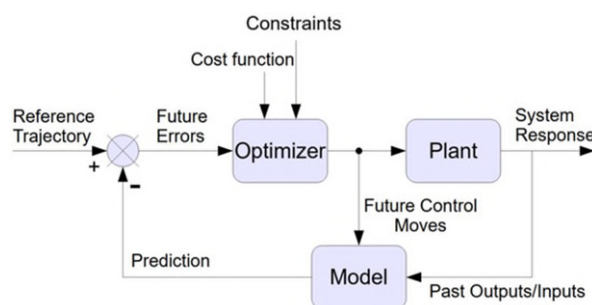


Figure 10: Control loop of a general MPC-controller.

Model Predictive Control (MPC) is a way to control a system by planning a short distance into the future. The controller uses a mathematical model to predict how the system will react. At each moment, it plans a short sequence of actions that will keep the system on target while staying within limits, like not exceeding speed or power. It then applies only the first action from that plan. A moment later, it measures the system again, updates its prediction, makes a new plan, and repeats. This rolling replan is what makes MPC good at handling

multiple goals and limits at the same time, though it does need some computing power and a reasonably accurate model.

4.5.1 Design choices

It was decided that energy consumption would be the primary optimizing parameter of the control algorithm along with indoor climate parameters like temperature and CO₂ levels. A higher monetary savings potential could have been realized if energy price signals were incorporated into the cost-function of the MPC, as demonstrated in a parallel project lead by DTI¹. However, it was chosen to leave out pricing signals from the control algorithm in this project as it would further complicate an already complicated task of normalizing the data across baseline year and demonstration year to get a reliable measurable effect of the control algorithm in practical use, as weather and energy prices are inherently chaotic.

The system was designed to minimize energy consumption through its cost-function while within allowed temperature- and CO₂-bands. However, the cost-function for the temperature was later changed to increase the cost when deviating from the mean target temperature, as the MPC had a tendency to work towards the maximum and minimum extremes in order to save energy.

4.5.2 System variables

Model predictive control

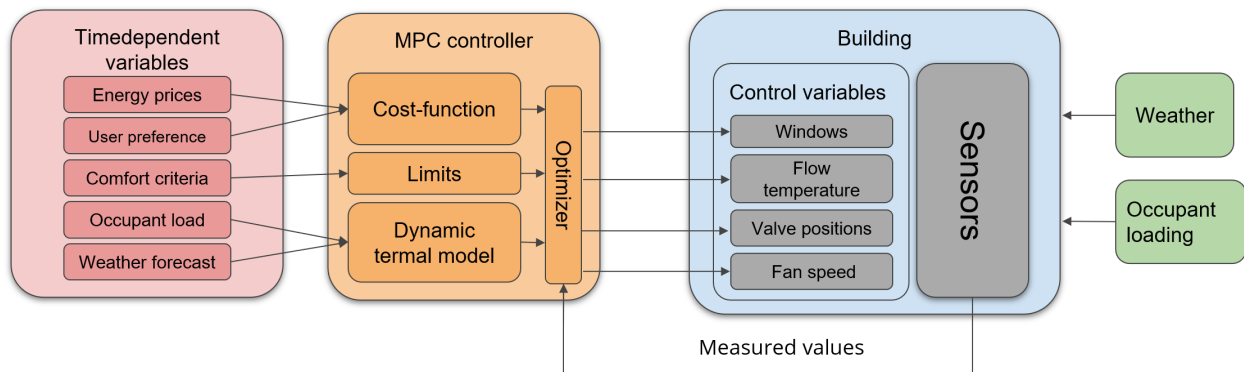


Figure 11: Block diagram of control algorithm.

¹ Elforsk ...

4.5.2.1 Sensor input for the system

Room sensors:

After the baseline data collection period, an analysis of the sensor requirements for the control system was conducted. The conclusion of the analysis was that the existing Airthings sensors would be sufficient as sensor-inputs for the control system and therefore a decision was made to build the control system around these sensors to avoid investing time and money into new hardware.

Outdoor sensors:

A sub analysis was made to determine whether local measurements of the outdoor conditions were required for reliable results or if a weather service API would be accurate enough as a direct system input and thereby saving the cost associated with local hardware.

Three sources of gathered weather data were compared. An Airthings sensor (identical to the indoor sensors) mounted outside. A semi-professional weather station DAVIS Vantage pro 2 and finally the current weather condition on the location provided by Yr.no weather service API.

The Airthings sensor was designed for indoor use and proved unusable for outdoor measurements. The Davis weather station provided high accuracy on its measurements, however due to its physical size it had to be placed in suboptimal locations around the plot. In one house it was in the backyard near a hedge and in the other houses it was placed on a flat part of the roof or on the garage. The analysis showed that even though the weather station's sensors were quite accurate, the location chosen by the families provided a greater source of error than the weather service. The conclusion was that the future system was better of using the weather service to measure the outdoor conditions, eliminating cost and sources of error from improper sensor locations.

Weather forecast:

Following on the findings from the analysis above, a natural question arose about which weather service was the most accurate one and another analysis was conducted. This proved very challenging as very few weather services provide public information about their internal models. However, an elaborate report comparing a dozen of the most popular weather services were discovered². The report had a comprehensive system of evaluating each weather service and on almost every single parameter there was a single service provider outshining all the others, The Weather Channel. However, it was later discovered that the report was commissioned by IBM who at the time owned the weather service, so validity of the report is highly questionable.

4.5.2.2 Thermal model

An MPC-controller requires a time-dependent mathematical model of the physical system it is trying to control (in this case the temperature inside a room). The model is essentially a set of differential equations describing how the system responds to external factors. In this case the temperature inside a room is derived from an energy balance of heat power entering the room vs. the heat power leaving the room. Factors that contribute to heat accumulation in a room are solar energy entering through the windows, electrical appliances and lighting, heating system and heat generated by people and animals. If the outdoor temperature is below the room temperature thermal energy will be leaving the room through thermal conduction through the walls, floor and ceiling as well as through the air change from the ventilation system (if the inlet air is not preheated). A simple illustration of the heat balance in a room can be seen in Figure 12.

² https://forecastwatch.com/wp-content/uploads/Global_and_Regional_Weather_Forecast_Accuracy_Overview_2021-2024.pdf

Differential equations were set up for each zone in the house to build up a thermal model.

With an accurate thermal model of the rooms in the house the MPC-controller can use forecasts of weather data (temperature and solar irradiation) along with expected use patterns to simulate into the future and take corrective action before a potential problem arises or simply save energy by turning down the heat when it is not needed.

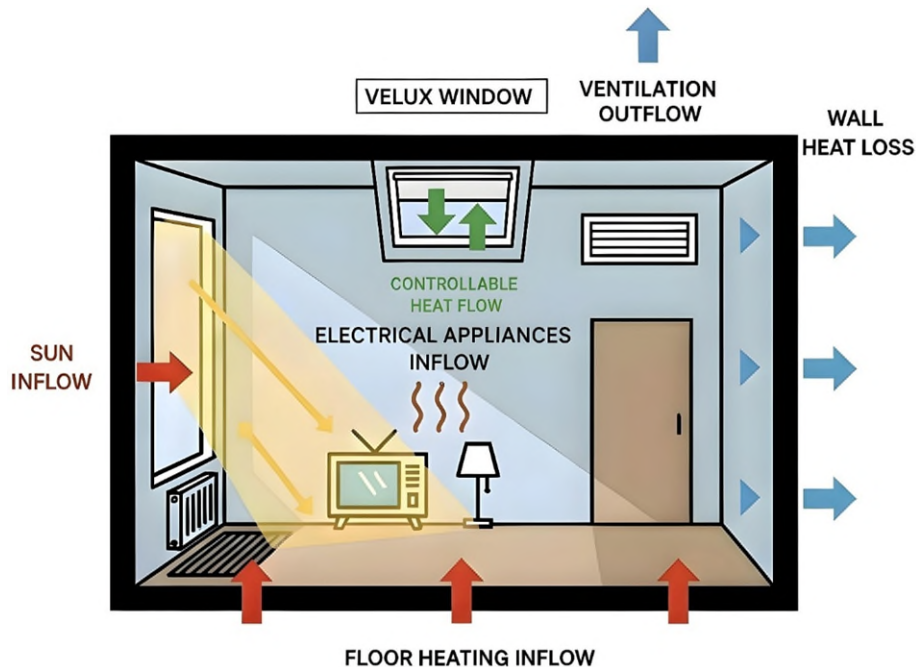


Figure 12: Illustration of the heat balance of a room which needs to be modelled mathematically for the MPC to be able to predict the future temperature of the room. Among other things the body heat from the occupants is also part of the model.

4.6 Implementation of the control algorithm

The control algorithm was developed in python and installed on the local gateway. A discussion was had regarding if the control algorithm should run in the cloud or on the simple user interface was made in the local node-red to allow the families to access basic information of the systems operational status and as a platform to give easy feedback to the research team.

