ARV
CLIMATE POSITIVE CIRCULAR COMMUNITIES

D7.7 GUIDELINES ON CLIMATE ZONE RELATED DESIGN PRINCIPLES

WP7 EFFICIENT OPERATION AND FLEXIBILITY

Ge Song, NTNU
Natasa Nord, NTNU
Henrik Madsen, DTU
Seyed Shahabaldin Tohidi, DTU
Reza Mokhtari, DTU
Khadija Barhmi, Utrecht University
Sofiane Kichou, CVUT
Tomáš Bäumelt, CVUT
Hicham Johra, SINTEF Community
Gianluca Grazieschi, EURAC Research

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Contributors	Natasa Nord, Henrik Madsen, Jan Eric Thorsen, Seyed Shahabaldin Tohidi, Reza Mokhtari, Khadija Barhmi, Sofiane Kichou, Tomáš Bäumelt, Hicham Johra, Gianluca Grazieschi			
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[1] *ARV is a Norwegian word meaning "heritage" or "legacy". It reflects the emphasis on circularity, a key aspect in reaching the project's main goal of boosting the building renovation rate in Europe.*

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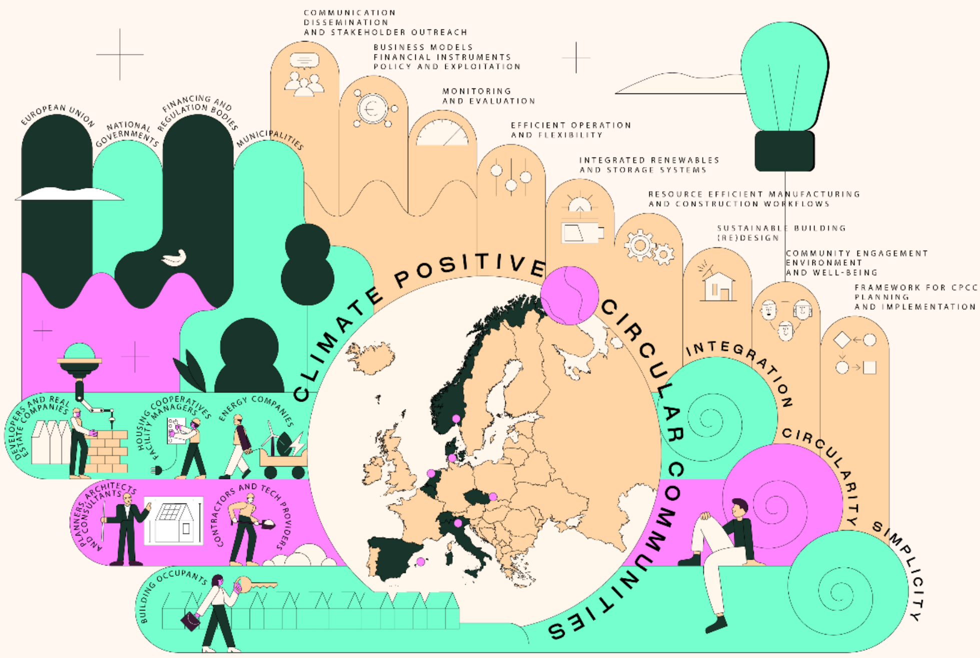
ABOUT THE ARV PROJECT

The vision of the ARV project is to contribute to speedy and wide scale implementation of Climate Positive Circular Communities (CPCC) where people can thrive and prosper for generations to come. The overall aim is to demonstrate and validate attractive, resilient, and affordable solutions for CPCC that will significantly speed up the deep energy renovations and the deployment of energy and climate measures in the construction and energy industries. To achieve this, the ARV project will employ a novel concept relying on a combination of 3 conceptual pillars, 6 demonstration projects, and 9 thematic focus areas.

The 3 conceptual pillars are integration, circularity, and simplicity. **Integration** in ARV means the coupling of people, buildings, and energy systems, through multi-stakeholder co-creation and use of innovative digital tools. **Circularity** in ARV means a systematic way of addressing circular economy through integrated use of Life Cycle Assessment, digital logbooks, and material banks. **Simplicity** in ARV means to make the solutions easy to understand and use for all stakeholders, from manufacturers to end-users.

The 6 demonstration projects are urban regeneration projects in 6 locations around Europe. They have been carefully selected to represent the different European climates and contexts, and due to their high ambitions in environmental, social, and economic sustainability. Renovation of social housing and public buildings are specifically focused. Together, they will demonstrate more than 50 innovations in more than 150,000 m^2 of buildings.

The 9 thematic focus areas are 1) Effective planning and implementation of CPCCs, 2) Enhancing citizen engagement, environment, and well-being, 3) Sustainable building re(design) 4) Resource efficient manufacturing and construction workflows, 5) Smart integration of renewables and storage systems, 6) Effective management of energy and flexibility, 7) Continuous monitoring and evaluation, 8) New business models and financial mechanisms, policy instruments and exploitation, and 9) Effective communication, dissemination, and stakeholder outreach.



The ARV project is an Innovation Action that has received funding under the Green Deal Call LC-GD-4-1-2020 - Building and renovating in an energy and resource efficient way. The project started in January 2022 and has a project period of 4 years, until December 2025. The project is coordinated by the Norwegian University of Science and Technology and involves 35 partners from 8 different European Countries.

EXECUTIVE SUMMARY

The aim of the report is to present a comprehensive framework for climate-specific flexibility design principles developed as part of Task 7.6 within the ARV project. This deliverable builds on the methodologies for describing and identifying energy flexibility functions (FFs) and demand response solutions, with a focus on local optimization across diverse climate zones represented by the six demo sites.

The primary objective of this deliverable is to provide detailed guidelines and practical examples of how to tailor flexibility functions to specific climatic conditions and operational requirements. This includes evaluating the effectiveness of FFs in real-world applications, such as district heating networks in Sønderborg, seasonal flexibility in city tunnels in Trento, and LowEx systems in Oslo. Each example highlights the integration of FFs into existing infrastructure to enhance energy efficiency, support local grid stability, and minimize carbon emissions.

Key to this deliverable is the application of the Flexibility Index (FI) and Smart Readiness Indicator (SRI) to assess the performance and adaptability of these functions. By utilizing operational data from the demo projects, D7.7 offers a detailed analysis of how different climate conditions impact the design and effectiveness of flexibility measures.

This executive summary underscores the importance of adapting flexibility solutions to local climatic and operational contexts to achieve optimal performance. The guidelines provided in this deliverable are designed to support the development of energy-positive districts by enabling the effective integration of smart technologies and flexibility measures. The insights and methodologies outlined in D7.7 will be instrumental in guiding future projects and ensuring scalable, climate-responsive energy solutions.

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1. INTRODUCTION

The ARV project is centered on developing and implementing methods and tools for optimizing energy flexibility in buildings, with the goal of supporting local grids and enhancing power system services. Building on the foundation established in previous work packages, including WP5 and WP6, Deliverable D7.7 focuses on the development of climate-specific flexibility functions and measures that align with the operational characteristics of the ARV demo sites. This deliverable emphasizes the role of Flexibility Functions (FFs) in addressing the varying energy demands across different climate zones while tailoring solutions that maximize self-consumption, reduce carbon footprints, and ensure energy-positive outcomes in buildings and districts.

This deliverable outlines methodologies for designing flexibility measures that are responsive to regional climatic conditions and energy needs, utilizing data-driven approaches for implementation across the six ARV demo sites. Each of these sites, located in Sønderborg (Denmark), Trento (Italy), Utrecht (Netherlands), Oslo (Norway), Karvina (Czechia), and Palma (Spain), presents unique challenges and opportunities for flexibility, particularly regarding heating, cooling, and electricity consumption. The flexibility measures are developed to optimize local energy use, integrate renewable energy sources, and adapt building operations to the needs of occupants and the grid.

The report is structured around key areas, including the description and deployment of flexibility functions for various building systems, such as heat pumps, low-exergy systems, and district heating networks. Additionally, it includes guidelines for climate-responsive flexibility design, offering practical insights on how to implement and evaluate energy flexibility in diverse environmental settings. By linking the Flexibility Index (FI) and Smart Readiness Indicator (SRI), Deliverable D7.7 provides a comprehensive framework for evaluating the impact of flexibility measures on energy efficiency, cost-effectiveness, and sustainability. Ultimately, D7.7 aims to contribute to the ongoing optimization of ARV demo sites and inform future flexibility strategies across different climate regions.

