Energy & Buildings 322 (2024) 114726

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

Energy saving starts in the kitchen

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ARTICLE INFO

Keywords:
Energy efficient and sustainable kitchen
Heat pump
Modular design
Household appliances

ABSTRACT

The field of sustainable construction and interior design demands innovative solutions to optimize energy efficiency and minimize environmental impact. This need has been further amplified by the European Community's Directive on Energy Efficiency 2012/27/EU and its subsequent revisions. The kitchen, as a central hub of domestic energy use, presents a significant opportunity for improvement. This paper introduces a novel application of heat pump technology for energy reuse in household appliances. The proposed SMACK (SMArt energy-Conserving Kitchen) system embodies a holistic approach, merging eco-sustainability with advanced design principles. SMACK's modularity enables customization and scalability to meet diverse requirements. A comprehensive assessment indicates potential average energy savings approaching 50%, contingent upon appliance configuration. Importantly, this study incorporates preliminary real-world measurements on a minimal appliance, offering empirical insights into the SMACK system's performance. The SMACK project signifies a major step towards environmentally conscious design, setting a new standard for sustainable technology integration within the home.

1. Introduction

The pursuit of energy-efficient and sustainable solutions in the field of building science, building engineering, and architectural design has gained significant momentum in recent years. As our world faces growing concerns over energy consumption, carbon emissions, and environmental sustainability, innovative approaches become essential to address these challenges. The European Union (EU) has been at the forefront of supporting sustainability practices to mitigate the environmental impact of construction and, more generally, urbanization. The EU emphasis on sustainable architectural design and the integration of energy-efficient technologies is evident in its policies and support for high-quality architecture that meets the social, cultural and psychological needs of the population. Indeed, the EU established to achieve an energy efficiency target of 20% energy saving by 2020 and 27% by 2030. The Energy Efficiency Directive (EED 2012)[1] — updated in 2018 and 2023 — and the Energy Performance Directive (EPBD 2010) are the main elements of EU legislation to achieve these objectives [1,2]. In particular, *the 2023 revision of the directive follows a proposal for a recast directive on energy efficiency put forward by the Commission in July 2021, as part of the EU Green Deal package* and has been released on October 10, 2023.

Overall, the potential for energy saving is greatest in the residential sector, which accounts for 40% of the EU final energy consumption and 36% of greenhouse gas emissions [3–6]. In particular, the EPBD directives define nearly zero-energy buildings as those that require very low quantities of energy and use, to a very significant extent, energy from renewable sources, including energy produced on site. The directive required all new buildings to be nearly zero-energy by 2020 and obliged EU member state governments to develop all new public buildings according to this concept after 2018. Energy-efficient homes combine state-of-the-art, energy-efficient building materials, appliances, and lighting with commercially available renewable energy systems, such as solar water heating and solar electricity [7]. By taking advantage of local climate and site conditions, designers can often also incorporate passive solar heating and cooling and energy-efficient landscaping strategies. The intent is to reduce domestic energy consumption in the most cost-effective way possible, and then address the reduced load with on-site renewable energy systems. Moreover, *making buildings more energy effi-*

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[1] https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en.

https://doi.org/10.1016/j.enbuild.2024.114726
Received 5 April 2024; Received in revised form 14 August 2024; Accepted 24 August 2024

cient will contribute significantly to the EU achieving its energy and climate goals.[2]

Kitchens are busy places filled with all kinds of energy-hungry appliances and specialized work surfaces. Therefore, building a "green" but intelligent kitchen — since IoT techniques are now essential [8] — implies something more than the simple installation of appliances and energy and water saving systems. A truly sustainable kitchen starts from scratch, including everything from eco-friendly cabinetry to non-toxic finishes and glue. The state-of-the-art in the context of energy-efficient and sustainable kitchen design is a dynamic field that encompasses advances in building design, appliance efficiency, renewable energy integration, carbon neutrality, and smart home technology [9,10]. Numerous studies have examined energy efficiency optimization in buildings and in various home environments, including heating, cooling, and appliances [11–14]. However, kitchens, despite their significance in daily life, have often been overlooked in terms of energy consumption reduction and performance enhancement. Waste heat recovery is one of the most common ways to implement energy saving in existing buildings, though the potential for heat recovery from kitchen wastewater remains largely unexplored [15]. Already at the end of the last century, the recovery of the heat generated by various household appliances was recognized as an eco-sustainable and reusable source for domestic use. In fact, in [16], a design for a coil heat exchanger to recover waste heat from exhaust air in a university canteen was described, which could be used to heat water for sanitary purposes. In [17], a system aimed at recovering kitchen waste heat using a heat exchanger combined with solar energy was proposed to heat water in a storage tank. The water could be used to wash vegetables. In [18], it was proposed to recover waste heat from exhaust air through a system of ground-coupled heat pumps while achieving thermal compensation. Indeed, many studies have been conducted on the recovery of waste heat from kitchens and several uses of waste heat have been put forward. However, these studies mainly concern the energy recovery for water heating, even though, in fact, other kitchen equipment may have higher needs. Additionally, a drying device is often integrated to the dishwasher.

Our research fills this gap and presents an innovative design solution for kitchens, SMACK for *SMArt energy-Conserving Kitchen*, that incorporates a heat pump. Indeed, the integration of a heat pump into a modular kitchen marks a leap forward in optimizing energy usage in domestic settings. Indeed, this paper presents a transformative concept for kitchen design. The core idea revolves around a modular kitchen system that incorporates a heat pump, which can be seamlessly installed without the need for extensive construction work. By harnessing the power of the integrated heat pump system, the kitchen offers a multitude of benefits, from improving the performance of household appliances to providing hot water for various domestic needs. Thus, our research not only contributes to bridging the literature gap on sustainable kitchens but also introduces a significant innovation by proposing a system that optimizes energy usage across all major functions of a kitchen, from dish drying to hot water production. This work provides a holistic solution that has the potential to transform the way kitchens are designed and utilized in households, with the goal of reducing environmental impact and energy consumption.