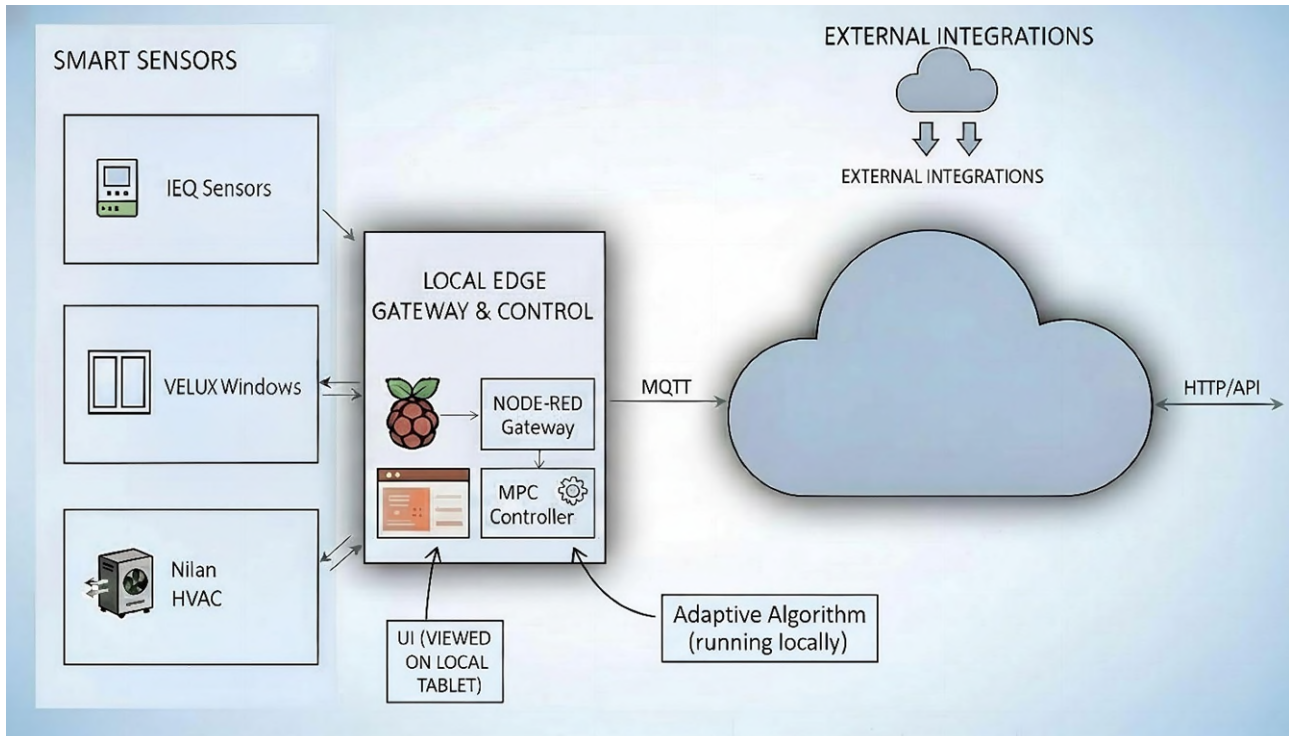


Figure 13: Illustration of MPC- and UI implementation on the local gateway. The control algorithm using MPC is running locally as well as the local UI for the family.

A tablet was provided to families for interaction with the UI. The tablets were physically installed in the utility rooms.

4.6.1 User Interface

A long discussion was held regarding the functionality and level of data access the user should have through the UI. The main dilemma was that the researchers had access to an abundance of data but didn't want the users to change behavior based on the feedback. On one hand the data could be used to inform the users of bad habits that if corrected could lead to increased savings or better indoor climate. On the other hand, if users changed consumption patterns based on informed awareness, it would be difficult if not impossible to determine how much of the savings contributed to the control algorithm itself and how much it was from change in user behavior.

The engineers and anthropologists of the research team agreed that giving the users access to the historical data, would change their use patterns as it was already evident the sensor readings on the local Airthings display had changed the family's behavior. Even though this behavioral change was an unintended oversight by the team, it did not affect the research results as the sensors were present during the entire baseline and demonstration period.

Another concern was that if the users had access to control the underlying setpoints of the system they might inadvertently cancel out any potential savings by turning up the heating if they momentarily felt cold and simply forget about turning it down again. A scenario that was very likely to happen as the MPC might lower the heating power in the morning because it was going to be a sunny day.

Ultimately it was decided that the UI should be used as a basic utility tool providing the families with a basic operational status and a way to report their inputs directly to the research team.

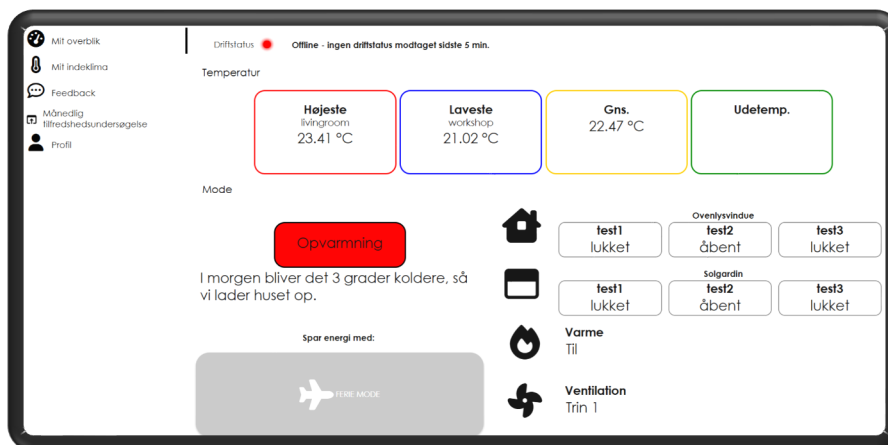


Figure 14: The prototype of a simple user interface used to inform and interact with the residents in the demo houses during the course of the project.

4.6.2 Presence detection

Allowing the system to operate the windows automatically presented a security problem during the hours the houses were unoccupied. Experimentation with a presence detection algorithm was conducted. While working fairly well the issue was that it was built around time-lacking indicators like rising CO₂ concentrations. The method was ultimately deemed too unreliable to control the windows directly and a maximum opening of the windows, making breaking-in impossible, was implemented instead.

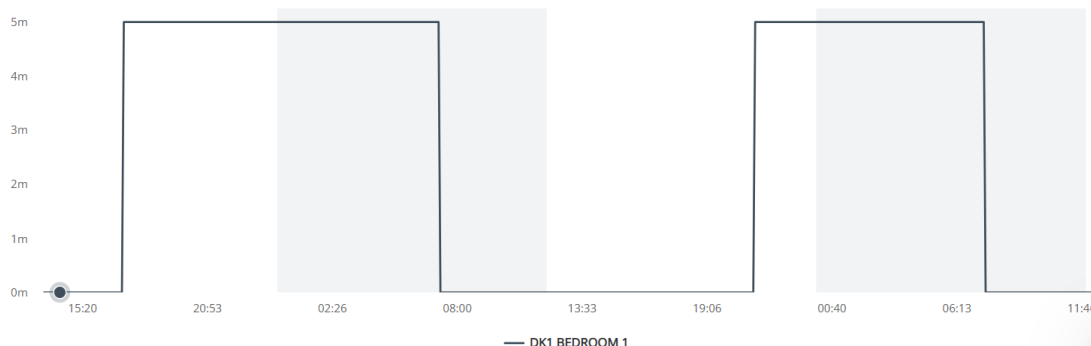


Figure 15: Presence detection algorithm output for a single room.

4.7 Context of implementation

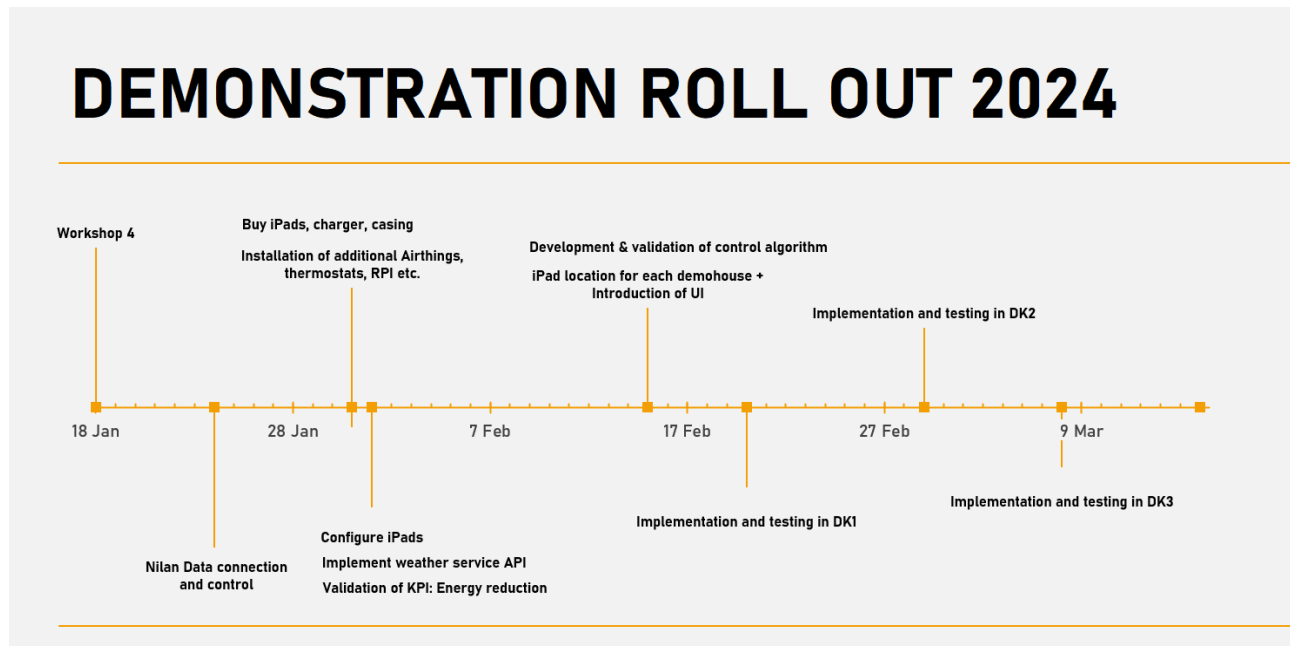


Figure 16: Initial roll out plan for the demonstration of the control algorithm. DK2 pulled out of the project few weeks prior to scheduled demonstration of the control algorithm.

