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Assessment of Swedish house thermal system using a resilience energy system framework

Kasuni Guruvita[1*], Eva Thorin[1], Anders Avelin[1], Fredrik Wallin[1]

Future Energy Center,Mälardalen University,Västerås, Sweden

(*Corresponding Author: kasuni.guruvita@mdu.se)

ABSTRACT

This study evaluates the thermal systems of Swedish houses through a holistic energy system resilience framework, incorporating engineering, economic, and social dimensions. The major limitation identified is the lack of a proper framework to measure resilience. To address this, the study proposes a synthesized framework for measuring resilience, considering dimensions, abilities, properties, and key performance indicators (KPIs). Using a selection of indicators, the framework is applied to a case study to demonstrate its usability. The assessment focuses on measuring the thermal resilience of houses, influenced by the integration of heat pumps and wood stoves. By analysing the properties and KPIs specific to the system, the study aims to measure the resilience abilities of the system. This comprehensive approach supports the idea that Swedish houses can withstand and recover from disruptions, contributing to a sustainable and resilient energy future.

Keywords: sustainability, engineering resilience, social resilience, economical resilience, resilience metrics

NONMENCLATURE

KPIs	Key Performance Indicators
ERF	Energy Resilience Framework

1. INTRODUCTION

Sweden's heating system is a testament to the country's commitment to sustainability, innovation, and resilience. Over the past few decades, Sweden has successfully transitioned from oil-based heating to more environmentally friendly solutions, significantly reducing greenhouse gas emissions and enhancing energy security [1]. This research paper aims to explore the relationship between Sweden's heating system and its energy resilience and highlighting impact of the technological advancements on economical and societal dimensions of resilience.

Central to Sweden's heating infrastructure is the widespread use of district heating which utilizes waste heat from industries and power plants to provide heat to urban areas through a network of insulated pipes. This system not only enhances energy efficiency but also contributes to the reduction of fossil fuel dependency [2]. Additionally, heat pumps have become increasingly popular in residential settings, extracting heat from the air, ground, or water to provide a sustainable and energy-efficient heating solution. The resilience of the thermal system is playing a major role in Sweden’s energy system. The energy resilience framework is characterized by its focus on resilience abilities which can be measured using resilience properties and key performance indicators (KPIs) [3]. These elements ensure that the heating system can withstand, adapt to, and recover from disruptions [3], thereby maintaining a stable and reliable energy supply. While various metrics and KPIs for evaluating resilience are suggested in the literature [4], few measure resilience at the system level. The novelty of this framework lies in its proposed measurements for assessing the resilience of the energy system, allowing for comparisons of resilience improvements across different application and this paper aims to contribute to the development of a novel framework for measuring how engineering, social and economic dimensions impact the energy resilience, by evaluation of the energy system resilience, including the heating system, of a Swedish household as a case study.

2. METHODOLOGY

The holistic energy resilience framework applied to an energy system of a Swedish one-family house, as shown in Fig.1, measure the resilience of the energy system using three of the dimensions as mentioned in the Fig2.The three dimensions (engineering, economic and social) were used to measure thermal system resilience in the Swedish household. Each dimension will be described by properties and measured by a set of resilience key performance indicators (KPIs).

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The proposed framework adopts a comprehensive approach to energy resilience, considering the entire energy system. It spans from the initial capture of diverse energy carriers' characteristics to addressing the needs of end users. This framework is designed to be utilized as a tool for assessing energy systems resilience.

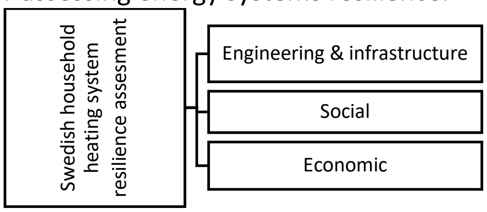

Fig. 1. Resilience assessment framework applied on a one-family Swedish house.