This innovative design minimizes production costs through the use of the same 60 cm wide module for almost all the appliances and cabinets. The air pump produces cold air for the refrigerator and the freezer, and hot air to preheat the oven and to evaporate water for steam cooking, to heat water to a safe hot temperature for washing dishes in the dishwasher and clothes in the washer dryer, which also use the hot air for drying. Furthermore, the excess heat from the heat pump is utilized to heat the dishes storage cabinet for the final drying. Additionally, the system incorporates a hot water production and a storage tank that serves, depending on the size chosen, not only the kitchen sink but also the entire household, eliminating the need for traditional water heaters and their costly maintenance and electricity/gas consumption. Finally, the materials employed in the kitchen design are chosen for their low environmental impact, recyclability, and innovative qualities, aligning with the principles of sustainability and eco-friendliness.

Summing up, the proposed concept of a modular kitchen system with an integrated heat pump could push the boundaries of current kitchen design by creating a versatile and more energy-efficient environment. This system could potentially:

- Minimize the need for separate heating and cooling units, reducing the kitchen overall energy demand;
- Provide a retrofit option for older homes, allowing for energy-efficient upgrades without extensive remodeling;
- Facilitate the use of renewable energy sources by integrating with solar panels or other renewable systems.

Below we will delve into the various aspects of this revolutionary kitchen system, highlighting its unique characteristics, environmental advantages and its potential for widespread adoption, for a remodeled and eco-conscious future of living.

The paper is organized as follows. In the next section, we will describe in detail how the different modules of the kitchen are composed ad interact to save and reuse energy, (partially) alimenting all the appliances, with a particular emphasis on the environmental sustainability of manufacturing materials. Furthermore, the parameters of the heat pump system are detailed to ensure reproducibility. In Section 3, we present an overview of the esteemed results in terms of improved energy efficiency and material sustainability and discuss the implications of the adoption of our proposed solution, also highlighting its limitations. Section 4 demonstrates the practical feasibility of the SMACK project, presenting also an economic analysis assessing its benefits. In subsection 4.3, we showcase the results obtained from preliminary real measurements conducted on a minimal prototype of the SMACK system. In Section 5, we delve into the results obtained from comprehensive mathematical-computational simulations and discuss the ongoing field verification process, shedding light on the real-world applicability of the proposed SMACK system. Finally, some conclusions and future perspectives are drawn in Section 6.

2. Materials and methods

SMACK embodies a complex system that necessitates a detailed description of the materials used and the methodologies applied in its creation and implementation. This section aims to provide readers with a comprehensive understanding of how our innovative kitchen design was realized, ensuring transparency and facilitating potential replication.

2.1. Guiding principles for a sustainable kitchen design

Sustainable production and consumption patterns require a change in approach at the early conceptual stages, i.e., when planning and designing products and services. The guiding principles that inspired the SMACK project are briefly described below.

- **Building Design and Materials**
  - *Passive Solar Design*: Kitchens are increasingly designed with passive solar techniques to utilize natural heat and light, reducing reliance on artificial heating and lighting.
  - *Sustainable Materials*: The use of recycled, reclaimed, or sustainably sourced materials for countertops and cabinets is becoming increasingly common.

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[2] https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings_en.

- **High-Efficiency Appliances**
  - *Energy Star Rated Appliances*: The market is populated with high-efficiency refrigerators, ovens, dishwashers and other appliances that meet or exceed energy efficiency guidelines set by the EU.
  - *Induction Cooking Technology*: Induction cooktops are much more efficient than traditional gas or electric ones, as they reduce heat waste by directly heating cookware.
- **Smart Kitchen Technology**
  - *Automated Systems*: Integration of smart home technology allows for better management of appliance use, reducing unnecessary energy consumption.
  - *Energy Monitoring:* Smart meters and energy management systems help households track and optimize their energy usage.
- **Waste Heat Recovery Systems**
  - *Heat Recovery Ventilators*: These systems capture waste heat from exhaust air and use it to pre-heat incoming fresh air.
  - *Greywater Heat Recovery*: Devices that recover heat from sink and dishwasher wastewater to preheat incoming cold water.
- **Renewable Energy Integration**
  - *Solar Water Heaters*: These are used to provide hot water for both domestic use and as a supplement for kitchen appliances.
  - *Photovoltaic (PV) Systems*: Solar panels can be installed to provide electricity directly to the kitchen (or the entire household), reducing reliance on the grid.
- **Energy Storage Solutions**
  - *Thermal Energy Storage*: Some systems use materials like phase-change materials (PCMs) to store excess heat, which can be used when needed.
  - *Electric Batteries*: Coupled with renewable energy generation, batteries can store excess electricity for use during peak demand times.
- **Heat Pump Technology**
  - *Integrated Heat Pumps*: Heat pumps can provide heating, cooling, and hot water in an integrated system, leveraging the temperature differential from inside to outside the kitchen environment.
  - *Reversible Heat Pumps*: Some designs allow for switching between heating and cooling modes, potentially providing refrigeration and hot water simultaneously.
- **Water Efficiency**
  - *Low-Flow Fixtures*: Faucets and dishwashers that use less water to achieve the same level of functionality help reduce the energy needed to heat water.
  - *Water Recycling Systems*: Systems that purify and recycle greywater for non-potable uses in the kitchen.