The Smart Green Indoor Climate Manager (SGICM) was implemented in two Danish households between 2023-2025. Each household was recruited based on presence of necessary infrastructure and willingness to participate in long-term monitoring and evaluation. The following sections presents the characterisations of the two households, establishing the baseline conditions, routines, comfort priorities, as well as general attitudes toward climate control technology prior to implementation and further involvement in the project.

Overall, both DK1 and DK3 had structured routines, minimal interaction with existing climate systems, and clear prioritisation of comfort over energy optimisation. DK1 entered the project with both VELUX windows and Nilan ventilation already installed, while DK3 required VELUX window installation as part of the demonstration.

Both households had summer overheating as their primary climate concern, though DK1 reported winter humidity issues with winter coughing, while DK3 cited adequate winter comfort at preferred heating levels. DK1 had a slightly greater pre-existing awareness of air quality parameters, while DK3 relied on subjective comfort assessment. And both families preferred automated, low-maintenance solutions and expressed some reluctance to adjust technical settings without clear need.

4.7.1 Demonstration House DK1 before implementation

The DK1 home is occupied by a family of four: two adults, and their daughters (10 and 7), along with a family dog. The family had resided in the house for three years prior to project involvement in 2022.

Daily routines were structured and predictable during weekdays, with mornings beginning early and afternoons designated to cooking, homework, and family activities. Weekends were typically spent away from home engaging in sports, hunting, and various social activities. Home-cooked meals were prepared daily.

Prior to project involvement, the home was already equipped with electric VELUX windows and a Nilan ventilation & heating system, both of which were manually operated. Interaction with these units was characterised by minimal manual intervention. The Nilan ventilation unit operated on default settings, having been manually

adjusted only once during an unusually warm summer. Heating thermostats had been set at initial occupancy three years earlier and remained unchanged, with the bathroom areas maintained at 22-23°C, living spaces at around 22°C, and the bedroom at 18°C.

VELUX windows were opened manually, primarily during cooking or extreme heat, as well as after sunset for nighttime cooling. A preference for mechanical ventilation over natural ventilation existed due to concerns about insects entering. The terrace door was open on a regular basis during summer months. Ventilation filters were replaced every three months, exceeding manufacturer's recommendations, due to visible dirt accumulation.

Solar panel installation shortly before the project commenced had introduced some energy awareness. The dishwasher and electric vehicle charger were operated during off-peak hours, though the washing machine was not, to avoid odour issues. Energy efficiency measures were adopted only when compatible with existing routines and comfort requirements.

Summer overheating was the primary concern prior to implementation, with temperatures inside regularly reaching 24-25°C and discomfort most pronounced during sleeping hours. On particularly warm nights, the family would occasionally sleep on the outdoor terrace. Winter conditions were characterised by relatively low humidity, associated with respiratory symptoms in the eldest daughter, i.e. dry coughing, resulting in difficulty in falling asleep.

The family had some awareness toward indoor air quality, particularly regarding particles- and CO₂-levels, though active monitoring was not part of any routine. Their view was generally that air quality should be managed passively through properly functioning ventilation systems. Although they did have some interest in performance data following solar panel installation.

4.7.2 Demonstration House DK3 before implementation

The DK3 home is occupied by a family of five: two adults, and their sons (8, 6 and 3), along with a dog. Family visits approx. once per week. The family had resided in the house for five years prior to project involvement in 2022.

Daily routines were structured around work and childcare. The family typically left home at 7:00 in the morning and returned around 15:45. One adult worked from home once a week. Weekends were primarily spent at home. Home-cooked meals were prepared most evenings, with occasional use of microwave reheating.

Prior to the project, DK3 did not have electric VELUX windows. These were installed as part of the demonstration. The house was already equipped with a Nilan ventilation/heating system and electric heating panel, but no underfloor heating. The house was designed for ventilation heating as primary heat source, however, the house was poorly designed requiring excessive use of the electric heating panels. The Nilan unit was upgraded with an electric after-heater to alleviate problems of the kids getting burned by the electric heating panels.

In the winter preceding implementation, energy costs were actively monitored during the electricity price crisis. The family experimented with reducing heating setpoints in response to the increases in price. The Nilan system temperature was lowered from 24°C to 22°C to maintain an indoor temperature of around 20°C. This was unlike their previous practices and was driven by energy cost concerns, though comfort was in fact compromised.

The ventilation system operated at level 3 during daytime hours and level 2 at night to minimise sleep disturbance. Inlet air temperature was set to 23°C. Beyond this configuration, no further manual adjustments were routine. Also, electric heating panels in children's bedrooms were not activated during winter, due to fire risk from floor mattresses.

The primary concern for DK3 was summer overheating, particularly in the kitchen and living area. The garden door was regularly left open during warm months, and children spent considerable time outdoors. Prior to VELUX window installation, natural ventilation options were limited.

Winter conditions were characterised by adequate temperatures in most areas, though they thought the kitchen lacked heating panels. The family did not report significant humidity or air quality concerns prior to system implementation, though awareness of such parameters was limited. Also, they did no active monitoring of CO₂ or particle levels.

The Nilan system operated on configured settings with minimal user intervention. Heating panels were manually controlled but rarely adjusted once initial setpoints were established. The family expressed reluctance to modify technical settings due to uncertainty about optimal parameters.

Attitudes toward energy efficiency were pragmatic, and cost savings were valued highly but not at the expense of comfort. This was showcased in their abandoned attempt to reduce heating when energy costs were high. Both adults demonstrated awareness of energy consumption patterns but did not engage in active monitoring beyond periodic review of electricity bills.

5. Project results

5.1 Achievement of project goals – technological results

The Smart Green Indoor Climate Manager system was successfully developed and tested in two Danish demonstration houses. The system integrates wireless indoor climate sensors (e.g. temperature, humidity, CO₂), a central gateway with data-driven control algorithms, a cloud-based data platform, a tablet-based user interface, interoperable modules connecting VELUX roof windows and blinds, Nilan ventilation and heating systems as well as Wavin and Uponor heating solutions.

Before activating the automated system, a baseline data collection period was conducted using a comprehensive sensor setup. This enabled comparison between baseline and demonstration periods. Families were instructed to maintain consistent behaviour across both phases, and minor adjustments (e.g. increased use of kitchen range hood) were already implemented during baseline, ensuring reliable performance comparisons.

The system operated continuously for over one year without any critical failures. Initial setup challenges, such as rain detection sensitivity and early morning curtain activation, were resolved early in the demonstration phase. After these adjustments, the system ran rather smoothly and unobtrusively, becoming a natural part of daily life for the families.

Interoperability between systems from different manufacturers was successfully achieved. The integrated control allowed coordinated operation of windows, ventilation, and heating systems across brands, demonstrating the feasibility of cross-manufacturer smart climate management.

5.2 Performance in Demonstration Houses – commercial results

The energy performance and the indoor environmental quality (IEQ) were assessed according to two main key performance indicators (KPI): comfort and energy savings (Table 4). The criteria adopted for thermal comfort were based on the recommendations of the EN 16798-1 standard. For the heating season, a fixed range of

indoor temperatures (20–25 °C) was defined, while for the non-heating season, the daily upper and lower limits of indoor temperatures varied according to the outdoor climate, as per the adaptive comfort model.

KPI	Assessment	Relevant measuring points	Criteria
Comfortable indoor climate	DS/EN 16798-1 + 2 User feedback	Indoor Temperature (T) Outdoor Temperature (Text) Relative Humidity CO ₂	T - Heating season: 20-25 °C T - Non-heating seasons: Adapted following outdoor temperature. Relative Humidity: max 65% CO ₂ : 1200 ppm (assuming 400 ppm outdoor concentration)
Energy savings	Actual energy use Heating Degree Hour	DK1: - Ventilation and hot water - Central heating DK3: - Ventilation, hot water and air heating - Ventilation electric afterheater	Initial estimate between 10-27% energy savings

Table 3: Key Performance Indicators (KPI) for the indoor climate and energy savings.

5.2.1 Indoor Environmental Quality (IEQ) improvements

The monitoring of the indoor climate resulted in a detailed database for both houses. Measurements included outdoor and indoor air temperature, relative humidity, CO₂ concentration, PM₁, PM_{2.5}, PM₁₀, VOC, and radon (limited to one room per house). We could visualize the data through dashboards in real-time and also as averages for a period of time. This way we could easily follow the outdoor and indoor climate. For instance, Figure 17 presents an example of a dashboard with average hourly measurements of the indoor climate for January, both baseline and demonstration, in DK 1 house.