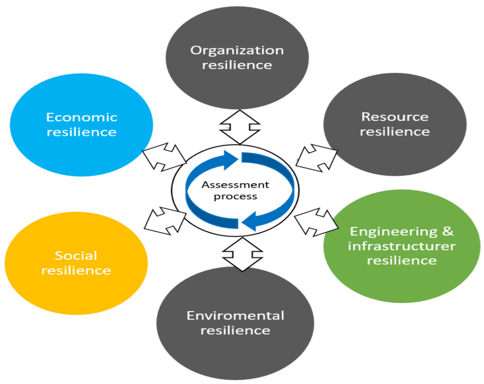

Fig. 2 Proposed energy resilience framework (ERF). In this study the application of the engineering social and economic dimensions, marked in green, yellow and blue is demonstrated.

In the selected case study, the resilience of the energy system in a Swedish house is measured and analysed. The house has two floors with a basement, five rooms and is occupied by 5 people. The house heating system is connected to a district heating system with radiators in floors 1 and 2 with thermostats and the basement is connected to water-based floor heating. This case study shows how to measure and improve energy resilience in a household using a holistic energy resilience framework.

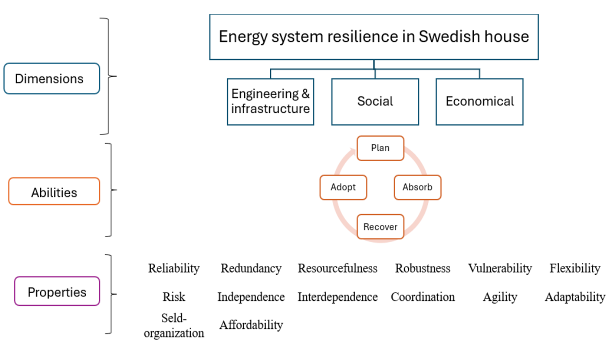

Fig. 3 Resilience assessment framework applied on a one-family Swedish house including abilities and properties.

Two options are discussed in this paper. Option 1 shows how a heat pump improves thermal energy resilience and option 2 how a wood oven option can improve the thermal energy resilience in the household system.

2.1 Resilience properties and KPIs

In this study the assessment of the heating system resilience of the engineering and infrastructure social and economic dimensions of the energy system for the case of a Swedish household has been done to demonstrate the application of the proposed ERF. First, resilience properties, considered as the most important ones for the area, are identified. Based on those sets of KPIs, to be used to measure the properties of the selected system, are designed. Selecting suitable properties should be done after analysing the area boundaries, local energy balance, infrastructure development and type of business. To measure the heating resilience of the case study the abilities (plan, absorb, recover and adopt) and properties, dependent on and different for the different dimensions and abilities evaluated, were used.

2.2 Assessment of resilience for the plan (ability) resilience (only considering heating system) in the house.

The ability plan concerns the state of the system during normal operation. In table 1. the selected properties and the KPIs for the ability plan given for the case are summarized.

Table 1. Properties and KPIs selected for the ability plan in the assessment of the Swedish house

Property	Engineering KPIs	Social KPIs	Economical KPIs
Reliability: Reliability refers to the system's ability to consistently provide the necessary energy to customers without interruptions [3].	End customer loss [3] Eq.1	-	-
	Capacity and load characteristic [3] Eq .2 & 3		
Resourcefulness: The ability of the system to always supply the aggregated demand requirements of the customers without depending on energy source.	Energy mix of the supply	-	-
Preparedness: The proactive measures and strategies implemented [5].	-	Encouraging energy efficiency in municipality energy plan [5]	Emergency aid insurance [5]
		Community engagement and participation [5]	Cost benefit analysis [5]
		Clear communication channel [5]	
Vulnerability: Weaknesses within an energy system that can be exploited by threats [5].	Threats identification (engineering)	Social threats identification	Economical threats identification
Availability: Ensuring that energy systems are resilient involves making them accessible to all parts of society [5]	-	End customer loss [3]	-

The calculation of end user loss (Eq.1) and capacity and load characteristics (Eq. (2), (3)) and availability (Eq. (4)) respectively.