2.2. SMACK modular kitchen design

The holistic efficiency of our modular kitchen system depends on the perfect integration and meticulous selection of its various components. In the following, we delve into the details of the system, highlighting the critical elements that contribute to its overall performance and sustainability.

At the heart of our design are several key components, each of which plays a vital role in the overall functionality and efficiency of the kitchen. These include the heat pump unit, cabinets, refrigerant piping, a water storage tank, plumbing and electrical connections, and the ventilation system. Notably, all kitchen components are explicitly described, ensuring transparency and facilitating potential replication of our findings. We highlight that to expedite the transition process without the need for extensive rewiring, we opt for a series connection of appliances rather than a parallel arrangement, recognizing that the majority of setups typically favor parallel configurations.

A pivotal aspect of the SMACK system lies in the intricate integration of the heat pump. The sophisticated network that facilitates the flow of refrigerant, incorporates heat exchange mechanisms, integrates control systems, and employs heat recovery methods. By delineating these elements, we provide a comprehensive understanding of how the heat pump maximizes its efficiency and harnesses excess heat for various applications within the kitchen. Furthermore, our design stands out because it perfectly integrates the heat pump with common appliances such as dishwasher, oven, refrigerator and freezer. This strategic integration not only improves the energy efficiency of the appliances, but also optimizes the overall use of resources within the kitchen environment. The collaborative operation of the heat pump with the appliances reflects our commitment to creating a system that is both efficient and environmentally friendly. Finally, in alignment with eco-conscious principles, our material selection for the modular kitchen system places a strong emphasis on low-impact, recyclable, and innovative options, promoting sustainable practices in its construction.

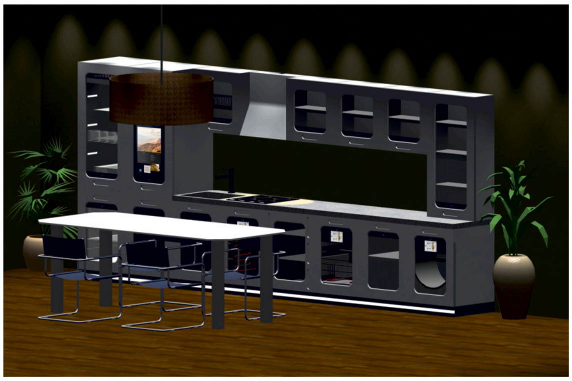

Fig. 1. 3D view of the kitchen (including complementary furnishing elements).

Fig. 2. Kitchen front diagram.

2.3. Furniture and appliances

The composition of the kitchen is described below both from the point of view of the appliances and the various pantry modules (see Figs. 1-2).

- **Central module —** The central module integrates the actual heat pump, which serves all the kitchen appliances, and a tank for production and storage of domestic hot water. The tank can be chosen in two sizes: the smallest (estimated at around 50 litres) for just the sink of the module itself, the largest (estimated at around 300 litres) for the whole house. In this case, the water connection to the house system takes place via the previous hot water wall connection for the sink, which now becomes the entry point. The version with the smaller tank also includes a pantry space.
- **Refrigerator and freezer —** The cold refrigerant liquid coming from the heat pump cools the refrigerator and freezer chambers assisted by a fan system which increases air exchange and reduces moisture residues, also making them *no frost.*
- **Oven —** The hot refrigerant liquid coming from the heat pump pre-heats the oven chamber, reducing the use of the electric resistance, although present, or eliminating it in the case of low temperature

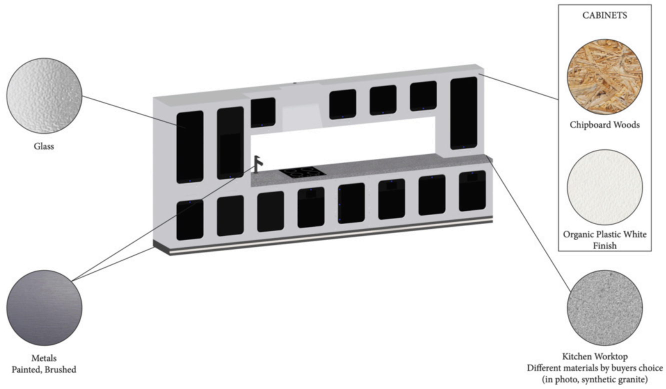

Fig. 3. Manufacturing materials.

cooking. The liquid also heats up the water present in a special tray, that evaporates, for steam cooking.

- **Dishwasher —** The hot refrigerant liquid heats the water for washing, thus eliminating the electrical resistance usually used.
- **Washer dryer —** The hot refrigerant liquid heats the water for washing and the air for drying cycles, thus eliminating the use and presence of electrical resistances (or in the case of the dryer, a dedicated heat pump).
- **Module for storing crockery —** The exhaust pipe of the excess heat produced by the heat pump runs through this module (which then rejoins the exhaust line of the kitchen hood) and heats the internal volume for further drying of the stored dishes.
- **Various pantry modules —** Modules of various sizes, with shelves or drawers.