DK1 – indoor climate

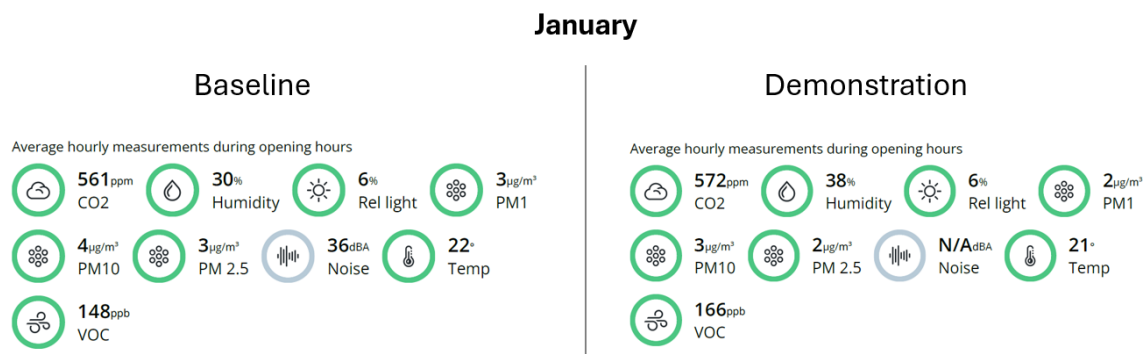


Figure 17: Average hourly measurements of the indoor climate for January (baseline and demonstration) in DK 1 house

- **Indoor temperatures**

Figure 18 and 20 are shown as examples of developed dashboards. Figure Figure 18 presents a dashboard displaying both outdoor and indoor temperatures, along with the upper and lower comfort limits for DK1. The dashboard allows to select specific rooms (i.e., zones) and time periods, enabling a more detailed analysis of the results, such as comparisons between the baseline and demonstration periods.

Figure 20 shows another dashboard plotting the indoor temperatures against the daily running mean outdoor air temperatures (a weighted average of recent daily average outdoor temperatures as described in standard), indicating the comfort bands (black lines) for the heating and non-heating season for DK1. The dashboard also illustrates the comfort bands (black lines) for both the heating and non-heating seasons. Specific rooms and time periods can be selected. Additionally, it shows the number of hours with heat or cold discomfort; in the example shown, 'Blank' indicates zero hours of discomfort.

Throughout the year, both demonstration houses maintained indoor temperatures consistently within or very close to the 20–25 °C range, demonstrating the effectiveness of the smart control system in regulating thermal comfort. Importantly, the introduction of smart control did not result in any new instances of overheating or overcooling. Temperature profiles for both the baseline and demonstration setups remained comparable, indicating that the system preserved comfort while enhancing energy efficiency.

The smart control system also played a crucial role in reducing temperature peaks during hot weather, employing strategies such as night purging to cool the indoor environment passively and efficiently. This proactive approach helped mitigate overheating during warmer periods without compromising energy performance.

On particularly hot days, the smart control contributed significantly to avoiding or mitigating overheating. In DK1 house, 100% of indoor temperatures remained below the upper limit of acceptability as defined by Category II of the EN 16798-1 standard, which sets benchmarks for indoor environmental quality. In the DK3 house, 95% of indoor temperatures also complied with this standard, underscoring the system’s reliability and effectiveness across different building contexts.

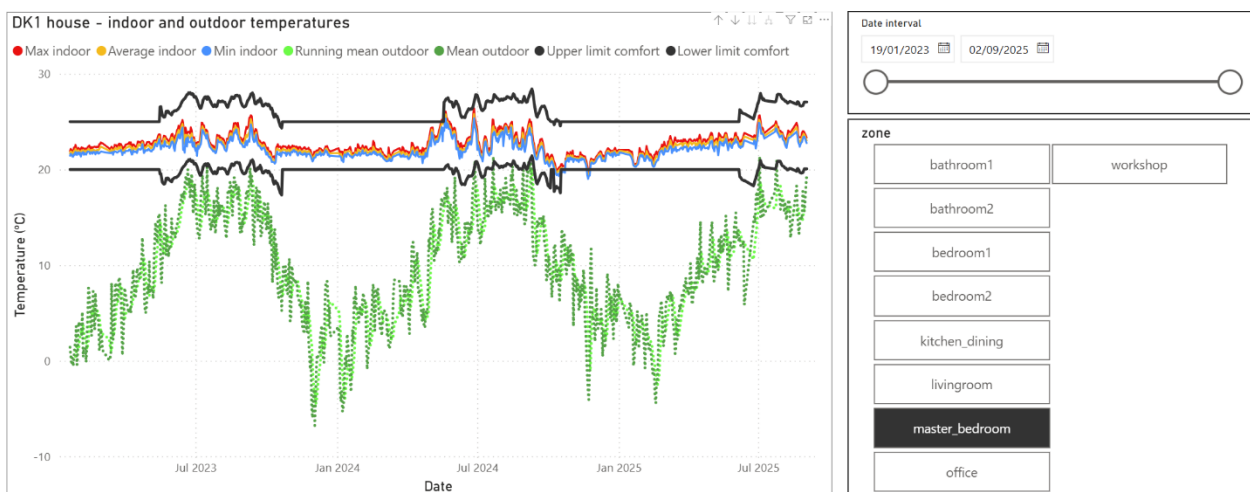


Figure 18: Outdoor air temperatures and indoor air temperatures for the master bedroom in DK1 (full monitoring period).

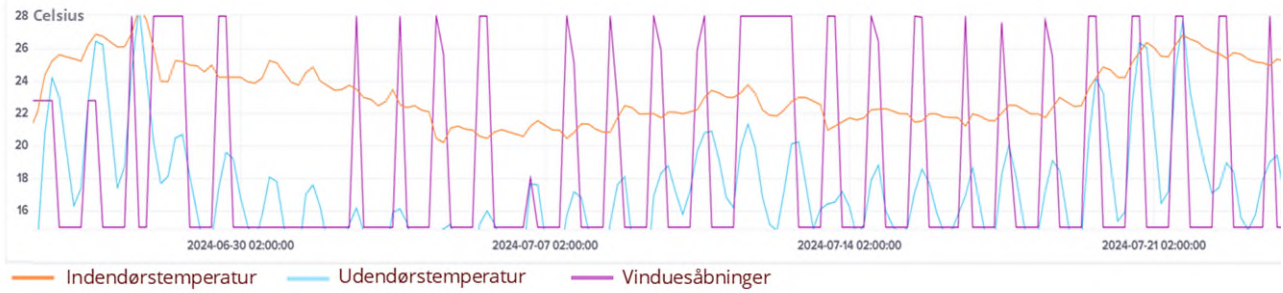


Figure 19: The graph shows how often the automatic opening of the VELUX windows affects the indoor temperature in relation to the outdoor temperature. The VELUX window is fully open when the small graph is at the top and closed when it is at the bottom. The windows are also being controlled to achieve satisfactory levels of CO₂ and particles, etc.