2. OVERVIEW OF ENERGY DEMAND FLEXIBILITY

Flexibility in energy systems refers to their ability to adapt efficiently to changing conditions, such as fluctuations in energy supply and demand, the integration of renewable energy sources, and evolving grid requirements. As renewable energy sources like solar and wind are inherently variable and depend on the climate zone, flexibility is crucial to maintaining grid stability and ensuring reliable and efficient power delivery. This adaptability can be achieved through a combination of strategies, including demand side management programs, energy storage solutions like batteries, and advanced grid management technologies. Additionally, by leveraging dynamic penalty signals optimized for the specific climate zone, energy systems and buildings can be designed to meet the challenges of a decarbonized future while supporting economic growth and energy security.

Demand Side Management is a strategy in energy systems aimed at optimizing energy use by shaping consumer demand rather than solely expanding supply. To actively support demand-side management, operators must be able to predict the demand, assess flexibility potential, and accurately characterize flexibility. This capability enables more informed decision-making, improving both the efficiency of energy systems and the activation of flexible resources. [1-3]

Numerous studies have focused on methods for capturing demand behaviour and modelling energy flexibility. Accurate modelling requires dynamic, detailed representations of energy systems that incorporate technical constraints, occupancy patterns, and external conditions. A linear, time-invariant dynamic model representing the price-demand relationship and characterizing energy flexibility for buildings and districts is presented in [4], where comparisons across buildings with varying flexibility characteristics are discussed. This model, which captures the temporal evolution of energy demand relative to price changes, is further employed in [5]. A nonlinear and more realistic model of energy flexibility is developed [6], termed the "flexibility function," which represents the price-demand relationship using a time-invariant nonlinear stochastic differential equation. The stability of the dynamics of the flexibility function is investigated in [7]. This function is utilized in an optimization algorithm to generate optimal price signals for incentive-based control and demand-side energy management [8]. In another study [9], the flexibility function is integrated into a holistic electricity market, including transmission and distribution system operators.

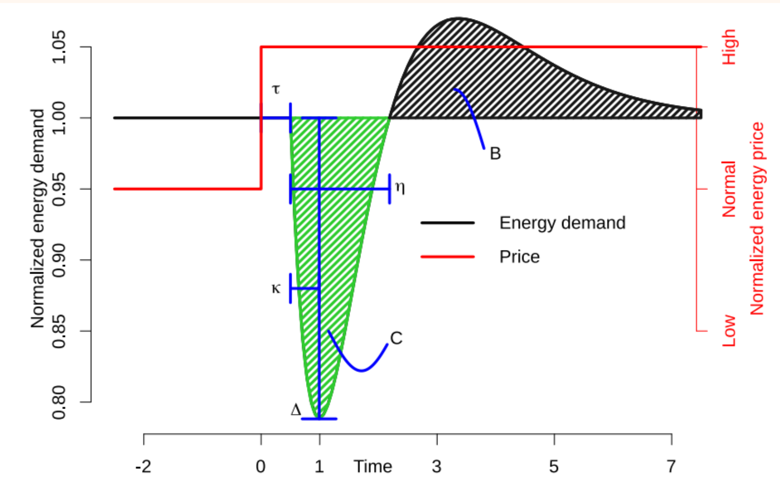

Figure 1 *Flexibility characteristics.*

As mentioned above, flexibility function can be utilized for identifying flexibility characteristics in energy systems. It provides information about 1) the delay between the energy price adjustment and observing its effect on energy demand, 2) the maximum overshoot and undershoot after price change, and 3) duration of overshoot and undershoot after price change. These characteristics are useful for determining the controller objective and energy source focus that would lead to optimal control implementation **Figure 1**. Although the information on flexibility characteristics has clear value for engineers and researchers in a design and control context, it is required to use an easier approach to interpret the flexibility for a wider audience, such as end-users and legislative bodies. To this end, an indicator is proposed in [4] to communicate the value of utilizing the flexibility dependent on its purpose, e.g., cost minimization or CO_2 minimization, in an interpretable manner.

$$FI = 1 - \frac{\sum((variable\ penalty) \times (energy\ consumption\ with\ variable\ penalty))}{\sum((variable\ penalty) \times (energy\ consumption\ with\ constant\ penalty))}$$

To demonstrate how the approach helps in analysing the flexibility we provide, Figure 2 showing completely different behaviours of different buildings to a price change. Building 1 is able to move the largest amount of energy, while Building 3 is able to move the least. On the other hand, Building 3 is able to respond faster than the others.

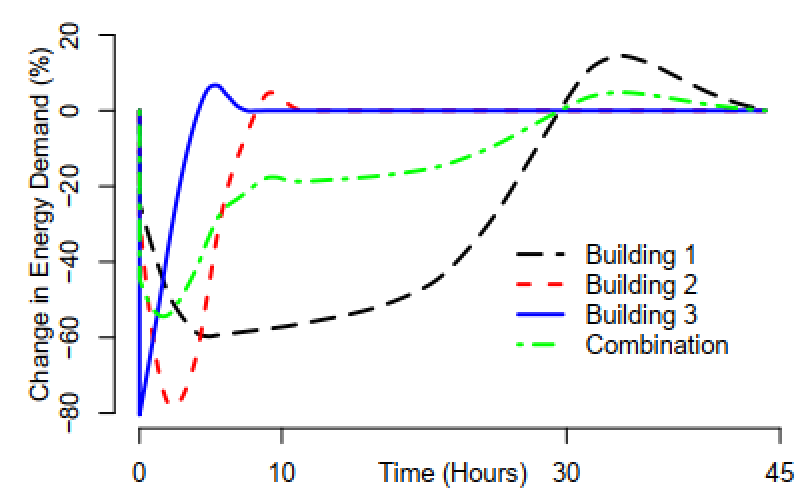

***Figure** 2. The Flexibility Function for different buildings.*

Let us consider how well each building performs in environments dominated by different kinds of renewable energy, namely wind, solar, and hydropower. For wind and solar power, we have used the production of 2017 in Denmark to make penalty signals inversely proportional to the amount of produced wind or solar power. Hydropower can be controlled thus, it does not experience the same kind of problems as wind and solar. The problems still experienced are mainly due to large ramps in demand during the morning and afternoon hours. Therefore, a penalty signal based on these ramps has been constructed from the 2017 data obtained from the Norwegian power grid. These penalty signals are provided in Figure 3. The daily variation is seen for the solar penalty, and since the period is during the winter where the solar power production is large only for short periods of the day. The wind penalty starts at zero due to the period starting with windy weather. Then, it changes for a couple of days where apparently the wind power production is small. However, after this period, we see almost three days of zero penalty, which means that there was lots of wind. The ramp penalty remains close to zero with only a few peeks when the ramp in demand is large.

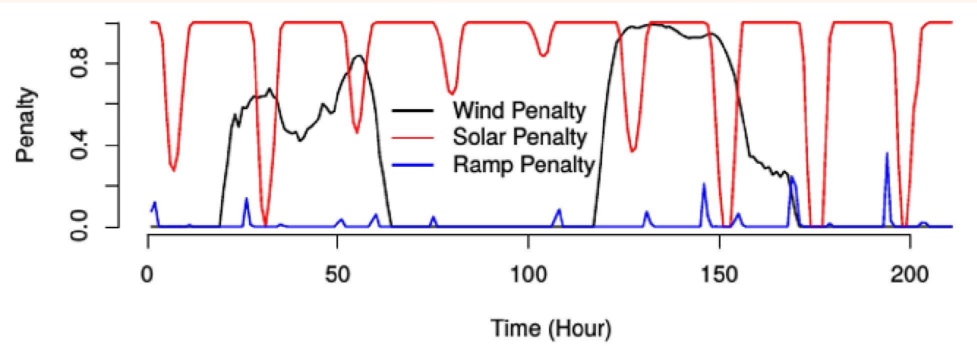

***Figure** 3. Penalty signals based on wind and solar power production in Denmark during 2017. Ramp penalty based on Consumption in Norway during the same period.*

By employing the above-mentioned penalty signals in a penalty-responsive controller for a relatively long period, one can calculate the flexibility index of three different buildings with three different penalty signals. The calculated flexibility index can be found in the following **Table 1**.