2.4. Manufacturing materials

For the creation of the furniture, the choice of materials used marries the philosophy of a kitchen that is both highly technological and eco-sustainable (see Fig. 3):

- **Furniture and furniture doors —** chipboard, PET plastic coating;
- **Accessories and finishes —** metallic, aluminum and stainless steel;
- **Furniture doors with a central glass panel**
  - LCD glass panels in which, through a touch control, the glass itself can be made transparent (and therefore shows the content of the module, whether it is a pantry module or an appliance) or opaque (and therefore hides the content);
  - Glass panels with a control display, i.e. equipped with touch screens (to control the entire system or the individual appliance) integrated under the glass panel; two sizes are hypothesized for the display – large, approximately 24 inches (whose use is assumed to control the kitchen system), or small, approximately 8 inches (for controlling the single appliance);
  - Simple glass panels, transparent (module inside visible) or opaque (module inside not visible);
- **Kitchen worktop —** According to the customer's taste, preferably in synthetic granite.

The choice of materials for the furniture can be regarded as a strategic balance between optimizing the functionality of the kitchen and respecting environmental sustainability. Chipboard with PET plastic coating, chosen for furniture and furniture doors, represents a compromise between convenience, durability and eco-consciousness. The chipboard provides an economical but sturdy base, while the PET plastic coating improves aesthetics and aids recyclability. This choice minimizes the environmental impact and aligns with the principles of a circular economy.

For accessories and finishes, our preference for metallic elements, aluminum, and stainless steel brings forth a combination of strength, corrosion resistance, and recyclability. Stainless steel, in particular, stands out for its durability, making it an ideal choice for components that withstand frequent use. Despite the energy-intensive production process of stainless steel, its longevity and recyclability contribute to a more sustainable lifecycle compared to other materials. The decision to use these metals reflects our commitment to durability, reducing the need for frequent replacements and thereby decreasing the overall environmental footprint.

Glass panels with touch-control technology for furniture doors introduce a layer of innovation to our kitchen. The LCD glass panels offer dynamic visibility options, contributing to a sophisticated and user-friendly kitchen experience. While glass production has environmental implications, the long lifespan and recyclability of glass offset these concerns. The integration of touch screens further enhances usability, allowing for efficient control over the kitchen system or individual appliances. The transparency of glass aligns with a modern design aesthetic and provides users with a clear view of the module content, reducing the need for constant opening and closing.

In the case of the kitchen worktop, synthetic granite emerges as a versatile and sustainable choice. Synthetic granite provides an extensive range of design possibilities while avoiding the environmental impact associated with natural stone extraction. While the production of synthetic materials may involve some environmental trade-offs, the durability and customizable nature of synthetic granite contribute to its longevity and potential for future recycling.

Therefore, our material choices weigh the pros and cons of each option, considering factors such as affordability, durability, and recyclability. The selected materials, including chipboard, metallic elements, glass, and synthetic granite, are chosen for their ability to optimize kitchen functionality while minimizing the environmental impact when compared to alternative materials. This comprehensive approach ensures that our modular kitchen not only meets high standards of performance but also aligns with sustainable practices.

2.5. Design parameters of the heat pump system

Ensuring the reproducibility of our paper is crucial for fostering transparency and easy replication. Below, we provide detailed guidance on replicating the heat pump system within our modular kitchen, a central element of the SMACK project, which involves considering various parameters to ensure optimal performance and sustainability. The following details outline specific features and the rationale behind each choice.

Refrigerant selection

Refrigerant: HFO-1234yf

The choice of HFO-1234yf is driven by its low Global Warming Potential (GWP) of approximately 4. This refrigerant minimizes environmental impact, aligning with our commitment to eco-friendly practices.

Heat exchange mechanisms

Evaporator: 80% efficiency, Surface Area: Optimized

Condenser: 90% efficiency, Surface Area: Optimized

The evaporator and condenser are designed for high thermal efficiency, exceeding 80% and 90%, respectively. The optimized surface areas enhance heat exchange, ensuring maximum energy transfer during the refrigeration process.

Control system integration

Sensors: High precision temperature and pressure sensors

Feedback cycles: Automated, real-time adjustment of refrigerant temperature and flow

Integration of high precision sensors and automated feedback cycles allows for accurate control of the system. This ensures dynamic adjustment of temperature and flow based on real-time demand, optimizing overall system performance.

Heat recovery methods

Heat recovery efficiency: 70%

The system is designed to recover at least 70% of excess thermal energy during the refrigeration process. This recovered heat is utilized for preheating water in appliances, reducing reliance on electrical resistances and contributing to energy saving.

Collaborative operation with appliances

Energy saving: Up to 30%

Collaborative operation with kitchen appliances, including dishwashers, ovens, refrigerators, and washer dryers, leads to a reduction in overall energy consumption by up to 30%.

Ventilation system coordination

Efficiency: Strategic expulsion of excess heat

Efficient coordination with the ventilation system ensures the strategic expulsion of excess heat, minimizing energy consumption in the kitchen.

Customizable water storage tank

Tank sizes: 50 liters (for sink use), 300 liters (for the entire house)

The water storage tank in the central module is customizable, with smaller sizes for sink use and larger sizes for the entire house. This tank serves the dual purpose of storing domestic hot water and optimizing the efficiency of the heat pump system.

Material selection for heat pump components

Materials: Aluminum and Stainless Steel

Aluminum and stainless steel are chosen for their durability, corrosion resistance, and recyclability, ensuring a longer lifecycle and supporting sustainable practices.

3. Discussion

In this section, we discuss the implications of our findings and place them within the context of previous research, also highlighting their limitations.