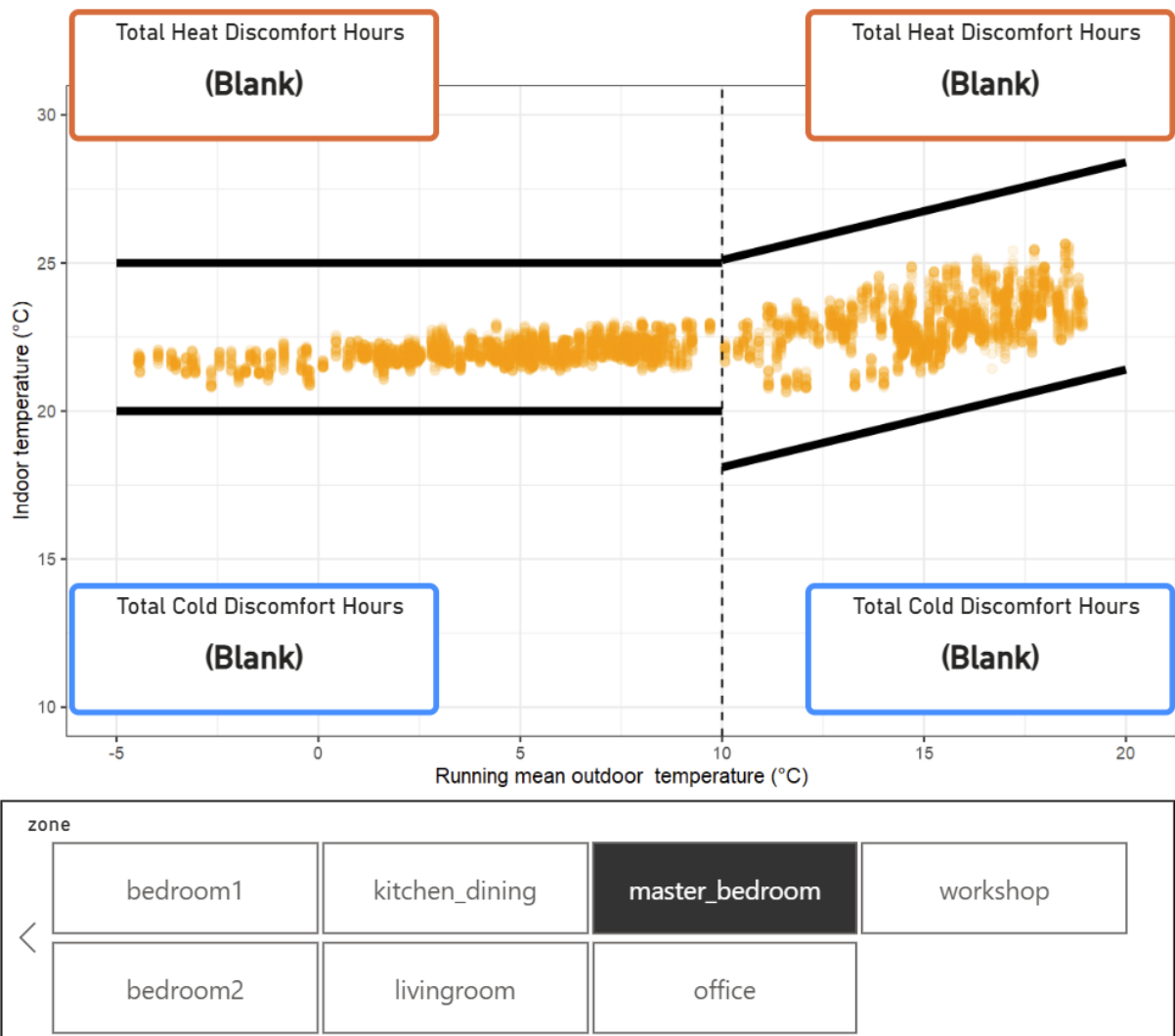


Figure 20: Hourly indoor air temperature as a function of running mean outdoor air temperature for the master bedroom in DK1 – demonstration period

- **CO₂ concentrations**

During occupied hours, indoor CO₂ concentrations were consistently maintained below 950 ppm, with the highest levels typically observed in bedrooms, as exemplified by Figure 21, which shows CO₂ concentrations for different rooms in DK1 for January (baseline and demonstration periods). This indicates that the ventilation system was effective in managing air quality.

Across both demonstration houses, CO₂ levels remained well below the target threshold of 1200 ppm, aligning with recommended indoor air quality standards. As expected, CO₂ concentrations rose during occupied periods, particularly in the evenings and mornings, but these increases were moderate, with peak values generally ranging between 800 and 1000 ppm in living areas. These levels are considered healthy and reflect efficient ventilation performance. Importantly, no instances of critical CO₂ buildup were recorded during the demonstration phase, underscoring the reliability of the smart control system in maintaining good indoor air quality. The rooms of the VELUX windows would open automatically at peak levels above 1200 ppm, to reduce the CO₂-levels.

DK1 – indoor climate

January

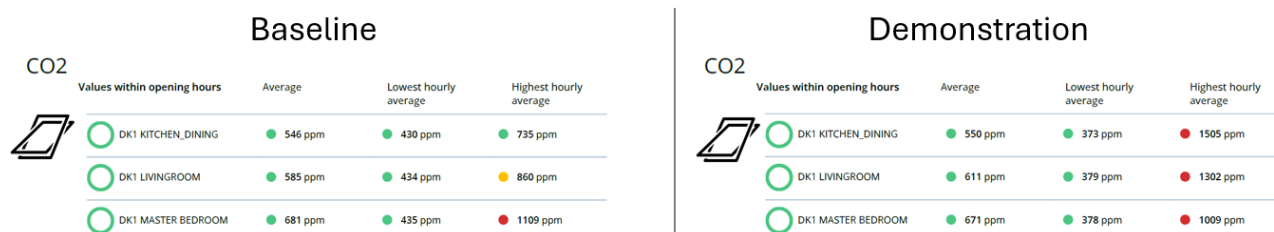


Figure 21: Average, max and min hourly measurements of CO₂ concentration for January (baseline and demonstration) in different rooms of DK 1 house. Some of these measurements were above the threshold (i.e. 1200 ppm) during the demonstration, but only for a single day and for shorter peak periods of 4-12 minutes, after which they were mitigated and CO₂ levels dropped below threshold.

- **Relative humidity**

In the DK1 house, indoor relative humidity levels were consistently maintained within the range of 35-60%, while in DK3, the range was slightly narrower, between 35-55%. These values fall well within the comfort zone for indoor environments and are indicative of a well-functioning ventilation and moisture control system. Crucially, neither house experienced any prolonged periods of high humidity, which could otherwise lead to occupant discomfort or condensation risks on surfaces and building materials.

During the winter season, the demonstration phase showed a slight increase in indoor humidity levels compared to the baseline, as exemplified by Figure 22, which presents the relative humidity for different rooms in DK1 for January (baseline and demonstration periods). This was a deliberate adjustment made to the NILAN ventilation system, which was fine-tuned to prevent excessively low humidity levels, particularly those falling below 30%, which can cause dry air discomfort and potential health issues. This proactive control ensured a healthier and more comfortable indoor climate during colder months.

DK1 – indoor climate

January

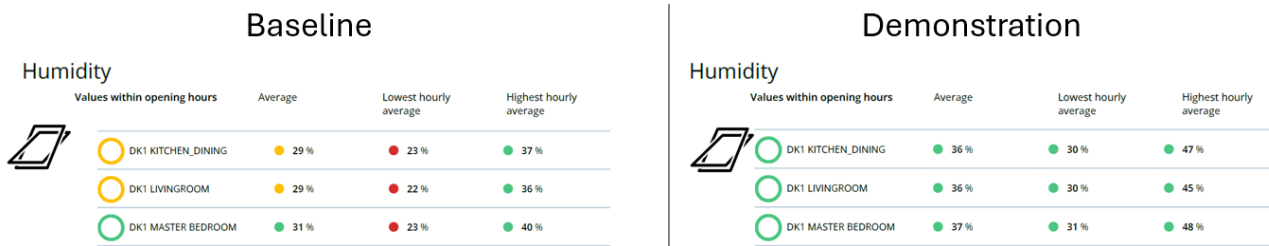


Figure 22: Average, max and min hourly measurements of humidity for January (baseline and demonstration) in different rooms of DK 1 house.

5.3 User experience

Overall, users were satisfied with the automated system and found that it improved their indoor climate and level of comfort. This primarily due to a feeling of a more vented indoor climate, which felt fresher and less stuffy and heavy on the head. The daughter in one of the families experienced diminished issues with dry coughing during the winter. They did not however find that the system could sufficiently bring down temperatures in the summer, where it gets very hot in a newly constructed house.

The families noticed the system to a limited extent throughout the demonstration period. They noticed the system mainly in the initial installation and adjustment period and again when they experienced issues with it. Once these issues were solved, the system became integrated into the everyday life of the families to a point where they did not think about it.



“The first couple of days after the sensors were set up, we thought about it and then it just became everyday life. I haven’t thought about it at all” (female user DK1).

5.3.1 User journey

The below figure shows the user journey of the two families before, during and after living with the automated system. The user journey shows the various phases of living with the system horizontally, and vertically the touchpoints with the system, the families’ perception of their indoor climate, their feelings and thoughts, which serves to explain the changes in perceived indoor climate, as well as changes in customer behaviour.

The families had very similar experiences, which have therefore been showcased in a combined user journey.

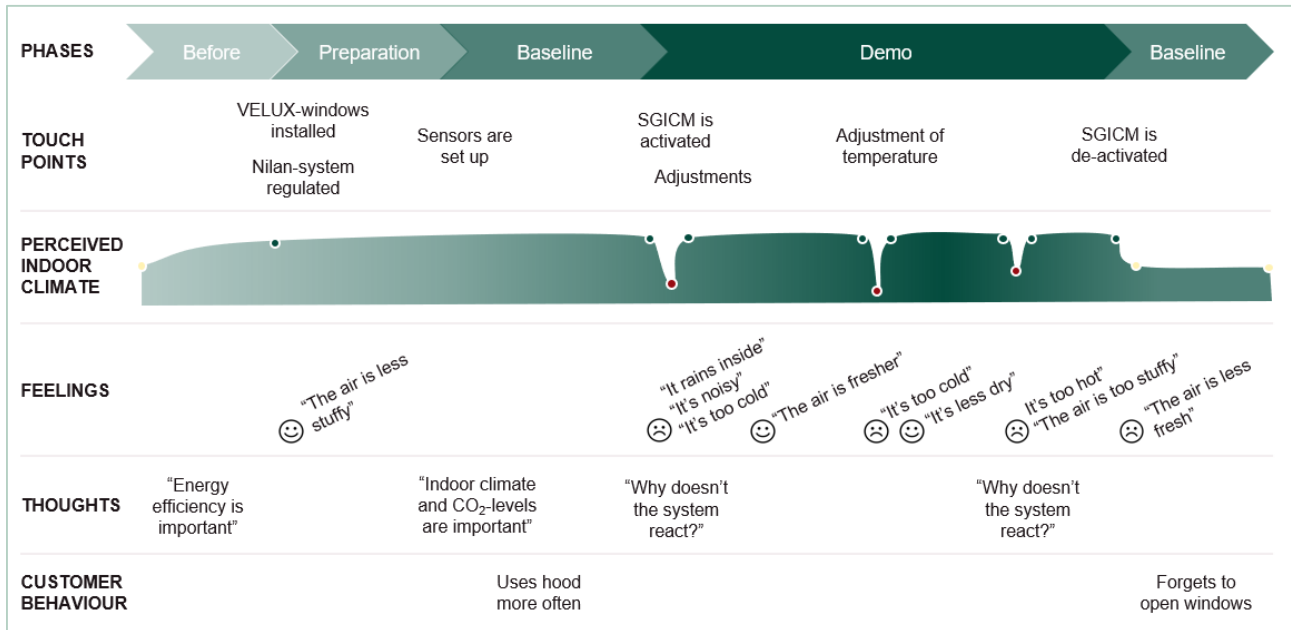


Figure 23: User journey

Before the system, the families were curious to see how much energy could be saved while still maintaining a similar level of comfort in the house. Energy savings were a higher priority than indoor climate and they had a limited awareness of the impact of CO₂ and particles. They found that their indoor climate was relatively good before the project aside from specific temperature issues like summer overheating or winter dryness.