Table 1 *Calculated FI for each building.*

	Wind (%)	**Solar (%)**	**Ramp (%)**
Building 1	11.8	3.6	1.0
Building 2	4.4	14.5	5.0
Building 3	6.0	10.0	18.4

This table quantifies how well each of the buildings' flexibility is utilized in the integration of wind power and solar power and in dealing with ramping problems. It is seen that Building 1 is able to make the most of the wind penalty since it is the only building that is able to sustain a demand response on a time scale similar to that which the wind penalty changes. For the solar and ramp penalties, it does not matter that Building 1 is able to sustain the demand change for such a long time since these two penalties change much more frequently. In fact, the response of Building 1 is so slow that usually it is not able to react to the changes in penalty when based on solar or ramp. The solar penalty is slower than the ramp penalty, making it better suited for Building 2, and can sustain its response for a while, while the very fast variations in the ramp penalty can only be captured by the fast response of Building 3.

The above discussions reveal that the control efficiency varies for buildings with different flexibility dynamics, and it is dependent on the type of penalty signal utilized in the controller. In climate zones where wind power is dominated, having buildings like Building 1, with slow flexibility dynamics, leads to higher control efficiency. It is different for climate zones where solar power is dominated. On the other hand, to deal with ramping problems, having buildings like Building 3, with fast flexibility dynamics leads to higher control efficiency. This approach can be used as a guideline for climate zone related control design. Additionally, the above discussion reveals the dependency of the flexibility index on the penalty signals. As introduced in [4], simplified reference penalty signals can also be designed and utilized for different climate zones.

3. CLIMATE ZONES AND DESIGN PRINCIPLES FOR ENERGY FLEXIBILITY

3.1. CLIMATE ZONES AND THEIR CHARACTERISTICS

When analyzing the **flexibility functions (FFs)** in the context of different climate zones for the six cities (Sønderborg, Trento, Utrecht, Oslo, Czechia, and Palma de Mallorca), it's crucial to consider how **climatic conditions** impact building energy use, demand patterns, and flexibility potentials. Each city's unique climate influences its energy flexibility needs, particularly regarding heating, cooling, ventilation, and electricity usage. Below is a breakdown of the **climate-specific flexibility functions** for each city based on their climate characteristics:

1. Sønderborg, Denmark

- **Climate Zone**: Temperate oceanic climate (Cfb) with mild, humid winters and cool summers.
- **Flexibility Functions**:
  - **Heating Demand**: High demand for heating during winters, making demand response in heating systems crucial for flexibility.
  - **Renewable Integration**: Significant potential for district heating systems powered by renewables, with flexibility to shift heating loads based on grid needs.
  - **Ventilation and Insulation**: Flexibility could also be enhanced by optimizing ventilation and improving building thermal insulation to reduce heating loads.

2. Trento, Italy

- **Climate Zone**: Humid subtropical and oceanic climate (Cfa, Cfb), with cold winters and hot, humid summers.
- **Flexibility Functions**:
  - **Dual Heating/Cooling Demand**: High demand for heating in winter and cooling in summer, meaning FFs need to balance both seasons effectively.
  - **Energy Storage**: Use of thermal storage systems for both heating and cooling flexibility, enabling peak load shifting.
  - **Renewable Integration**: Solar energy potential can help to provide flexibility in power generation and cooling loads in summer.

3. Utrecht, Netherlands

- **Climate Zone**: Temperate oceanic climate (Cfb), with mild, rainy winters and cool summers.
- **Flexibility Functions**:
  - **Moderate Heating/Cooling Needs**: Less extreme temperature variations, meaning flexibility can focus on optimized heating systems rather than extensive cooling systems.
  - **Demand-Side Management**: Flexibility can be enhanced by demand-side energy management and smart thermostats that respond to occupancy and grid signals.
  - **Wind and Solar Power**: There is significant potential for wind and solar integration, and flexibility can be derived from managing renewable energy production peaks.

4. Oslo, Norway

- **Climate Zone**: Humid continental climate (Dfb), with cold, snowy winters and mild summers.
- **Flexibility Functions**:
  - **High Heating Demand**: **Heating flexibility** is essential due to long, cold winters, with potential in demand response systems for electric or district heating.
  - **Building Envelope Efficiency**: Improved insulation and air-tightness are critical flexibility measures to reduce heating demand.
  - **Renewable Energy**: Hydropower and integration with electric heating systems allow for flexibility based on available water resources and grid demand.

5. Czechia (Karvina)

- **Climate Zone**: Humid continental climate (Dfb), characterized by cold winters and warm summers.
- **Flexibility Functions**:
  - **Seasonal Energy Storage**: Strong potential for seasonal flexibility through thermal energy storage that can shift heating and cooling loads across seasons.
  - **Heating Flexibility**: Similar to Oslo, flexibility in heating systems can be achieved through smart thermostats and district heating optimization.
  - **Renewable Integration**: Biomass heating and solar PV offer opportunities for integrating flexible energy sources into the building systems.

6. Palma de Mallorca, Spain

- **Climate Zone**: Hot-summer Mediterranean climate (Csa), with hot, dry summers and mild winters.
- **Flexibility Functions**:
  - **Cooling Demand**: High demand for cooling in summer, requiring flexibility through smart cooling systems and thermal energy storage to shift cooling loads.
  - **Renewable Solar Power**: Significant potential for solar PV integration, with flexibility functions centered on self-consumption and grid feed-in during peak production.
  - **Smart Building Controls**: Use of smart shading, dynamic building envelopes, and natural ventilation to reduce cooling loads and enhance flexibility.

3.2. DESIGN PRINCIPLES FOR ENERGY FLEXIBILITY ACROSS CLIMATE ZONES

The design principles for energy flexibility in buildings are crucial to adapting energy systems to local climate conditions, ensuring efficient integration of renewable energy sources, and meeting specific regulatory and operational needs. These principles align with strategies for improving the SRI and FI and are shaped by the characteristics of different climate zones and their corresponding energy requirements.

1. **Cold Climates (e.g., Oslo, Norway):**
   In cold regions, heating dominates energy needs. Flexibility design here prioritizes the integration of advanced heat pumps and thermal storage systems. For instance, buildings can employ LowEx (low-exergy) heating systems that operate efficiently with low-temperature heat sources, such as district heating. Demand response strategies like pre-heating during off-peak hours and leveraging predictive algorithms help in managing fluctuating energy loads caused by variable renewable energy sources such as wind power.

2. **Temperate Climates (e.g., Sønderborg, Denmark, Utrecht, Netherlands):**
   Temperate zones experience balanced heating and cooling demands. Design principles emphasize the use of hybrid energy systems, combining solar PV with thermal energy storage to optimize self-consumption. Heat pumps in district heating networks and flexible controls for shifting loads, especially for electric vehicle charging or water heating, are critical. Flexibility measures also support grid stability by dynamically managing loads in response to energy price signals.

3. **Mediterranean Climates (e.g., Palma, Spain):**
   In warmer Mediterranean climates, cooling demand is predominant. The design focuses on enhancing passive cooling techniques, efficient air-conditioning systems, and leveraging thermal mass to store coolness during the night. Integration of solar PV systems and energy storage enables flexibility in managing peak loads. Cooling-as-a-service models, combined with real-time optimization systems, contribute to a lower carbon footprint and increased grid resilience.

4. **Continental Climates (e.g., Trento, Italy, Karvina, Czechia):**
   These regions experience significant seasonal variations, requiring systems that are versatile across different weather conditions. Seasonal thermal energy storage, such as underground reservoirs, supports long-term flexibility. Smart district heating and cooling networks, combined with real-time data analytics, enable efficient energy distribution. Such setups can adapt to heating and cooling needs while reducing dependency on fossil fuels.

5. **Design Implications Across Zones:**
   - **SRI:** High SRI scores require buildings to adopt advanced monitoring, control, and automation systems. These systems enable effective load shifting, better integration of renewable sources, and user-oriented energy management.
   - **FI:** Enhancing the FI involves identifying dynamic load capabilities and implementing systems that allow rapid response to grid signals. This includes demand-side management, energy storage, and predictive maintenance tools.

These principles, tailored to the climatic and operational needs of each zone, ensure the ARV project's demo sites can maximize energy flexibility. They provide a framework for scalable and replicable solutions across regions, enabling energy-positive buildings and districts to adapt to future energy challenges.

4. CLIMATE-SPECIFIC ENERGY AND FLEXIBILITY DESIGN EXAMPLES

The Climate-Specific Flexibility Design Examples section showcases tailored flexibility strategies for the six ARV demo sites in distinct climate zones. These examples demonstrate how local weather patterns, seasonal variations, and energy demands influence the design and implementation of flexibility functions. From district heating optimization in Sønderborg's temperate oceanic climate to cooling demand management in Palma de Mallorca's Mediterranean climate, each case highlights innovative approaches to maximizing energy efficiency, grid interaction, and renewable integration. By focusing on climate-specific challenges, this section provides practical insights into unlocking energy flexibility through intelligent, data-driven operations tailored to local environmental conditions.