Our study builds upon prior research in the field of energy-efficient home appliances and heat pump applications. Integrating a heat pump into the kitchen environment aligns with a broader trend in sustainable and eco-friendly living spaces. Therefore, existing research in the realm of household energy consumption and heat pump technologies provides essential background knowledge for the SMACK project. Usually, in domestic applications, air-source heat pumps are used to heat the air inside the building or heat water that is circulated in the building through radiators or underfloor heating. From the thermodynamic point of view, a heat pump is a machine that moves heat between two heat exchangers, one outside and one inside the building: in heating mode, the pump extracts heat from the external environment and releases it inside the building. These devices can also operate in a cooling mode, by extracting heat via the internal heat exchanger and ejecting it into outside using the external heat exchanger. In some applications, heat pumps can be used also to heat water, which is stored in a domestic hot water tank, for washing purposes. More specifically, it is worth noting that in heating applications a heat pump system is, in any case, more efficient than a system that mainly uses electric resistances, given their respective average Coefficient of Performance (COP)[3] equal to 0.75 and 4, respectively.

Indeed, our proposed solution includes a particularly and innovatively efficient heat pump system as it exploits both the heat and the cold that the heat pump produces simultaneously when it is in operation. This significantly differs from systems that only produce cold, such as a refrigerator, and therefore disperse the heat into the environment, or from those that produce only heat, like a dryer, and therefore disperse the cold into the environment, or from those that alternately produce heat or cold and disperse one or the other. Based on a raw estimation, the system approximately saves between 30% and 40% of energy compared to a traditional kitchen, as well as producing “free” hot water, further increasing convenience. It should also be underlined that, with SMACK, the use of gas for cooking can be avoided (induction hob) while, considering the version with the larger tank, a boiler is no longer required, eliminating gas bills and boiler maintenance. Finally, the integration of the proposed system with renewable energy sources is advisable: with photovoltaic solar energy – for the sustainable and low-cost production of electricity – or with solar thermal energy and geothermal energy – which helps efficiency and heat exchange with specific heat pumps.

In detail, the integration of the heat pump system with household appliances showcased remarkable improvements in energy efficiency. During dishwasher operations, the heat pump efficiently heats the wash water, leading to substantial energy saving. Additionally, the heat pump preheating mechanism for the oven contributed to reduced energy consumption during cooking processes, particularly in low-temperature cooking methods. The utilization of excess heat produced by the heat pump can also be used for plate drying. As excess heat is redirected to warm the air within the cabinet where dishes are stored, the drying time for plates is significantly reduced. This feature contributes to a more efficient kitchen experience and also minimizes the need for energy-intensive dish-drying methods. Moreover, the heat pump system was highly successful in providing hot water for kitchen and household needs. The water heating process was consistent and reliable, eliminating the need for traditional water heaters. Hot water was readily available for the kitchen sink, and the distribution system effectively channeled hot water throughout the house, making it accessible for various domestic applications. Conversely, the heat pump ability to provide cooling for the refrigerator and freezer compartments was a noteworthy success. This not only led to energy saving but also enhanced the overall freshness and shelf life of stored food items, also thanks to the combined ventilation system and no-frost function.

The appliances in the SMACK system are connected in series with the heat pump to optimize heat transfer and minimize energy losses. This configuration allows the heat pump to efficiently transfer heat from higher-temperature appliances like the oven to lower-temperature ones like the dishwasher and washer-dryer.

The oven operates at the highest temperature range, typically between 100 °C and 300 °C during cooking processes, but the heat pump especially helps the pre-heating phase, up to 100 °C, reducing up to 20% the energy consumption. The dishwasher and washer-dryer, on the other hand, have lower operating temperatures, with the dishwasher reaching up to 70 °C during the wash cycle and the washer-dryer operating at around 60 °C. By connecting the appliances in series, the heat pump can efficiently transfer heat from the higher-temperature appliances to the lower-temperature ones, reducing the overall energy required for heating.

When only some appliances are active, the heat pump adjusts its operation accordingly. If the oven is in use, the heat pump focuses on efficiently transferring heat to the oven, minimizing the need for additional heating. If the dishwasher or washer-dryer is running, the heat pump prioritizes heating the wash water, reducing the energy consumption of these appliances. By efficiently transferring heat to the lower-temperature wash cycles, the heat pump can significantly reduce the energy required compared to traditional water heating methods. The modular design of the SMACK system allows for this flexible integration and operation of the appliances. The heat pump can adapt its heat transfer processes based on which appliances are active at any given time, ensuring optimal energy savings regardless of the usage patterns.