$$\mathrm{CAIDI} = \frac{\text{Total minutes of customer}}{\text{Total number of interruptions}} \tag{1}$$

$$\text{Reserve margin ratio} = \frac{\text{Total installed capacity} - \text{Peak Deamd}}{\text{Peak Demand}} \tag{2}$$

$$\text{Reliable capacity ratio} = \frac{Available\ capacity\ - Peak\ Deamd}{Peak\ Demand} \quad (3)$$

$$\text{Availability of the energy} = \frac{Avialable\ time}{Total\ time} \quad (4)$$

2.3 Assessment of resilience for the absorb (ability) resilience (only considering heating system) in the house.

The ability absorb is crucial in the energy resilience framework as it focuses on the system's ability to withstand and manage disruptions. This ability ensures that the energy systems can absorb risks from various vulnerabilities, such as natural disasters, cyber-attacks, or supply chain failures. Having proper resilience for absorbing the shock is important for all dimensions. By maintaining functionality during adverse conditions, the absorption ability helps prevent complete system failures and ensures continuous and independent energy supply. It involves proactive measures, such as robust infrastructure design and contingency planning, to prepare for potential threats [5] [6] [7].

Table 2 Properties and KPIs selected for the ability absorb for the assessment of Swedish house

Property	Engineering KPIs	Social KPIs	Economical KPIs
Risk: Risk in an energy system is the potential for adverse events that can disrupt the supply, reliability, or security of energy [5].	Heating loss due to threat	Lifestyle change	Economic risk
Redundancy: Redundancy in energy system resilience refers to the inclusion of additional or backup components and systems that can take over if primary components fail [3] [8].	Storage system [3]	-	Economical redundancy
Independence: Independence in energy resilience refers to the ability of an energy system to operate and meet its energy demands without relying on external sources [8].	The number of hours the house can work in standalone system	Ability of residential to work during the absorption time	Economic independence

The economic risk and economic independence are calculated with Eq. (5) to (6) respectively.

$$\text{Economical risk} = (\text{Number of hours power loss} * \text{per hour energy value}) + \text{Occupation loss other damages} \quad (5)$$

$$\text{Economical indepedence} = (\text{Number of hours working as indepedence} * \text{per hour value energy value}) + \text{Occupation saving} + \text{other ecnomic savings} \quad (6)$$

2.3 Assessment of resilience for the ability recover (only considering heating system) in the house.

The ability recovery is a critical component of the energy resilience framework. It focuses on restoring normal operations and improving systems after disruption. The primary goal of the ability recovery is to quickly restore energy services to normal levels, minimizing downtime and ensuring that consumers and critical infrastructure have access to energy. This stage involves analysing the disruption to identify weaknesses and implement improvements, making the system more resilient to future disruptions. Effective recovery requires efficient allocation of resources, including manpower, equipment, and financial support, to repair and rebuild damaged infrastructure. Coordinating with various stakeholders, including government agencies, utility companies, and the public, is essential for a smooth and effective recovery process [11].

Table 3 Properties and KPIs selected for the ability recover in the assessment of the Swedish house.

Properties	Engineering KPIs	Social KPIs	Economical KPIs
Agility: Measuring how quickly the system can recover from disruptions and adapt to new conditions [6] [7].	Recovery duration	-	-
Robustness: This property exercises the system's strength to withstand internal and external shocks without suffering from major impairment in major functions [8] when system is in recover stage	Performance level of the Swedish house	-	-
Flexibility: It is the ability to perform necessary functions under a wide variety of conditions [8] [10]	Load shading of the Swedish house	-	-
Coordination: Effective coordination and control are crucial to recover from the disturbance [10]	Communication and control		Cost to manage different stakeholders
Interdependence: It refers to having mechanisms in place that enable a system, as part of an integrated network, to receive support from other systems in the network [8]	Possibility to micro grid integration	Communication channels across supply chain [5] Community engagement and participation [5]	Financial contracts and insurance mechanism [5]
Accessibility: **Accessibility** is one of the components of intra-generational equity. During the recovery stage house should have proper accessibility for the electricity system	-	Eq.9	-

The accessibility of the social dimension is calculated according to the Eq. (9).

$$\text{Accessibilty of the energy} = \frac{Supplied\ energy}{Required\ energy} * 100 \quad (7)$$