4.1. CASE STUDY: SØNDERBORG, DENMARK (CLIMATE-SPECIFIC FLEXIBILITY FUNCTIONS)

The Sønderborg demo case is called SAB22 and comprises of 19 multi-family buildings. These buildings were constructed in the 1970s but have been renovated frequently. Each building has a similar floor plan and the only differences between them are their orientation, floor area and number of floors. **Figure** 4 depicts an aerial view of the demo case and a photo of one of the blocks.

(a) **(b)**

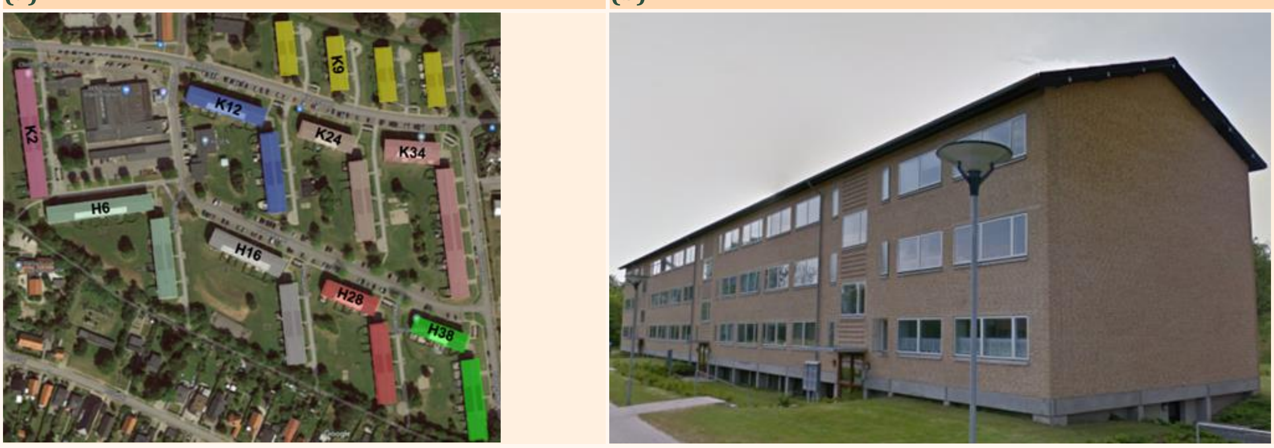

***Figure** 4. (a) Arial view of the neighborhood and district heating substations in Sønderborg. Colors represent individual substations. (b) Photo taken from one of the buildings of SAB22*

The heating demand in the area is satisfied by a nearby district heating plant. There are nine substations that distribute heat to 19 building blocks. Each of the substations is labelled with its corresponding block. The exact information about the building construction elements was not available. Therefore, valid datasets were used to gather this information. These datasets include the Danish Building and Housing Register (BBR) [10], the Danish building standard (DS/EN 15251) [11], and the TABULA project [12]. The components of the buildings that were considered in the building models are listed in **Table** 2.

***Table** 2. Components used in creating building models of SAB22*

Component	Materials (thickness)
Roof	Roof tiles (59 mm) Insulation (300 mm) Hollow core concrete (270 mm)
Exterior wall	Brick (108 mm) Insulation (375 mm) Aerated concrete (100 mm)
Floor/ceiling	Concrete (220 mm) Insulation (93 mm) Concrete (80 mm) Oak planks (14 mm)
Ground floor	Insulation (350 mm) Concrete (120 mm)
Windows	Clear double glazing with air
Internal wall	Concrete (200 mm)

For space heating, district heating supply water is mixed by the return water from the radiators (by controlling the mixing ratio) to provide a proper supply temperature for the radiators. The proper temperature is determined by a Weather Compensation Curve (WCC) that ensures a reliable heat supply to the blocks in all weather conditions. The radiators are equipped with Thermostatic Radiator Valves (TRV), automatically adjustable valves for maintaining indoor temperature at a certain range.

In the Sønderborg case, the space heating system has been chosen for analysis and calculation of its flexibility. The indoor temperature is used as a direct indicator of heat use in buildings, which can be flexibly changed within the comfort range. To achieve this, a suitable controller is required to control the components. Price-aware controllers are simple and efficient controllers that can unlock the energy flexibility of systems. Therefore, a simple rule-based controller has been considered for the Sønderborg case, which can directly control the indoor temperature by changing TRV setpoints. The indoor temperature is assumed to change between 18°C and 26°C according to the price. However, to ensure that high setpoints are reachable, and to prevent high return water temperatures at low setpoints, the forward temperature of radiators should also be controlled. Therefore, it is also considered to change according to the setpoint and ambient temperature, as shown in **Figure** 5.

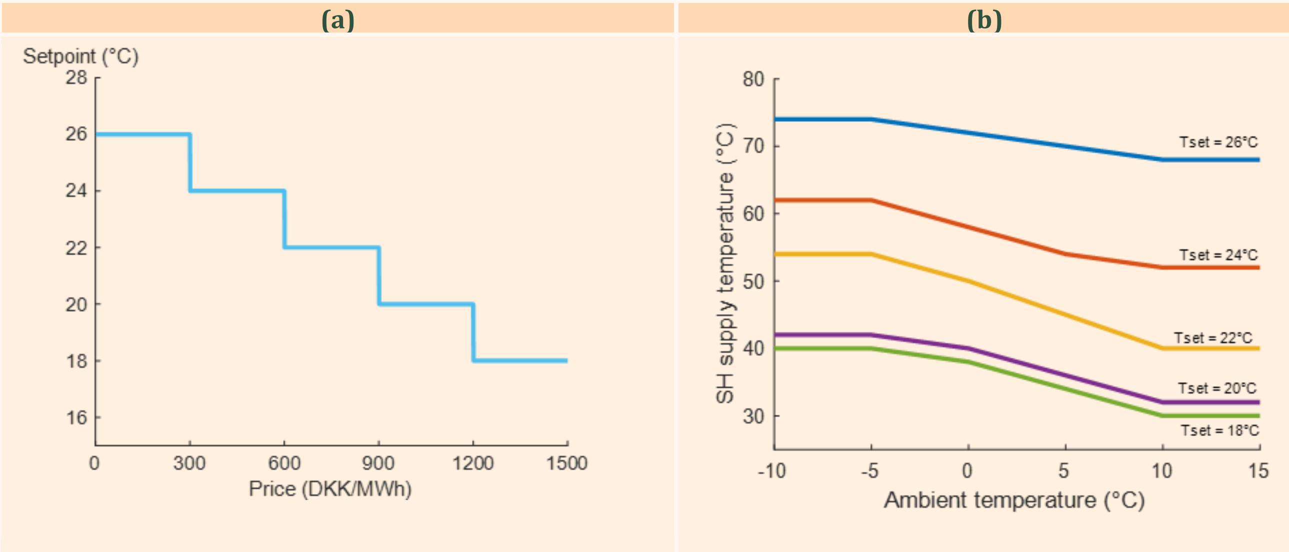

***Figure** 5. (a) Indoor setpoint control based on the heating price. (b) Space heating supply temperature as a function of indoor setpoint and ambient temperature.*

Baseline power, observed power, and applied heating price data for a specific period are needed to determine the parameters of the flexibility function for the neighbourhood. An iterative method is used to fit the model to the data and calculate the parameters. For this purpose, a one-month period in February 2022 has been chosen. As the heating cost is currently fixed in Denmark, the dynamic electricity price from Nordpool Day-ahead market for DK1 was taken as the heating cost. Simulations were conducted using the white-box Modelica model and present the results in **Figure** 6.