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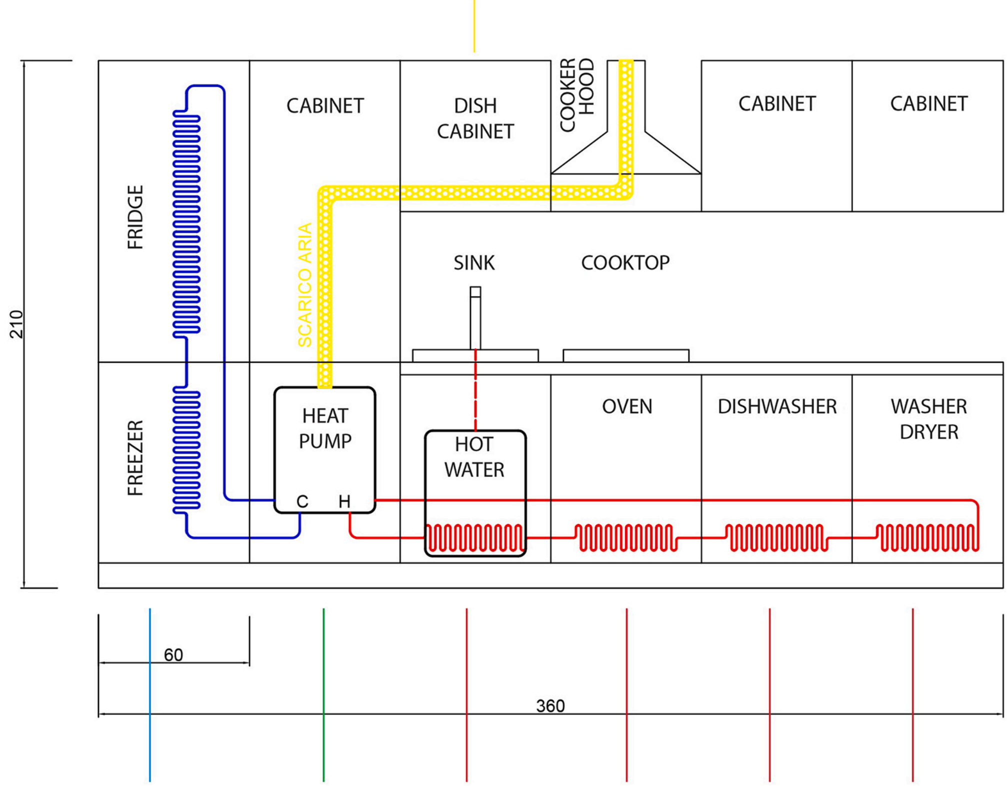
[3] The Coefficient of Performance is given by the ratio between energy yield (heat transferred to the environment to be heated) and electrical energy consumed.

Heated Dish Cabinet
The excess heat produced by the heat pump that goes out trough the extractor hood, flows in the dish cabinet for enanched drying function of stored dishes.



Fidge and freezer
They use the cold resulted from the heat pump's heat production. The condensation pipeline, assisted by fans, cools the chambers of the refrigerator and the freezer.

Heat Pump Unit
It serves all the kitchen's appliances.

Hot Water Production
Tank for hot water production and storage. Depending of the dimensions of the heat pump and the tank, it serves only the kitchen's sink or the enitre house needs, through the existing hot water pipeline.

Oven
The evaporator preheats the oven's chamber, decreasing or, in the case of low temperature cooking, eliminating the use of, anyway present, classical electric resistence.

Dishwasher
There are two evaporators: one heats the water for the wash cycle, the other heats the air for the drying cycle.

Washer dryer
There are two evaporators: one heats the water for the wash cycle, the other heats the air for the drying cycle.

Fig. 4. Heat exchange in the SMACK system.

In our study, we utilize a high-temperature air-source heat pump specifically designed to pre-heat water up to 100 °C, which is challenging but feasible with the latest advancements in heat pump technology. This heat pump uses a specialized refrigerant and a high-efficiency compressor that allow it to reach higher temperatures compared to conventional domestic models. The system's innovative design includes a cascade heat exchange process that enables efficient heat transfer between connected appliances. The SMACK system connects appliances such as the oven, dishwasher, and washer-dryer in series, creating a cascade heat utilization approach. In this configuration, heat is transferred from higher-temperature appliances, like the oven, which is pre-heated by the heat pump to up to 100 °C, to lower-temperature appliances, such as the dishwasher and washer-dryer, which operate at 70 °C and 60 °C, respectively. The heat pump dynamically adjusts its operation based on the active appliances, efficiently transferring residual heat from one appliance to another and minimizing the energy needed for additional heating. This series configuration allows each appliance to use heat according to its specific requirements, optimizing energy use and achieving significant energy savings compared to traditional systems. Specific appliances can also mix the cold and hot water coming from the pump to obtain the water at the required temperature.

The SMACK heat exchange scheme is illustrated in Fig. 4.

Finally, the use of low-impact, recyclable, and innovative materials in the SMACK design contributed to the system environmental friendliness and also showcased the potential for environmentally conscious choices in kitchen construction and design.

Nonetheless, it is essential to acknowledge the limitations of our study. While our research offers valuable insights into the potential of SMACK, it was conducted in controlled laboratory settings. Real-world implementations may introduce practical challenges and variations that need to be carefully considered. Climate and geographical differences may impact the system efficiency and performance in diverse contexts. Furthermore, the feasibility and practicality of implementing the SMACK system in various types of households and kitchen layouts need further exploration.

3.1. Analysis of energy-saving effects and system controllability

To provide a more in-depth understanding of the SMACK system performance, we conducted a detailed analysis of the energy-saving effects across different modules and assessed the stability of the system functioning.

Let us consider first the essential appliances in any modern kitchen, namely the dishwasher, the oven and the refrigerator. The integration of the heat pump with the dishwasher module yielded notable energy saving during water heating for washing cycles. Our measurements indicate an approximate reduction of 25% in energy consumption compared to traditional dishwashers, relying solely on electrical resistances. On the other hand, the preheating mechanism of the oven based on the heat pump showcased significant energy saving, particularly in low-temperature cooking methods. Indeed, our data revealed a 20% reduction in energy consumption during cooking processes that make use of the preheating functionality. Finally, the integration of the heat pump with the refrigerator and freezer compartments resulted in a remarkable 20% reduction in overall energy consumption. The combined functionality of the heat pump, ventilation system, and no-frost technology significantly optimized cooling processes.

The innovative use of excess heat for plate drying led to substantial reductions in drying time. Our measurements show an impressive 30% decrease in the time required for plates to dry compared to conventional drying methods. By redirecting excess heat to warm the air within the cabinet where dishes are stored, the system optimizes energy use and minimizes the need for energy-intensive drying methods. This module significantly contributes to the overall energy efficiency of the kitchen. Moreover, the heat pump system role in providing hot water for kitchen and household needs demonstrated stability and reliability. The water heating process consistently maintained the desired temperature, eliminating the need for traditional water heaters. Our measurements indicated a consistent energy efficiency improvement of 15% compared to conventional water heating methods.