Neither family thought much about air quality before the project. DK1 had some awareness that CO₂ and particles mattered for health, particularly when concerned about their daughter's winter coughing, but generally viewed indoor climate and air quality as something the ventilation system should handle. DK3 had not considered air quality parameters at all prior to the project, relying entirely on whether the house felt comfortable. Both families trusted that their ventilation systems were doing their job without any need to monitor or configure settings, and the idea of tracking CO₂ or particle levels was not part of their routines or general concerns.

In preparation for the automated indoor climate system, VELUX-windows were installed, and the families had their Nilan-system regulated. This already improved their experience of the indoor climate. They found that more light was coming in from the window in the roof. Moreover, the air felt "fresher" and "less stuffy" and they no longer experienced noise from the previous overheating of the ventilation system.



"The Nilan system was adjusted. We had some issues before where, when it was really hot, it was as if something in the system was boiling and making a 'dung dung'-sound. So, it probably benefited from being adjusted. And we could also feel the improvement in comfort. Your mother also said that the air felt fresher" (male user DK3).

Once sensors were set up for the baseline data collection, the families could start to see the change in CO₂ and particulate levels on the displays and the effect of various everyday activities on the indoor climate. This started to increase their awareness of indoor climate and the importance of lowering CO₂ and particulate levels. While they were informed to limit changes to the behaviour in order to better compare data before and during the project, both families mentioned that they already then started to use the kitchen range hood more often while cooking. As this was already done in the baseline, we did not expect to see significant differences in

behaviour between the baseline and the demonstration period, which allowed us to compare results more independent of behaviour.

In the demonstration period, both families experienced problems in the beginning, where adjustments had to be made to the system. In both houses, the windows were too slow to close when it was raining, and they would therefore find rain on the floor or in the windowsill when they came home. One of the users in DK1 explains how she was at home when it started to rain and that she tried to manually close the windows, which would automatically open again shortly after while it was still raining. This caused some frustration and was later used as an example of why they would have liked an overrule button.

DK3 additionally found that in the beginning, the windows and curtains were activated too early in the morning, making noise and waking up their children. While they appreciated that the windows would open in order to take in cold air in preparation for a warm day, they opened too early in the morning – at least in the bedrooms or rooms close to the bedrooms.



“In the beginning, we had a bit of trouble with it, where the windows and curtains would close automatically. At 5 o’clock in the morning, the curtains would open and the children were woken up by it. And then there was something with the sensors at first – it had to rain a lot before they would close. They are somewhat blocking the rain sensors, but there was some software they could change” (male user DK3).

The system was activated at different times of year in the two houses allowing for insights related to the seasons. DK1 started the demonstration period in February and found that it got too cold in the beginning. They explained that it seemed that the system was set to prioritize energy savings too high and was running at a bare minimum when it came to the temperature. This was quickly adjusted, and the family found that it was running smoothly after that.



“Last winter, it was a bit cold because it was running right at the limit to save energy. But we contacted them, and they adjusted it. There haven’t been any problems since” (male user DK1).

DK3 started the demo in May and found that the air got too “stuffy” and “heavy” on the head in the beginning. Their Nilan system had been regulated in preparation for the baseline, which had improved their indoor climate, but when the automated system was activated, they found that it went back to how it was before. Once adjustments were made, they explained that the system created a more natural and fresh air.



“We let them know we were getting headaches, and it felt kind of heavy at first. Then it was adjusted again. And while you’ve been managing it and the windows have been open, it’s created that natural, fresh air feeling” (female user DK3).

After sorting out the initial problems, the families explained that the system was running in the background without them thinking about it. The startup issues were perceived as small and to be expected with testing out a new system, and once they were sorted, both families experienced that the air in general was “fresher” and

less “stuffy” during the demonstration period. In DK1, the daughter additionally explained that she had less issues with dry coughing during the winter. Before the project, the air got very dry in the winter, which caused the whole family to cough in the morning and the daughter to have extensive coughs throughout the night as well. She did however not experience this during the demonstration period, where the air was less dry and more “fresh” and “natural”.



“It’s actually been a bit better. We used to have this dry cough when we woke up in the morning. And our eldest would cough all evening” (female user DK1).

“Yeah, I couldn’t fall asleep because I was coughing so much” (daughter).

“That was last winter, because this winter [during the demonstration], it’s been better!” (female user DK1).

The families noticed the presence of the system again mainly when they experienced issues with it. For the family in DK3 starting up in May, it also got too cold when they reached the winter months and like in DK1 they had to have adjustments made to the temperature. In DK3 they experienced several times that the air got very “stuffy” and “heavy” on the head in the children’s rooms during playdates. They wondered why the system did not react faster and had to open windows themselves. They would however close again shortly after causing some frustration for the parents. In DK1 they additionally experienced problems with bugs entering the house in the evening because the mosquito net did not follow the opening of the windows.

Both families additionally experienced that the system was unable to keep the temperature down in the summer. They had similar problems before the project and emphasized that it does get very hot in a newly built house in high summer. They had hoped that the automated system would be able to lower the temperatures but found that it was not noteworthy colder than before the project. They appreciated that the system would take in cold air in the morning, which created the feeling of waking up to a slightly colder house. The system however could not maintain the desired temperature throughout the day. The families are understanding of this but consider it a major selling point for a future solution if it is capable of lowering the temperatures.



“It’s probably been about the same, or at least not noticeably colder. The sun has the power in terms of raising the temperature. In the mornings, we could really tell that it had opened the windows and tried to cool things down overnight. When we went to bed, it was still warm, but by morning it had managed to cool the house down quickly. But it hasn’t been able to keep the temperature down during the day” (male user DK1).

Upon de-activation of the system, the families found that the indoor climate degraded again and returned to roughly the same level as before the project. Their increased awareness of the importance of indoor climate however created an increased focus on CO₂ and particle levels, which are more difficult to maintain at a minimum themselves versus having a system take care of it.

The families especially miss not having to think about opening the windows and it being taken care of by the automated system. They forget to open the windows themselves and highlight that it had a big effect on the indoor climate that it proactively ensured the opening of the windows while they were asleep or out of the house. Both families use the kitchen range hood more often while cooking. They open the door to the garden

to more or less the same extent as before the project, but it does not have the same effect as with the automated system.



“The fact that it’s running automatically and that you don’t have to do anything yourself – that’s something I miss. That it’s easy. Now, we have to remember to open the windows. We just don’t do it” (male user DK1).

5.4 Added value

The automated indoor climate system has proven to create added value for the families having lived with the system for one year. The analysis shows that the added value has taken the form of both economic savings, improvements to indoor climate, health and comfort as well as value in the sense of removing some mental load by automating the steering of indoor climate parameters.

The added value points are explained in the following.

5.4.1 Acceptable automation

The experiences of the two families show that users can rather quickly accept and learn to live with an automated indoor climate system. The families explain that the system quickly became an integrated part of everyday life to a point where they did not think about it.

This is also reflected in the fact that the families had only a limited number of requests for adjustments to the steering. For the most part of the demonstration period, they allowed the system to steer the indoor climate.

Reflecting upon the system, the families see considerable value in the automation. The automation ensures that the families do not have to think about aspects of indoor climate and energy savings themselves – it has been delegated to the system, which they trust to invisibly work to ensure the optimal steering. The automation thereby removes some of the mental load of having to ensure a good indoor climate and maintain a balance between indoor climate and energy savings. This invisible optimisation proved particularly valuable for tasks that require consistent and proactive timing such as windows opening in the nighttime or while they were out of the house. As the quote from one of the users below demonstrates, it almost seems to be perceived as a “little helper” trying to support the family in securing a good and healthy indoor climate.



“It keeps an eye on the CO₂-levels and the particles and tries to help bring them down. That’s really nice. It’s not something we would have thought about ourselves” (male user DK1).

5.4.2 Energy savings

While the users did not know if the system enabled energy savings during the demonstration period, this aspect is considered to be of great importance if they were to invest in the solution. Both families mentioned that indoor climate has become more important throughout the project but still emphasized that if they were to buy the solution, insights into potential energy savings would be of great importance. This also because indoor climate is harder to grasp especially for potential customers who have not experienced the effect of an improved indoor climate.