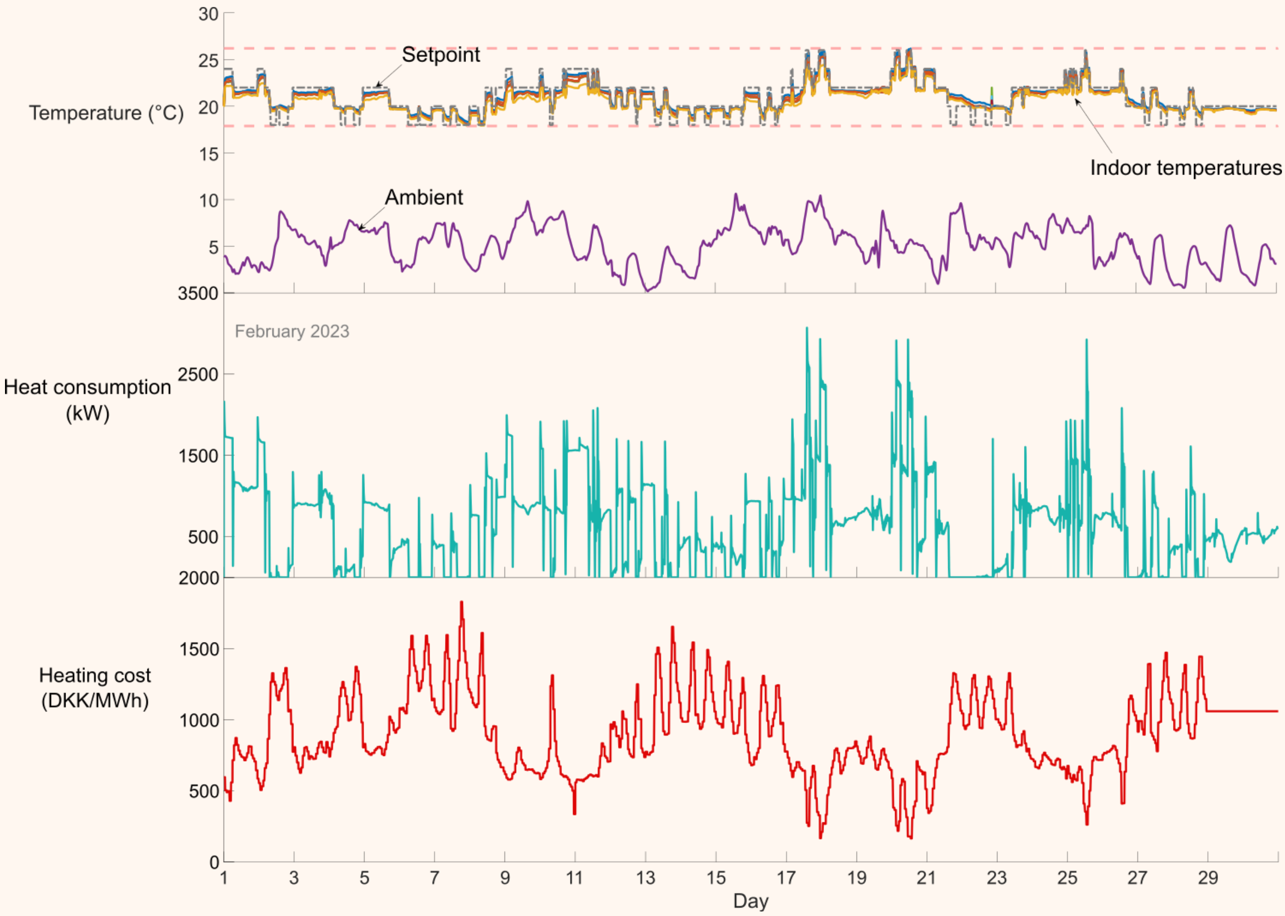

***Figure** 6. Results of applying dynamic heating cost to the buildings with price-responsive controllers. (Top) indoor temperatures together with ambient temperature, (middle) total space heating consumption of the neighborhood and (bottom) the heating cost taken from Nordpool DK1 day-ahead electricity price.*

The indoor setpoints, determined based on the heating cost, are represented by a dashed line on the top. The indoor temperatures were found to successfully follow the setpoints. However, when the setpoint drops to the lowest value, the indoor temperatures take more time to reach the setpoint, due to the thermal lag of the buildings (for instance, days 21-23). This is good news as it indicates that the heating system can be turned off during high price periods, and the flexibility is being utilized effectively. Additionally, the total space heating use profile shows a strong correlation with the heating cost. For example, drops in the heating cost on days 18 and 20 are followed by spikes in heat use during the same periods.

To determine demand of the price-ignorant system, a similar system was tested under the same conditions but with normal controllers with fixed TRV settings of 22°C, instead of price-aware controllers. The resulting data was then used to estimate the parameters of the nonlinear flexibility function, which are listed in **Table** 3.

***Table** 3 Parameter estimates of the flexibility function model for the neighborhood.*

Parameters	values
Δ	1
C	4.659363
α_1	-0.068133
α_2	0.210158
α_3	0.181272
α_4	0.607677
K	1.581067
x_0	0.263674

log(sY)	-1.85215
β_1	0.103038
β_2	0.292141
β_3	0.142494
β_4	0.158005
β_5	0.306071
β_6	0
β_7	0
lambda	16.5031

Finally, the heat demand of both price-ignorant and price-aware systems to a dynamic price in a heating day are shown in Figure 8.

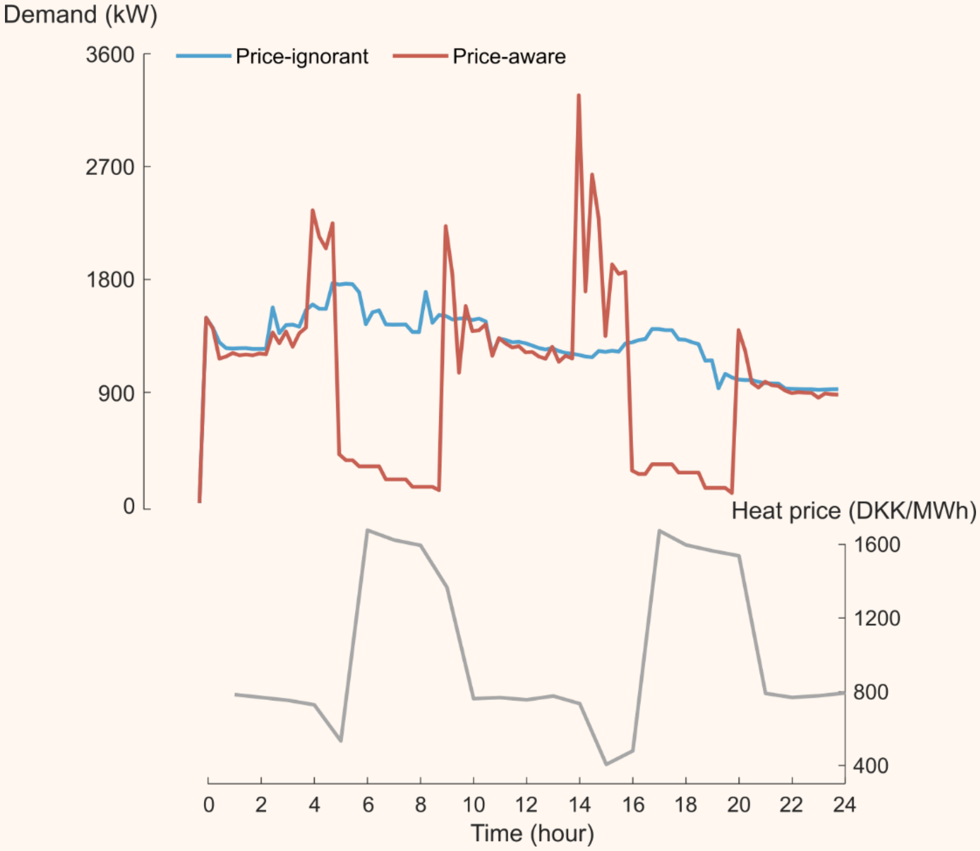

Figure 8. *Simulated demand of the neighborhood with the baseline and reference loads, together with the optimum heat price in the bottom.*

The price-aware system is influenced by the price profile, with the ability to decrease its demand during expensive hours. On the contrary, the demand of the price-ignorant system is solely driven by the weather conditions and indoor activities. According to [4] the energy flexibility potential can be shown as the amount of saving achieved by utilizing the flexibility of the system. Accordingly, the ratio between the cost of price-aware controller to the similar price-ignorant controller can be used as a method to quantify the flexibility potential of the system. With this approach, Flexibility Index (FI) is calculated as follows:

$$FI = 1 - \frac{\sum_{k=1}^{T} \lambda_k \, p_k^{price-aware}}{\sum_{k=1}^{T} \lambda_k \, p_k^{price-ignorant}}$$

Where FI is the so-called flexibility index (FI), M is the horizon for measuring the FI, and p_k is the heat demand, which is measured when including the price signal and when ignoring it (baseline), and λ_k is the price (heat price in here) at timestep k.