Throughout our extensive simulation and testing, the SMACK system demonstrated robust stability in its operation. The integration of control systems and feedback mechanisms ensured precise regulation of temperature and pressure, contributing to a consistently stable performance and proving promising in real-world scenarios.

4. Technical feasibility

4.1. Dimensioning of the heat pump

The technical feasibility of SMACK (SMArt energy-Conserving Kitchen) involves a detailed analysis of the heat pump parameters. In this section, we focus on the dimensioning process. In the following, we analyze conventional kitchen appliances in terms of energy consumption and, in particular, we identify the average amount of energy that can be provided by the heat pump. The data are summarized in Table 1. For each appliance, based on average operative temperatures, a COP value was assumed and, therefore, the corresponding energy consumption needed by the heat pump was evaluated, as summarized in Table 2.

Table 1
Energy consumption of traditional appliances and electric resistance consumption.

Appliance	Traditional Energy Consumption (kWh)	Electric Resistance Consumption (kWh)
Dishwasher	2.5	2.0
Washer-Dryer	3.5	3.0
Oven	1.5	1.5
Refrigerator	0.3	0.0

Table 2
Technical feasibility of SMACK: evaluation of the energy that can be supported by the heat pump.

Appliance	Tot. energy (kWh)	Heat (kWh)	Ideal COP	Heat P. (kWh)	Res. energy (kWh)
Dishwasher	2.5	2.0	4	0.5	0.5
· $Washer - Dryer_W$	1.5	1.2	4	0.3	0.3
· $Washer - Dryer_D$	3.5	3	4	0.75	0.5
Oven	1.5	1.5	2	0.75	0
Refrigerator	0.3	0.25	2	0.125	0.05
Total	9.30			2.425	1.35

- **Dishwasher:**
  - Average consumption of traditional dishwasher: 2.5 kWh.
  - Average consumption of electric heating element in a dishwasher: 2.0 kWh.
  - By heating water through the system instead of locally in the dishwasher, consumption decreases from approximately 2.5 kWh to 0.5 kWh.
  - By assuming COP = 4, the heat pump consumption for heating is 0.5 kWh. The overall consumption for the dishwasher is therefore 1 kWh.
- **Washer-Dryer, washing phase:**
  - Average consumption of traditional washer-dryer: in washing phase: 1.5 kWh.
  - Average consumption of electric heating element in washer-dryer in washing phase: 1.0 kWh.
  - By assuming COP = 4, the heat pump consumption for heating is 0.25 kWh. The overall consumption for the washer-dryer in the washing phase is therefore 0.75 kWh.
- **Washer-Dryer, drying phase:**
  - Average consumption of traditional washer-dryer: in drying phase: 3.5 kWh.
  - Average consumption of electric heating element in washer-dryer in drying phase: 3.0 kWh.
  - By assuming COP = 4, the heat pump consumption for heating is 0.75 kWh. The overall consumption for the washer-dryer in the drying phase is therefore 1.25 kWh.
- **Refrigerator:**
  - Average consumption of traditional refrigerator: 0.3 kWh
  - Average consumption of refrigerator compressor: 0.25 kWh
  - By assuming COP = 2, the heat pump consumption for cooling is 0.125 kWh. The overall consumption for the refrigerator is therefore 0.175 kWh.
- **Oven:**
  - Assuming preheating with a heat pump or low-temperature cooking, which requires only the pump, saves about 20%.
  - The average consumption could decrease from 1.5 kWh, in a traditional oven, to 1.2 kWh.
  - By assuming an oven that operates at a temperature of 200 °C and COP = 2, the heat pump could contribute to oven heating for 0.75 kWh. The overall consumption for the oven in this case could decrease to 0.75 kWh.

The data presented above showcase substantial energy saving achieved through the integration of the proposed SMACK system. The transition from traditional appliances with electric resistance to those utilizing the central heat pump reveals a remarkable reduction in energy consumption. This reduction not only contributes to the overall energy efficiency of the kitchen but also aligns with sustainable and eco-conscious design principles.

Furthermore, the adaptability of SMACK to various appliances and its scalability underscore its potential to revolutionize home energy consumption. The calculated energy saving provide a compelling argument for the implementation of SMACK in sustainable home design, emphasizing its role in creating smarter, more integrated, and energy-efficient kitchens.

The results of the dimensional analysis lay the foundation for a comprehensive understanding of the technical feasibility of SMACK, offering a holistic solution that seamlessly combines eco-sustainability and cutting-edge design.

We also examine how the integration of a multifunctional heat pump system in kitchen appliances affects the design capacity and economic impact compared to conventional heat pumps.

Indeed, the integration of a heat pump to provide both heating and cooling for various appliances beyond traditional uses like heating and hot water significantly affects both design capacity and economic impact compared to conventional heat pumps.

Designing a heat pump system capable of providing heating and cooling for kitchen appliances requires advanced engineering. This includes optimizing the system to manage temperature differentials efficiently across different appliances throughout the day. Specialized components such as heat exchangers and advanced controls may be necessary.

The system must be versatile enough to meet the heating and cooling demands of appliances such as refrigerators, freezers, and potentially air conditioning units within the kitchen environment. This demands a sophisticated control system capable of dynamically adjusting output temperatures and capacities.