The total annual heating energy savings amounted to 1,393 kWh for DK1 and 968 kWh for DK3. With an estimated average cost of 2.95 DKK/kWh during the 2024-2025 heating season, this translates to savings of approximately 4,108.00 DKK for DK1 and 2,856.00 DKK for DK3 over the demonstration period (i.e. one year).



“When you are constructing a house, you have no idea about an improved indoor climate or what that entails. You have to talk about energy savings. [...] If we were to build a new house and it was something we could choose to add or not, I would want to know what I got out of it economically” (male user DK3).

5.4.3 Improved indoor air quality and improved comfort

Improvements to indoor climate have meant a better perceived air quality for the demonstration families. Users could visually keep track of particle- and CO₂-levels rising during cooking, social gatherings or other high pollution activities on the displays. This immediate visual feedback made the connection between activities and air quality tangible, with the users actually reacting to the data.

The ability of SGICM to automatically open the windows and ventilate mitigated high peaks of CO₂-levels, in this demonstration the system was configured to prioritize energy savings, so the windows were not opened during the winter period, as it would have been too costly in terms of heating demand. On the other hand windows were opened frequently during warm summer days.



“As soon as we get over 1,200 [ppm CO₂], it starts to get stuffy” (male user DK3)

Both families became conscious of certain thresholds early in the project and that led to immediate changes in behavior. DK3 observed that using their bio-fireplace drove CO₂-levels above 1,500-2000 ppm, generated VOC-levels more than 5 times above threshold and PM-levels more than 50 times above mean throughout the entire house after a single hour of activity. Therefore, DK3 ended up selling their bio-fireplace.

Furthermore, users experienced an improved level of comfort as a result of the improvements to the indoor climate. This especially due to the automatic opening of the windows in the early morning hours and during the day when they were out of the house. This created the feeling of waking up and coming home to a vented house, where the air was more “fresh” and less “stuffy” and “heavy” on the head.



“After you stopped taking over the controls, you can really feel that the air has gotten more stuffy in here. It’s something you managed with the windows – especially here in the kitchen and in the kids’ rooms, the windows would be open when we got home, and there was that really fresh air” (female user DK3).

The daughter in one of the families additionally experienced diminished issues with dry coughing during the winter. Since the automated system is set to not ventilate when there is no need for it, there is a higher relative humidity, causing less irritation of the air ways. This improved her and the entire family’s level of comfort considerably during the winter.

5.4.4 Increased awareness of indoor climate

The families find that their participation in the project has increased their awareness of the importance of indoor climate. Before the project, energy savings were a higher priority and reason for agreeing to participate, but seeing the development in particle and CO₂-levels on the displays and feeling the difference in their everyday life has had a big impact.

The increased awareness has resulted in changes in behaviour among the families. Both families use the kitchen range hood more often while cooking and accept the noise from the range hood at the higher levels than before the project. While they acknowledge that they forget to open the windows as much after the demonstration period, they do remember it when e.g. putting on nail polish which causes spikes in the particle levels. Moreover, one of the families sold their bio fireplace after seeing how much it effected the CO₂-levels in the whole house.



“I’ve become much more aware of how important a good indoor climate really is – especially after the sensors were installed. [...] Before this project, energy savings were the top priority, but now it’s having a healthy indoor environment. Now we can actually see it” (male user DK3).

5.5 Target group

The families having lived with the automated system see a potential for going to market with the solution. They find that the automated system has potential as a solution for owners of newly constructed buildings or buildings, which are undergoing major renovations. In such situations the system can be integrated into the construction/renovation from the very beginning.

For customers living in older buildings, the families regard it as too big of an investment to redesign the whole indoor climate system. They highlight that there are most likely other investments, which would be more lucrative if customers were looking to make energy savings or improve their indoor climate.



“Mainly new buildings or renovations, where you need to replace the entire package. It would be expensive if you had to do it from scratch – that is, if you need to change the entire floor heating system and the ventilation. That would just be too costly” (male user DK1).

The SGICM-technology creates value across the entire building value chain, from design and construction to daily operation and maintenance. In the following section the different target groups are described.

End Users (Home owners)

The primary target group is the end users. These include especially homeowners in single-family houses who are environmentally conscious and demand comfort and energy savings.

Added value:

- Reduced energy costs through energy efficient operation
- Healthy indoor climate (with simple app-based control)

- Improved and convenient comfort via automatic and proactive operation based on weather forecasts
- Reduced CO₂-footprint and increased building value
- Particularly beneficial for people with allergies or asthma through automatic ventilation and air-quality monitoring

Beyond homeowners, the SGICM-technology creates value across the construction and building management value chain, to stakeholders who specify, install, and maintain these systems and thereby play a crucial role in enabling and implementing the solution.

Architects, Professional Builders and Contractors

Companies designing, constructing or renovating energy-efficient buildings and smart homes.

Added value:

- Easier compliance with current and future EU regulations on energy and indoor climate
- Competitive advantage offering integrated smart climate solutions
- Improved marketability and increased value of completed buildings
- Enhanced "green" profile and innovation image

Installers and Service Technicians

HVAC installers and service providers responsible for system installation and maintenance.

Added value:

- Reduction of system conflicts (e.g., heating vs. natural cooling from open windows)
- Single-point integration across VELUX and Nilan products

5.6 Project dissemination

The Smart Green Indoor Climate Manager (SGICM) project has been actively communicated both internally and externally through a variety of channels. Dissemination activities have targeted stakeholders across the building industry, research partners, suppliers, and the general public. Below is a structured summary of key communication activities, including events, publications, digital channels, and social media, as well as planned future dissemination.

5.6.1 Social media, events, and publications

Completed dissemination activities

Date/Period	Channel/Event	Description	Audience	Engagement/Notes
2022	VELUX Sustainability Report 2022	Project featured on page 33 ³	Public, global	Official publication
Q2 2024	VELUX Board of Directors Meeting (Hamburg)	Project presented as part of strategic innovation updates	~10 board members	Executive-level impact
Q3 2024	VELUX Supplier Day	Tina Mayn (EVP, VELUX Products & Innovation) Presented the project as part of her presentation to all preferred suppliers at annual event	~200–300 suppliers	High industry visibility
Q1 2025	ConTech Conference	Tina Mayn (EVP, VELUX Products & Innovation) Presented the project as part of her presentation to participants at the ConTech event.	~200+ industry professionals	External, high-profile event
Q2 2025	VELUX LKR Innovation House Opening	Project video shown to visitors as part of a product innovation exhibition display	~300 visitors	Video planned for social media
Ongoing	VELUX LinkedIn Posts	Multiple posts showcasing SGICM, e.g. Example 1 , example 2 , example 3	Hundreds of likes	Likes, comments, shares
Ongoing	VELUX Sustainability Webpage	Project featured under Digital Solutions Link	Public, global	Continual online presence

Planned/ongoing dissemination activities

A few dissemination activities will be conducted after the project has ended because the final analysis had to be completed before the results were able to be published.

Date/Period	Channel/Event	Description	Audience	Engagement/Notes
Late 2025	Social Media Campaign	Repurposing SGICM video, made for VELUX LKR Innovation House opening for broader social media outreach	5,000+ impressions expected	Targeting industry and public
Nov 2025	Article Submission	An informative article about the developed technology in the HVAC magazine	>5100 subscribers	Targeting industry, planned for publishing in the November/December edition

³ <https://vkr-holding.com/wp-content/uploads/2023/04/velux-sustainability-report-2022.pdf>

6. Utilisation of project results

6.1 Lessons learned for future work

The Smart Green Indoor Climate Manager project has yielded several important lessons for future development and deployment of integrated indoor climate solutions. These insights span technical implementation, user experience, and system optimization.

Implementation Lessons & Challenges

- **Participant Retention:** Recruiting more households than strictly necessary proved essential, as one family withdrew during the project. This ensured sufficient data collection despite dropouts.
- **International Demonstration:** While the original plan included test homes in France and Germany, challenges of identifying and onboarding users in these countries limited demonstrations to Denmark. Early, realistic assessment of international site feasibility and loosening of requirements for demonstration houses are recommended for future projects.

Control of the Windows – Critical to Results

- **Automated Window Operation:** The ability to control windows automatically was central to achieving both energy savings and improved indoor climate. However, reliability and responsiveness are crucial. Delays in window closure during rain or lack of user override options led to frustration among participants. Future systems should include robust rain detection and allow for user-initiated overrides to increase trust and acceptance.
- **User Autonomy:** While automation reduces the mental load on users, some degree of manual control is necessary, especially during initial setup or unexpected situations. A user-friendly interface for temporary overrides and feedback is recommended.
- **Sensor Selection and User Experience:** Feedback from DK3 highlighted annoyance with the green indicator light on indoor sensors, which would activate with small movements and disrupt sleep. As this light provides no value to users and is only relevant for technical monitoring, future projects should prioritise sensors that do not emit unnecessary light or signals in living spaces. Sensor selection should always consider user comfort as well as technical requirements.