It should be noted that FI is not necessarily linked with the flexibility function, and it can be applied to any price-aware controller (e.g. rule-based control, MPC). In Figure 8, the price profile at the bottom of the figure shows λ, and demands are shown in the top figure. Therefore, an FI value of 39.4% is calculated for this neighborhood case study, indicating the flexibility potential of the neighborhood, given the system setup, building properties, weather conditions, price profiles, etc. The same approach can be used for other cases to quantify the flexibility potential and make a comparison between the cases, systems and technologies.

4.2. CASE STUDY: OSLO, NORWAY

The demo site of Oslo (Norway) is the Voldsløkka School and Cultural area, located in the Northern part of Oslo. The demo includes the construction of a new secondary school building (S-building) and retrofitting of an existing cement factory (the Heidenreich buildings) to host 810 students **Figure 7**. In addition to the school, the demo case includes a cultural centre, a cultural hall, and a sports hall. The school and cultural activities cover an area of 11 100 m² in the new construction and 2 900 m² in the Heidenreich building (H-building). The two buildings are connected via a bridge on the second floor. The total floor area of the building complex is 14 400 m². The renovation timeline of the demo site is 2021-2024, with an investment cost of 88.2 million euros.

Figure 7*. Aerial view of the Voldsløkka school project*

The Oslo demo site is a plus energy school (the annual onsite generation must be greater than the energy needs of the building): it must fulfil the requirements of the *FutureBuilt Plus Energy*[2] level and generate an energy surplus of 2 kWh/m² per year.

The building site is connected to the local electrical grid and to the local district heating network **Figure 8**. The main supply and heating and (free) cooling is provided by a low-exergy heat pump connected to a ground source heat exchanger. The use of ground-source heat pump (GSHP) and free cooling supports energy efficiency by reducing electrical demands for compressors and maximizing system performance.

[2] https://www.futurebuilt.no/content/download/40406/219290

The low-exergy GSHP operates at low temperatures for heating and high temperatures for cooling. The GSHP provides heat for the preparation of sanitary hot water and supplies space heating via hydronic radiators, ventilation heating coils and TABS (thermally active building systems). The latter consists of an embedded underfloor heating network in the concrete screed to maximize the activation of the building thermal mass and enable great potential for demand response and energy flexibility strategies. Cooling is provided to the ventilation (hydronic cooling coil) and the TABS.

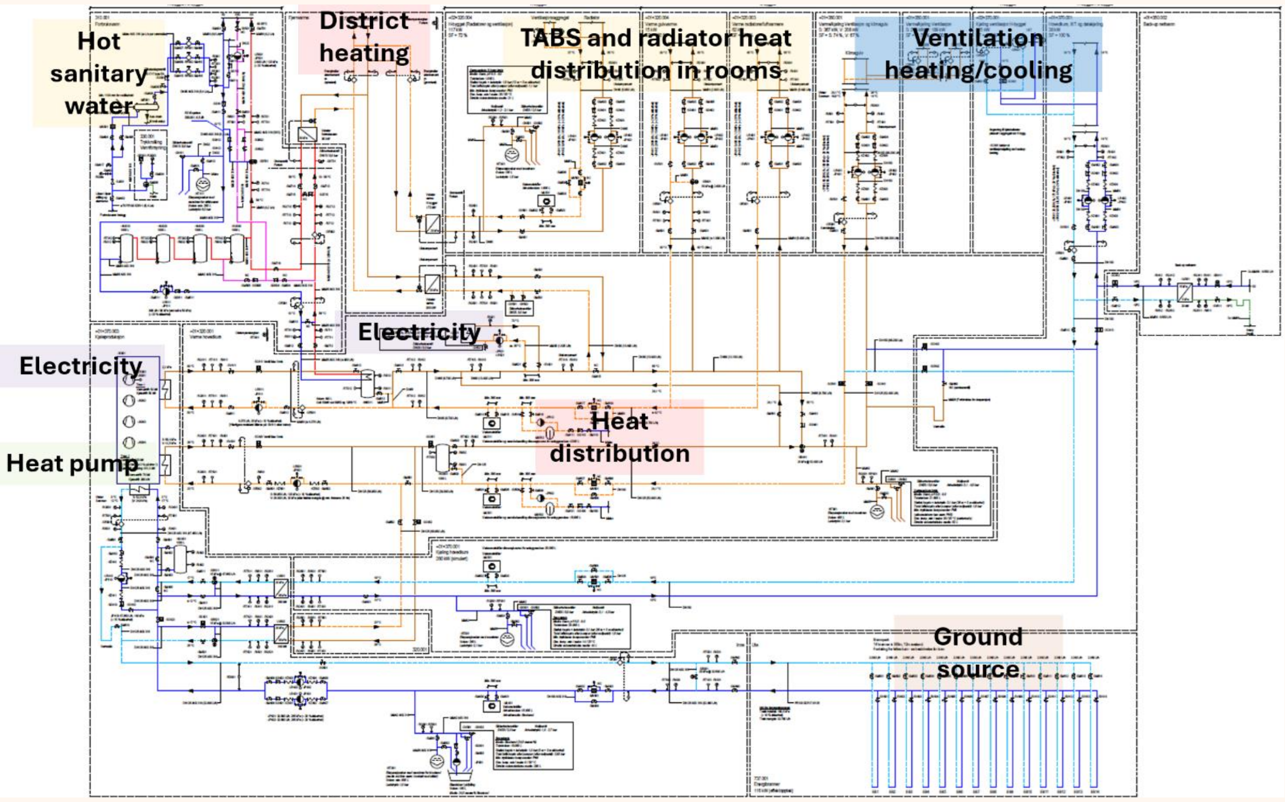

Figure 8. *Overview schematic of the energy system at the Voldsløkka school project.*

The GSHP consists of 14 boreholes, each with 300 m of depth, separated from each other with 12 m. The total capacity of the boreholes is 116 kW of thermal capacity. The use of TABS enables stable operation for the GSHP, which can be supplied with electricity from the on-site PV systems. Moreover, using a GSHP reduces the total energy use of the building, as less electricity is required to cover the heating demand of the school. This results in less dependency on seasonality or a mismatch between energy delivered and energy used. The high performance of the ground-source heat pump and heating/cooling distribution results in a very low energy need for conditioning the indoor environment with only 3-10 kWh/m2 per year of heating/cooling demand.

In terms of PV-systems, BAPV (Building Applied Photovoltaics) are installed on the roofs, and BIPV (Building Integrated Photovoltaics) are installed on the façades. A total of 690 PV panels are installed on the façade and rooftop of the H-buildings, for a total installed capacity of 273 kWp. The PV panels have an East-West orientation to optimize the matching between demand of the buildings and PV production. A total of 1217 PVs are installed on the S-building for a total installed capacity of 337 kWp.

The following tables ***Table*** *4,* ***Table*** *5 and*
Table 6 provide an overview of climate-specific energy flexibility design strategies, addressing replication potential, limitations, policy considerations, regulations, and investment requirements for each demo case.

Table *4. Climate-Specific Replication Strategy and Design Constraints (SRI and FI Focus)*

Case Study Location	[Oslo]

Climate Characteristics	Humid continental climate (Dfb), with cold, snowy winters and mild summers.
Energy Flexibility Design (SRI)	The building is equipped with a building management system collecting measurements from multiple indoor environmental quality sensors (indoor temperature, relative humidity and CO2 concentration) and controlling building systems. The monitoring of the building systems comprises multiple energy meters. The buildings have a large potential for energy storage and load-shifting within the indoor environment because the heating and cooling is mainly delivered to the indoor environment via TABS (thermal activated building systems) which present a very large effective thermal mass. The building has an appreciable effective thermal mass in the rest of its structure, coupled to a well-insulated envelope, which provides a very good thermal storage capacity in the indoor environment. The building site is also equipped with hot water storage tanks for the sanitary hot water, which has additional energy storage capacity. Finally, the heating and cooling supply for the building site is mainly provided by a ground-source heat pump. The ground-source heat exchanger has also some potential for seasonal energy storage: the free cooling during summer can regenerate the temperature of the ground-source heat exchanger, and part of this thermal energy can then be supplied back to the building during the winter period.
Energy Flexibility Design (FI)	The overall aim of the smart control for this building site is to reduce the energy demand, maximize self-consumption of the locally-produced electricity from the photovoltaic panels installed on the buildings, reduce the peak power demand, and perform fuel switch from electricity (supplying the ground-source heat pump) to the local district heating network to provide heat (space heating and sanitary hot water) to the buildings when the dynamic electricity price is too high. The energy flexibility capacity of the indoor environment is exploited by means of indoor temperature setpoint modulation.
Replication Strategy (SRI)	The building must be equipped with an appropriate building management system which allows the implementation of advanced

	control (economic model predictive control or rule-based fuel-switching control)
Replication Strategy (FI)	Dynamic electricity tariffs with sufficient variability and amplitude are required.
Technical Limitations	The pilot site has a rather complex heating and cooling system combined with a TABS. The heating/cooling system has thus a very large time constant. The use of model predictive control is thus required to optimally operate the TABS and ensure good thermal comfort inside the built environment.