2.4 Assessment of the resilience for the ability adopt (only considering heating system) in the house.

The ability to adopt is essential in the energy resilience framework as it focuses on the system's ability to evolve and improve in response to changing conditions and new challenges. This stage involves making proactive adjustments to energy systems to address emerging threats and vulnerabilities, ensuring long-term resilience. Adaptation encourages the integration of innovative technologies and flexible strategies, such as smart grids and renewable energy sources, to enhance system performance. By continuously monitoring and analysing system performance, the ability to adapt helps to identify areas for improvement and implement changes that strengthen resilience. Effective adaptation requires collaboration with various stakeholders, including policymakers, industry experts, and the public, to develop and implement adaptive measures.

2.5 Scenarios for improved energy system resilience in the house.

After studying the current state of the household energy system resilience, the next step is to analysis the feasibility to possible changes of the thermal system.

- Option 1: Installing heat pump

- Option 2: Installing wood or pellet stoves

Table 4 Properties and KPIs selected for the ability absorb for the assessment of Swedish house

Property	Engineering KPIs	Social KPIs	Economical KPIs
Affordability: To examine the affordability of the social dimension the percentage related expenses for electricity related to the income using to measure the affordability of the social dimension. Statistics Sweden [9] was used as the data source for the price analysis [3].	Electricity and heating prices or bills	Electricity and heating prices with related household income	Economical resilience development cost
Adaptability: It refers to a system's capacity to learn from past disturbances and its flexibility to adapt to the changing conditions [22].	Customer average interruption duration index (Indicates average time to restore service)	Community engagement and participation in energy resilience improvements social adaptability [5]	Financial adaptability
Self-organization: Teaching from the past and re-arranges the system. It means that house self-organization ability when there is a disturbance happen [10].	Advanced distribution grid technologies [5]	-	-

3. RESULTS & DISCUSSION

The results of the case study presented in Table 5,6 and 7 and further explained below.

3.1 Results of the assessment of engineering and infrastructure resilience.

When assessing the result of the engineering dimension the resilience for the abilities plan reliability, resourcefulness and vulnerability properties were assessed. Current characteristics were calculated assuming total breakdown in the heating system. Currently system reliability is assumed to depend on the district heating system, and the district heating system daily load variation values were used to calculate the reliability level of the district heating system. Current characteristics and the two options for changing the system, mentioned in Chapter 2, were considered to see how large reliability improvement each option can give. The next property is resourcefulness. Currently the system only depends on the district heating and does not have resourcefulness. When a heat pump is installed, in option 1 the house will have 100% resourcefulness of the system, the current heating system of the house only depends on the district heating system after applying option 1 system has different source opportunities. During a shock situation the system can work on option1. When considering option 2 the wood burner, the household heating system can totally depend on option 2 and make 100 % resourcefulness during shock time. When planning the engineering system, identification of the threats and vulnerabilities of the system is important. The ability plan is important for continuous supply of the system. The ability absorption can identify the risk and how the system will behave for that risk, based on the risk, redundancy can be planned to maintain the system resilience threshold level. During this time the house works independently and absorbs the shock. During recover stage the system can withstand the minimum threshold. The flexibility of the system also should be maintained in this stage using load shading. When the system reaches the adopt stage the characteristics are measured by the properties-affordability, self-organization and adaptability. Three KPIs were used and according to the comparison the resilience level of the current system is low in all three properties. After applying for option 1 there is a considerable improvement in the resilience level in the heating system. Compared to option 1, option 2 doesn't become a good option for improving the heating system resilience improvement but still it is an option that can be actionable. With the resilient abilities of the engineering dimension of the house it has planning stage reliability for handling load variations, but the system is lacking some of the most important properties of the system such as vulnerability, resourcefulness, robustness, flexibility and self-organization. This means the thermal system of the house does not have resilience abilities inside the system to absorb the shocks which is the major impact to the resilience of the regional level. Thermal system resilience in a house can significantly impact the resilience of the regional energy system in several ways. Resilient thermal systems can help manage energy loads more effectively and support integration of renewable energy. Resilient thermal houses can be part of the thermal distribution grid. These microgrids can operate independently during outages, providing localized energy resilience and reducing the impact on the larger regional grid.