Additional Lessons

- **Integration and Added Value:** The value of the solution increases when integrated with other household systems, such as mosquito nets and external sun protection. This not only improves comfort but also addresses practical concerns.
- **Demonstrating Value:** For many users, the benefits of improved indoor climate are not immediately tangible. Demonstrating clear economic and health benefits — such as energy savings and improved air quality — will be crucial for market adoption. The increased awareness about indoor air quality had an influence on participants behavior, e.g. discontinuing their use of a bio-fire place. Even more impactful, participants reported that they increased their use of the kitchen range hood

during cooking, which according to research⁴ decreases exposure to harmful and potentially carcinogenic particulate matter and avoids lost life years.

6.2 Going to market

The Smart Green Indoor Climate Manager (SGICM) enters a rapidly growing and highly competitive market for smart climate control and indoor air quality solutions. The market is characterised by increasing consumer demand for energy efficiency, comfort, and healthy indoor environments, as well as a proliferation of smart home technologies and platforms. Recent market studies, confirm robust growth in both the Danish and international markets for smart climate solutions. Growth is driven by regulatory requirements (e.g. CoC and ecodesign), consumer awareness, and the integration of smart devices into everyday life.

6.2.1 Competing solutions

The competitive landscape is dominated by established HVAC and building automation companies, as well as new entrants focused on smart home integration. Key competitors include:

HVAC market leaders & integrators: Bosch, Wavin, Danfoss, Genvex, Viessmann, Vaillant, Daikin, Honeywell, Johnson Controls, Schneider Electric, Siemens, Nest (Google), Ecobee, Lennox: These companies offer home energy management systems, connecting and integrating heating, cooling, ventilation, and sometimes air quality monitoring. Their solutions are mature, widely adopted, most focus on convenience, while some also focus on indoor climate and energy efficiency.

Smart home platform providers: Google, Apple, Amazon, and others are increasingly integrating climate control into their ecosystems, offering interoperability and user-friendly interfaces.

Window and shading automation specialists: Companies like Somfy and Window Master focus on automated window and shading solutions but often lack integration with HVAC and air quality systems.

SGICM's unique value proposition lies in its ability to orchestrate natural ventilation (roof windows), mechanical ventilation, and heating/cooling in a unified, intelligent system focusing on the whole building. By integrating with both VELUX and Nilan products, and leveraging AI-driven control, SGICM aims to deliver additional energy savings and comfort beyond what is possible with standalone systems.

6.2.2 Entry and sales barriers

Insights from the project and market studies highlight several barriers to successful market entry and sales:

1. Showcasing the Value

- **Tangible benefits are hard to demonstrate:** While users in the demonstration project experienced improved indoor climate and could see real-time changes in CO₂ and particle levels, new customers cannot easily “feel” these benefits before purchase. This underlines the importance of effective value demonstration through visual feedback, case studies, and possibly trial installations—to bridge the gap between technical performance and perceived value.
- **Economic value must be clear:** For most customers, energy savings and cost reductions are more compelling than abstract health or comfort improvements. Communicating concrete, data-backed sav-

⁴ Benjamin Jones, Nottingham university: Investigating measurements of fine particle (PM2.5) emissions from the cooking of meals and mitigating exposure using a cooker hood: <https://onlinelibrary.wiley.com/doi/abs/10.1111/ina.12542>

ings is essential. The increased energy efficiency, which resulted in energy savings without compromising indoor environmental quality (IEQ) during the demonstration, can be used to support future marketing claims about the solution's performance.

2. Market Maturity and Customer Education

- **Initial costs and retrofit complexity:** The cost and complexity of installing smart climate systems, especially in existing buildings, can be a barrier. Customers may be reluctant to invest unless the payback is clear and installation is straightforward.
- **Need for education and awareness:** Many consumers are not fully aware of the impact of indoor climate on well-being. Educational campaigns and transparent communication are needed to raise awareness and drive adoption.

7. Project conclusion and perspective

7.1 Conclusions

The Smart Green Indoor Climate Manager (SGICM) project successfully developed and demonstrated an intelligent, integrated climate control system that delivers measurable energy savings while improving indoor environmental quality and user comfort.

The system achieved 15-18% annual heating energy savings across the demonstration houses, translating to approximately 2,900-4,100 DKK in annual cost reductions per household. These savings were realized without compromising indoor climate quality—in fact, comfort and air quality improved significantly during the demonstration period.

Indoor environmental quality was maintained consistently within recommended standards (EN 16798-1), with 95-100% of indoor temperatures staying within acceptable comfort ranges. CO₂ levels remained well below the 1,200 ppm threshold, and relative humidity was effectively managed between 35-60%. Notably, one family reported elimination of winter respiratory issues (dry coughing) due to improved humidity control.

User acceptance was high once initial setup challenges were resolved. Families appreciated the automation removing mental load while proactively ensuring healthy indoor climate—particularly through automated window operation during nighttime and unoccupied hours. The system became "invisible" during normal operation, seamlessly integrating into daily life.

Technical achievements included successful interoperability between VELUX windows and Nilan HVAC systems, demonstrating the feasibility of a unified smart climate management. The system operated continuously for over one year without critical failures following initial adjustments.

The project also delivered important non-technical outcomes: increased user awareness of indoor air quality led to sustained behavioural changes (e.g., increased use of kitchen range hoods, discontinuation of bio-fireplaces), demonstrating educational value beyond the technology itself.

In conclusion, SGICM represents a viable solution that pays for itself through reduced heating bills while delivering healthier, more comfortable indoor environments - a smart investment for energy-conscious homeowners and a promising platform for future market development.

7.1.1 Innovation degree

The project has almost achieved all the expected technological readiness levels. As the intelligent control was not designed to take into account energy tariffs, the gateway as a whole did not achieve 7-8 in TRL, but the part of it relating to the weather data was demonstrated (TRL 7). Besides, it was carefully considered to develop the user interface to a TRL of 5-6, instead of the initially planned/expected TRL 7-8. This was because the project team found out that it was necessary to reduce the influence from homeowners changing the parameters and their own behaviour, as this would generate ‘noise’ and bias to the dataset – as explained in chapters 5.1 and 5.3.1.

Technology and componets	TRL - project start	TRL - project completion
Wireless sensor solutions combining measured and experienced indoor climate - depending on space size, design and load.	2-3	7
(Digital interfaces and actuators for controlling technologies)	(7)	(7)
Gateway with intelligent adaptive control including weather data and energy tariffs	3-4	5-7 (7 for weather data)
User interface via app. and / or control panel – developed and evaluated in three EU countries	3-4	5-6
Configuration tool	Not relevant	Not relevant

7.2 Next steps

The Smart Green Indoor Climate Manager (SGICM) project has demonstrated the technical feasibility and user value of automated indoor climate control. Building on these results, several important next steps have been identified to maximize the system’s impact, address current limitations, and unlock new market opportunities.

7.2.1 System adaptations

While the families were overall satisfied with the automated system, they did experience some issues and unmet needs throughout the demonstration period. The families highlight that the following could further improve the solution and their experience of it:

- **User autonomy:** The families experienced issues with the system especially in the beginning and during seasonal, where they would have liked to have the option of an overrule button to overrule the system. Having more user control will weaken the system’s ability to make adjustments and ensure a balance between indoor climate and energy savings, but some degree of user control might be necessary for users to be able to buy in on the solution.
- **Integration with other systems:** The families emphasized that there is a potential for integrating the system with other systems in the household to extent the automation further. This includes:
 - The mosquito net so that bugs cannot enter the house when windows open, especially in the evening when it is dark outside and light inside.
 - Shading devices for façade windows that could limit the heating from the sun in the summer.
 - Floor heating system so that there is just one sensor for all functions in each room.

7.2.2 Building type and market opportunities

Recent simulations and market studies have shown that newly established buildings in the Nordic region represent the building type with the lowest energy savings potential for smart indoor climate automation. These buildings are already highly insulated and energy efficient, limiting the additional gains from automated control. In contrast, renovation projects, especially in warmer climates where air conditioning use and overheating are significant challenges, represent a much larger opportunity for both energy savings and improved comfort. Targeting these segments should be a strategic priority for future development and commercialization.

7.2.3 Adaptive models and system intelligence

A key technical limitation identified during the project was that the system did not dynamically adapt to the unique characteristics of each house and room. Parameters such as window size and orientation, thermal performance of walls, and other building-specific factors were hardcoded into the control system. This approach limits scalability and performance across diverse building types. There is therefore a substantial opportunity to develop adaptive, data-driven models that can automatically learn and adjust to the specific properties of each home or room. Such models would enable more accurate control, easier deployment, and better results in both new and existing buildings.

7.2.4 Scalability and broader application

- **Applicability to other building types:** An opportunity going forward is the use of SGICM systems in multi-family residential and commercial buildings, not just single-family homes. This will require analysis of façade openings, integration with more complex HVAC systems, and consideration of diverse user needs.
- **Retrofit potential:** Sensor-based automated window control is a viable “light-renovation” strategy for improving comfort and air quality in existing homes, supporting Denmark’s energy renovation goals.

7.2.5 Energy flexibility

- **Energy flexibility:** Further development could enable the system to respond dynamically to external signals such as electricity prices, supporting energy flexibility and grid integration. This aligns with future energy policy objectives and can increase the system’s value proposition.

7.2.6 Market viability and productization

- **Long-term monitoring and research:** Continued monitoring in new demonstration homes and pilot houses will provide valuable data on long-term performance, user behavior, and system reliability. Comparative studies with both traditional and other smart climate solutions will help quantify the added value further in terms of energy savings, comfort, and indoor air quality.