***Table** 5. Policy, Regulation, and Investment Considerations (SRI and FI)*

Case Study Location	**[Oslo]**
Policy and Regulatory Context (SRI)	The building regulation TEK17 provides requirements for new buildings and their energy system (https://www.dibk.no/regelverk/byggteknisk-forskrift-tek17). This includes a requirement to measure energy for heating and DHW in new buildings. Prosumers are regulated in FOR-2023-05-08-671 (https://lovdata.no/dokument/LTI/forskrift/2023-05-08-671). Energy systems (electricity and district heating) are regulated in the energy act FOR-1990-12-07-959 (https://lovdata.no/dokument/SF/forskrift/1990-12-07-959/)
Policy and Regulatory Context (FI)	The policies and tariffs motivate energy flexibility behind each energy meter (electricity AMS and district heating). For solar PV, surplus electricity can be shared on the same property, after certain conditions (Prosumer regulation noted above).
Relevant Standards & Compliance (SRI)	Building regulation TEK17 NS 3700 and NS 3701 specify requirements for passive houses and low-energy buildings. BREEAM-NOR: Building Research Establishment Environmental Assessment Method) certification system EU Smart Readiness Indicator
Relevant Standards & Compliance (FI)	NEK 399:2018: Defines the interface between the electricity grid and buildings, including provisions for grid connection points. It supports integrating distributed energy resources (DERs) like solar panels and storage systems.

	NEK 400: Covers electrical installations in buildings, including guidelines for the safe installation of energy storage systems (ESS) and their connection to renewable energy systems. IEC 61850: A global standard adopted in Norway for communication within and between distributed energy resources (DERs), including storage systems, enabling demand response and grid interaction. NS 3031: This standard addresses energy performance in buildings and indirectly encourages energy-efficient solutions that can benefit from demand response and storage.
Investment Needs	To enable demand response and fuel switch capabilities, it is necessary to invest in a building management system which allows the implementation of advanced controllers leveraging dynamic energy prices. The BMS should accommodate for an easy implementation of the control program directly in the system, or an external access (API) to read the necessary monitored variables and control directly the different actuators of the heating/cooling systems participating in the demand flexibility action.
Funding Sources	Enova provides financial incentives for projects focusing on energy efficiency, flexibility, and storage in buildings, although primarily aimed at pilot projects and innovation. Some municipalities support projects in their region. EuroFlex supports investments to allow energy flexibility within areas of member DSOs.
Economic Viability	Norway has Time-of-use tariffs for electricity (hourly Nordic spot prices) and grid tariffs (normally based on monthly peaks). EuroFlex finances flexibility provided to DSOs. Statnett's flexibility markets facilitate the participation of energy producers, consumers, and aggregators in providing demand response and grid balancing services to enhance power system stability and efficiency. The implementation of the smart controller for demand response and fuel switch within the BMS should not cause significant costs. The energy costs savings of the demand response and fuel switching smart controller is estimated to be around 7000 NOK per month during heating season.

Stakeholder Involvement	Grid operators – e.g. the ones organise under EuroFlex (https://www.euroflex.no), building owners, tech providers.
Scalability Potential	High scalability potential, especially due to hourly spot prices, and since programmes such as EuroFlex are introduced.

***Table** 6. SRI and FI Design Components*

SRI and FI Design Components	Description	Impact on Flexibility	Challenges
Heating and cooling control	Smart control of heating and cooling with model predictive control	Increases occupant thermal comfort, supports grid response, enable fuel switch to reduce costs	Cost of system upgrades, technical integration of advanced controller in existing building management systems, get necessary authorization to modify the control system when high concerns are present regarding the cybersecurity of school buildings managed by a municipality
Energy Storage Integration	Thermal storage systems for peak load support.	Allows load shifting and reduces peak demand.	Complex heating/cooling systems and TABS require advanced controllers to ensure good indoor thermal comfort when performing load shifting in a built environment that has a large time constant

4.3. CASE STUDY: OVERVECHT NOORD AND KANALENEILAND-ZUID DISTRICT, THE NETHERLANDS

The ARV project is a European Union initiative focused on building and renovating in an energy and resource-efficient way. The project aims to develop and implement advanced methods and tools to optimize energy flexibility in buildings across diverse European climates. The core objective is to support local grids, enhance power system services, and reduce carbon footprints by creating climate-specific flexibility functions tailored to the operational characteristics of various demonstration sites across Europe. Data-driven approaches maximize self-consumption of renewable energy, enabling buildings and districts to achieve energy-positive outcomes.

The Dutch demonstration focuses on the Overvecht-Noord and Kanaleneiland-Zuid districts in Utrecht. Built in the 1960s and 1970s, these districts consist mainly of high-rise social housing units housing a multicultural, low-income community. The districts rely on district heating, gas, and the electricity grid, which presents significant challenges in terms of energy efficiency and grid stability. The Dutch demo targets the renovation of approximately 5,000 social housing units, transforming them into Zero or Positive Energy Buildings (ZEB/PEB) by integrating:

- Building Retrofits: Improving insulation, installing efficient heating systems, and integrating renewable technologies.
- Renewable Energy Integration: Installing photovoltaic (PV) systems, battery storage, and vehicle-to-grid (V2G) infrastructure.
- Energy Flexibility Measures: Utilizing advanced energy management systems to enhance self-consumption, reduce peak loads, and support local grid stability.

The Dutch demonstration tailor's flexibility measures to the temperate oceanic climate (Cfb) typical of the Netherlands, characterized by mild winters and cool summers with frequent cloud cover. Key strategies include:

- PV Forecasting Using Sky Imagers: Sky imagers capture real-time cloud data, which is processed by Support Vector Machine (SVM) models to predict solar irradiance. This allows for accurate PV output forecasting, optimizing self-consumption and peak shaving within PV-battery systems.
- Flexibility based PV Forecasting and battery modelling: This control strategy evaluates and optimizes the buildings' flexibility functions and responsiveness, supporting energy efficiency and grid stability.

The Dutch demo demonstrates a replicable model for urban areas with similar climates. Key guidelines include:

- Adapting Forecasting Models: Use of machine-learning-driven PV forecasting to predict and stabilize renewable output.
- Stakeholder Collaboration: Engaging local authorities and residents in the renovation process to foster confidence in long-term energy savings.
- Demand-Side Management: Implementing occupancy-based heating and automated energy systems for real-time demand response.

***Table** 7 Climate-Specific Flexibility Design for Dutch Case Study*

Case Study Location	**Overvecht-Noord and Kanaleneiland-Zuid, Netherlands**
Climate Characteristics	Temperate oceanic climate (Cfb): mild winters, cool summers, frequent cloud cover
Energy Flexibility Design (SRI)	- Temperature control with smart thermostats - Automated lighting control - Grid-responsive PV and battery systems
Energy Flexibility Design (Flexibility Index)	- PV-battery integration for peak shaving - Demand response capabilities - Adaptive heating based on occupancy patterns
Replication Strategy (SRI)	- Utilize sky imagers and PV forecasting in similar urban regions - Implement automated energy management systems that respond to occupancy and grid signals

Replication Strategy (Flexibility Index)	- Deploy grid-supportive battery storage solutions - Establish local training for occupant interaction with energy systems - Enhance demand-response readiness in residential buildings
Technical Limitations	- Effectiveness of PV forecasting reduced on heavily overcast days - Limited roof space for large PV installations
Regional Adaptability	High adaptability for temperate oceanic climates with similar grid and weather characteristics

Table 7 is a structured summary of the flexibility measures tailored to the Dutch climate, emphasizing replicability and addressing the unique challenges in urban social housing. It aligns with the ARV project's objectives to promote integration, circularity, and simplicity in creating climate-positive communities across Europe.

The Dutch demonstration in Utrecht's Overvecht-Noord and Kanaleneiland-Zuid districts highlights how climate-specific energy flexibility measures can transform social housing into sustainable, energy-positive buildings. By integrating retrofits, renewable energy systems, and advanced management tools like PV forecasting with sky imagers, the project optimizes self-consumption and supports grid stability in response to the Netherlands' temperate climate.