Table 5 Results of the assessment of the engineering and infrastructure resilience

Abilities	Properties	KPI	Current characteristics	Option 1	Option 2
Plan	Reliability	Capacity and load characteristics [3]	17% [1] (daily load variation)	100%	100%
			4.5% [1] (annual load variation)	-	-
	Resourcefulness	Energy mix [3]	-	100%	100%
	Vulnerability	Identified engineering threats and vulnerability of the house heating system	-	Yes	Yes
Absorb	Risk	Heating outage due to threat	Yes	-	Yes
	Redundancy	Backup supply	Natural circulation [12]	Heat pump storage	Wood storage
	Independence	Villa can work in standalone system	6 hours	100%	100%
Recover	Agility	Recovery duration	2.75 days	0 days	0 days
	Robustness	Villa performance level	-	100%	30%
	Flexibility	Load shading of the villa	-	100%	30%
	Coordination	Communication and control	Yes	Yes	Yes

Adopt	Adaptability	Percentage of the ability to tackle situation	8.3%	100 %	100%
	Self-organization	Changing the settings and flexibility energy consumption	No	Yes	Yes
	Affordability	Heating price	1 SEK/kWh [13]	0.65 SEK/kWh [13]	4 SEK /kWh [14]

3.2 Results of the assessment of social resilience

How social resilience impacts energy resilience is presented in Table 6. Four abilities were used to do the assessment. Three properties preparedness, availability and vulnerability included and four KPIs were used to measure resilience of the plan. This dimension is mainly assessed based on the qualitative KPIs. The current resilience level in plan is considerable low. This can be improved by proper use of option 1 and option 2. For the ability to absorb the properties risk and independence was used. Option 2 shows higher resilience for managing risk and working as independence but option 2 still can't decrease risk and increase the independence of the system. It can further increase the level to certain resilience. Ability recovers the properties interdependence and accessibility were included. The properties adaptability and affordability were used to measure the resilience for the ability adopt.

Table 6 Results of the assessment of the social resilience

Abilities	Properties	KPI	Current characteristics	Option 1	Option 2
Plan	Preparedness	Encouraging heating system efficiency	Yes	Yes	Yes
		Community engagement and participation workshops and working groups	No	No	No
		Clear communication channel	Yes	Yes	Yes
	Availability	Availability of the heating supply	99% [15]	100%	100%
	Vulnerability	Threats identification	No	Yes	Yes
Absorb	Risk	Lifestyle change in the house	Yes	No	Yes
	Independence	Ability of residential to work during the absorption time	No	Yes	Yes
Recover	Interdependence	Dependency on other parties to support to recover from the situation	Yes	No	No
	Accessibility	Access to the Heat	No	Yes	Yes
Adopt	Affordability	Heating prices with related household income [16] [17] [18]	6.3%	4.5% [19]	16% [20]
	Adaptability	Adaptability of society to situation or technology (resilient community)	60%	43%	20%

After estimating the social resilience related to energy system resilience, we can clearly see that social resilience related to absorbing the shocks or disturbance is on a low level. High engineering resilience alone is insufficient if society lacks crisis awareness and action. The ability plan shows room for improvement. Strong preparedness, social networks, and community engagement enhance coordination during energy crises. Communities that are well-connected can share resources, support each other, and implement collective energy-saving measures. According to the current characteristics of the social dimension properties plan, absorption resilience abilities vulnerabilities and awareness of risks and independence need major improvements. This includes understanding vulnerabilities and awareness of risks independence and emergency response need major improvements. This result shows that social resilience regarding energy resilience is at a lower stage. There are properties which show higher acceptable range (availability, adaptability) and other properties show lower level, which make significant impact on total energy resilience. Social resilience depends on education and energy awareness, which are key for planning. Current absorption capacity is low, but applying targeted options can reduce risk and increase system independence. Recovery and adoption improve in informed communities that embrace energy-efficient practices. Affordability, adaptability, communication, and applicability are essential for resilience. In [21] it is shown that socially resilient communities are more likely to initiate community solar programs. Resilient communities support energy resilience through renewable investments and infrastructure upgrades. Key actions include raising awareness, encouraging engagement, and removing barriers to participation in energy programs. [21].