This case study provides a replicable model for other European urban areas, demonstrating the effectiveness of Flexibility using PV and battery in evaluating and scaling energy solutions. Challenges such as space constraints and community engagement underscore the importance of ARV's pillars—Integration, Circularity, and Simplicity—in achieving lasting energy performance.

Overall, the Dutch demonstration supports Utrecht's fossil-free 2030 goal and sets a standard for climate-adapted, flexible energy systems across Europe, aligning with the EU's broader decarbonization targets.

4.4. CASE STUDY: TRENTO, ITALY

The Italian law (Decreto del Presidente della Repubblica 412/1993) divided the territory in different climatic zones ranging from A to F, in increasing order of Heating Degree-Days (HDD). Basically, the buildings located in extreme zones do not require heating in winter (zone A) and cooling in summer (zone F). This classification is crucial for determining energy efficiency standards and regulations for buildings in different regions of Italy for defining the level of energy efficiency required for new constructions and renovations. With its 3001 HDD, Trento is in zona E, the alpine zone, which is characterized by a very cold climate in winter and extremely high heating demand.

The design of new buildings and renovations in the different climate zone is regulated by the DM 26/6/2015, called "Minimum Requirements Decree". This legislation basically defines the thermal performance of building envelope components and energy systems.

The energy efficiency legislation for buildings located in climate zone E imposes a high performance of the building envelope (see **Table** 8). The design should also pay attention to the correction of thermal bridges. In order to meet the legislation standards, the Trento case study proposed innovative wall insulation panels realized through prefabrication. The Renew-Wall panel, for instance, was installed in the renovated building and in the new positive energy building. It is characterized by a very low thermal transmittance (i.e. about 0.142 W/m²K) which has been measured on-site after the installation of the panel.

***Table** 8. Climate-Specific thermal energy performance of envelope components in Italy.*

Climate Zone E	U-min (W/m²K)			
Intervention	**Vertical walls**	**Roofs**	**External floors**	**Windows**
Renovation	0.28	0.24	0.29	1.40
New building	0.26	0.22	0.26	1.40

Another good strategy in designing buildings inside climate zone E is to consider sun exposure, prioritizing south-facing orientations to maximize solar gains during winter and avoiding locations shaded by hills or mountains. However, the maximization of solar gains in winter could require the installation of solar shading devices to prevent summer overheating. The consideration of the prevailing wind direction and the design of the building to minimize wind exposure is also an effective strategy to reduce heat losses.

Air tightness is another important aspect to be considered when designing buildings in an alpine climate zone. To minimize air leakage and prevent heat loss, mechanical ventilation units with heat recovery are installed in the new building realized in the ex-Zuffo car park.

Low temperature heating systems are considered for the new building of the Trento case study in order to increase the efficiency of the energy generation systems and indoor thermal comfort. Renewable energy integration is maximized through the installation of geothermal systems and the integration of PV power plants. When energy conservation measures are in place, energy flexibility could be implemented. Energy Flexibility Measures: utilizing advanced energy management systems to enhance renewable energy exploitation, self-consumption maximization and reduction of peak loads.

4.5. CASE STUDY: KARVINA HEALTHCARE CENTRE, CZECHIA

The Czech demo case in Karvina is positioned as a pioneering model for innovative energy solutions with significant potential for scalability throughout the region and the broader Czech Republic. Central to the ARV project is the achievement of the nearly Zero-Energy Building (nZEB) standard, which is pursued through an integrated approach that combines extensive renovations to the building envelope with the strategic deployment of advanced ARV technologies. These include Building-Applied Photovoltaics (BAPV), Building-Integrated Photovoltaics (BIPV) systems, small-scale heat pumps, second-life stationary batteries, and Photovoltaic-Thermal (PV-T) collectors. Each of these technologies works together to enhance the building's energy performance, pushing it beyond the typical nZEB standards. **Table** 9 and **Table** 10 provide an overview of climate-specific energy flexibility design strategies, addressing replication potential, limitations, policy considerations, regulations, and investment requirements for each demo case.

***Table** 9. Climate-Specific Replication Strategy and Design Constraints (SRI and FI Focus)*

Case Study Location	[Czechia]
Climate Characteristics	Humid continental climate (Dfb), characterized by cold winters and warm summers.

Energy Flexibility Design (SRI)	Multivalent heat pump with two 300 l-storages for both hot and cold water, EV-charging station and PV-Battery system all electricity price responsive.
Energy Flexibility Design (FI)	Grid max power control using second life battery storage and EV charging station. Electricity bill reduction using PV and both electric and thermal load forecasting based on day-ahead market (DAM) prices. EV charging control based on grid limit and DAM.
Replication Strategy (SRI)	Smart meters (or power meters in general) and real time data accessibility is needed. Developed smart control algorithms are run as a supervisory control level in the cloud. Occupant training (occupancy data) can improve further the electric and thermal load forecasting, therefore improve the energy efficiency and reliability of the overall energy system.
Replication Strategy (FI)	Appropriate sizing of the energy storage is necessary. Accurate load forecasting (learning from historical data) is also needed.
Technical Limitations	Effective sizing of the energy systems reflecting the climate zone is necessary for the optimal operation. There is also a technical limit (related to the extreme ambient air temperatures) for the optimal heat pump operation.
Regional Adaptability	Electric load forecasting is not dependent on the climate, only a PV production.

***Table** 10. Policy, Regulation, and Investment Considerations (SRI and FI)*

Case Study Location	**[Czechia]**
Policy and Regulatory Context (SRI)	Czechia as an EU member state is adopting legal framework of SRI in its legislation and policies according to the obligations coming from the EU Directive 2018/844 (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.156.01.0075.01.ENG) and the Commission Delegated Regulation (EU) 2020/2155 (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2020.431.01.0009.01.ENG&toc=OJ:L:2020:431:TOC). Right now, the SRI is in the test phase in Czechia together with 7 other piloting countries (https://srienact.eu/sri-in-policy-framework-policy-framework-and-national-context-for-the-smart-readiness-indicator/), (https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/smart-readiness-indicator/sri-eu-countries_en#czech-republic) (https://srienact.eu/preliminary-results-in-czech-republic/)

Policy and Regulatory Context (FI)	Demand response in a form of the ancillary services is regulated by the Czech TSO's codex (https://www.ceps.cz/cs/kodex-ps).
Relevant Standards & Compliance (SRI)	Technical framework of SRI is being defined and implemented by national authorities in Czechia – official test phase (https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/smart-readiness-indicator/sri-eu-countries_en#czech-republic). During the test phase the common SRI methodology is applied, and depending on the sensitivity of the results, some adaptations may be undertaken in a later phase.
Relevant Standards & Compliance (FI)	Demand response in a form of the ancillary services is regulated by the Czech TSO's codex (https://www.ceps.cz/cs/kodex-ps).
Investment Needs (SRI)	Cost estimation of SRI can be found in (https://neuroject.com/smart-readiness-indicator-sri-5/) and (https://www.sciencedirect.com/science/article/pii/S2210670722002438).
Investment Needs (FI)	A basic set-up for building flexibility exploitation comprises properly sized energy storage and a control software optimizing the flexible assets' operation while considering smart-grid signals like dynamic pricing, demand-side response etc.
Funding Sources	At present, energy efficiency measures as part of the SRI are mainly supported through government grants (https://www.nzu.cz/).
Economic Viability	Examples: the return of investment for an average PV system is about 5-7 years. In case of air source heat pump with a storage the ROI is about 3-10 years depending on what it is compared to; when a smart control (with spot pricing) is applied it can be additionally reduced by another 15-20 %. The given examples of ROIs are considered with usage of government subsidies.
Stakeholder Involvement	Grid operators (DSOs, TSO, utility companies), building owners and users, technology and BMS providers.
Scalability Potential	Estimation of the potential can be found in the methodology released by the Czech green building council (https://www.czgbc.org/files/2021/01/ca29f538a6e2605225e248a1d2085f5a.pdf) .

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APPENDIX A – GLOSSARY OF TERMS

Table A1. Glossary of Terms

Abbreviation	Term
FF	Flexibility function
FI	Flexibility Index
SRI	Smart readiness indication
PEB	Positive Energy Building
CPCC	Climate Positive Circular Community
PV	Photovoltaic
DH	District Heating
GHI	Global Horizon Irradiation
BAPV	Building Applied Photovoltaics
DHW	Domestic Hot Water
BESS	Battery Energy Storage System
GSHP	Ground-Source Heat Pump
TABS	thermally active building systems

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