3.3 Results of the assessment of the economical resilience

The economical dimension results highlight both weaknesses and strengths in the current resilience. The selected KPIs, derived from heating, electricity costs, and consumption rates, are calculated using a simple solution method and a combination of direct and aggregated data. To assess the resilience level of the economical dimension a combination of qualitative and quantitate method was used to do the analysis. Three key performance indicators (KPIs)—emergency aid, cost-benefit analysis, and threat identification—were used to assess economic resilience during heat outages. Risk was evaluated through estimated financial losses, while independence and interdependence properties measured cost savings and recovery capabilities. Affordability and adaptability were used to assess the system's ability to adopt resilient strategies. A mixed-methods approach confirmed that resilient infrastructure and economically stable households are essential for minimizing disruptions and maintaining heat supply.

Table 7 Results of the assessment of the economical resilience

Abilities	Properties	KPI	Current characteristics	Option 1	Option 2
Plan	Preparedness	Emergency aid	Yes	Yes	Yes
		Cost benefit analysis	No	Yes	Yes
	Vulnerability	Threats identification	No	Yes	Yes
Absorb	Risk	Estimated cost due to disturbance (3 days)	13500SEK	0	2000SEK
	Redundancy	Economical redundancy	Yes	Yes	Yes
	Independence	Estimate cost due (saving) to energy independence	-	13500SEK	7500SEK
Recover	Coordination	Managing cost with different stakeholders	Yes	Yes	Yes
	Interdependence	Financial contracts and insurance mechanism	Yes	Yes	Yes
Adopt	Affordability	Resilience development cost	-	30000 SEK [22]	30000 [23]
	Adaptability	Financial stability of the household	Yes	Yes	Yes

4. CONCLUSION

By defining dimensions, properties, and key performance indicators (KPIs), system resilience can be measured and evaluated, though this process is complex and multidimensional. This paper presented a framework for measuring household heating system resilience, demonstrating its adaptability to different contexts, and evaluated three out of the proposed six dimensions. The framework supports analysis of resilience at dimensions (Fig.4), abilities (Fig.5), properties (Fig.6) and KPIs. Energy resilience at the property level requires different scales for measurement. In Fig.6, green-coloured properties are measured inversely, meaning lower values indicate higher resilience in the system. Engineering resilience alone cannot ensure total energy system resilience due to gaps in preparedness, risk management, and stakeholder coordination. Educating households on energy disruptions boosts social resilience and recovery. A Swedish case study highlights the need to expand the evaluation framework for broader regional energy system analysis.

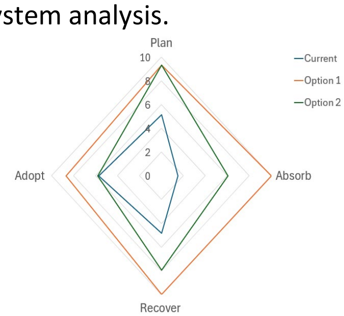

Fig.4 Results from a resilience analysis process using the proposed Framework (Resilience abilities)

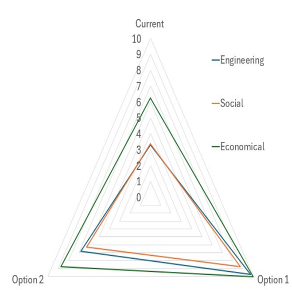

Fig.5 Results from a resilience analysis process using the proposed Framework (Resilience dimensions)

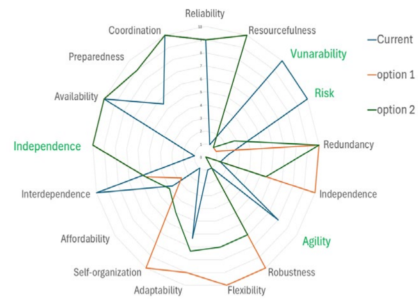

Fig. 6 Results from a resilience analysis process using the proposed Framework (Resilience properties)

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