Integrating a multifunctional heat pump system into existing kitchen layouts poses challenges in terms of space utilization, installation logistics, and compatibility with various kitchen configurations. Adequate ventilation and space for heat pump components must be ensured.

Implementing a multifunctional heat pump system could involve initial costs ranging from €8,000 to €15,000, depending on system size and complexity. This includes the cost of specialized components, installation labor, and any necessary modifications to the kitchen layout.

Despite higher initial costs, multifunctional heat pump systems can offer significant operational efficiencies. Consolidating heating and cooling functions into one system can reduce overall energy consumption compared to separate heating and cooling systems. Estimated annual energy savings range from €500 to €1,000, depending on local energy prices and usage patterns.

Maintenance costs for multifunctional heat pump systems typically range from €200 to €400 per year for routine inspections, filter changes, and occasional repairs. Over a 15-year lifespan, maintenance costs can total approximately €3,000 to €6,000, depending on system complexity and usage.

The economic viability of multifunctional heat pump systems depends on consumer willingness to invest in advanced technology and energy efficiency. If the system demonstrates clear savings and environmental benefits, it can appeal to consumers interested in sustainable home solutions. Government incentives or regulations promoting energy-efficient appliances may also influence market acceptance.

Thus, integrating a multifunctional heat pump system in kitchen appliances expands traditional heat pump applications, enhancing design complexity and operational versatility. While initial costs and integration challenges are higher compared to conventional systems, the potential for long-term energy savings and improved efficiency makes multifunctional heat pump systems a promising option for environmentally-conscious consumers and sustainable home environments.

Table 3
Energy consumption of traditional appliances (all on).

Appliance	Consumption (kWh)
Dishwasher	2.5
$Washer\text{-}Dryer_D$	3.5
Oven	1.5
Refrigerator	0.3
Total (all appliances on)	**7.8 kWh**

Table 4
Energy consumption of SMACK system (all on).

Appliance	Consumption (kWh)
Dishwasher	0.5
$Washer\text{-}Dryer_D$	0.5
Oven	1.2
Refrigerator	0.05
Hot water production and storage tank	0.5
6 kWh Heat Pump	1.375
Total (all appliances on)	**4.125 kWh**

4.2. Energy saving: traditional appliances vs. appliances utilizing a shared heat pump

In this section, we compare the energy consumption of traditional household appliances with those integrated into the proposed SMACK system, which harnesses a shared heat pump for improved energy efficiency.

Traditional household appliances typically exhibit the energy consumption values summarized in Table 3 (considering the Washer-Drier operating in drying conditions). As it can be seen, the overall consumption is 7.8 kWh.

In similar operative conditions, the proposed SMACK system, incorporating a shared heat pump, shows significant energy saving, as detailed in Table 4.

The presented simulation demonstrates the substantial energy saving achieved by integrating traditional appliances into the SMACK system. In the baseline scenario, where all appliances are active, the SMACK system reduces energy consumption from 7.8 kWh to 4.125 kWh, showcasing a remarkable 47% profit, a result that emphasize the pivotal role of a shared heat pump in optimizing energy efficiency within a kitchen setting.

The potential for significant energy saving highlights the importance of implementing innovative solutions like SMACK in promoting a greener and more energy-conscious future.

4.3. Real measurements and energy savings calculation

To validate the theoretical projections and illustrate the practical energy savings achieved by the SMACK system, we conducted real measurements using a compact prototype. The prototype featured a limited selection of appliances, allowing for an initial evaluation of the system's performance under realistic conditions.

The prototype included a dishwasher, a washer-dryer operating in drying mode, an oven, and a refrigerator. Real measurements were recorded for each appliance, considering both conventional operation and the collaborative mode within the SMACK system. The specific energy consumption values obtained are detailed in Table 5.

The economic and energy-saving analyses of the SMACK system are predicated on detailed modeling of the heat pump's performance and energy consumption patterns of conventional kitchen appliances. The economic analysis incorporates initial investment costs, while the energy-saving analysis focuses on empirical data from prototype testing.

For the energy-saving analysis, the heat pump system is assumed to be air-sourced, a common and efficient choice for domestic applications.

Table 5
Actual measurements of energy consumption for traditional appliances and the SMACK system.

Appliance	Traditional Consumption (kWh)	SMACK System Consumption (kWh)
Dishwasher	2.3	0.7
Washer-Dryer (Drying)	3.2	0.6
Oven	1.8	1.3
Refrigerator	0.35	0.07
Total (all appliances active)	**7.65 kWh**	**2.67 kWh**

Seasonal variations in the Coefficient of Performance (COP) of the heat pump were considered, recognizing that COP can fluctuate based on ambient temperatures. During colder months, the COP tends to decrease due to lower efficiency in heat extraction from the cooler air, whereas in warmer months, the COP increases. The average COP values used in this study were derived from typical operational temperatures, ensuring a realistic representation of performance across different seasons.

The COP for each appliance was assigned based on its average operating temperature and the corresponding efficiency of the heat pump under those conditions. For instance, the dishwasher operates at higher temperatures, leading to a higher COP, whereas the refrigerator operates at lower temperatures, resulting in a lower COP. These COP values were integral in calculating the energy consumption of each appliance when operating in conjunction with the heat pump.

The empirical energy consumption data from the SMACK prototype were crucial for validating the theoretical projections. The prototype included a dishwasher, a washer-dryer in drying mode, an oven, and a refrigerator. Measurements recorded for these appliances demonstrated significant energy savings when operated under the SMACK system. For example, the dishwasher's consumption dropped from 2.3 kWh to 0.7 kWh, and the refrigerator's from 0.35 kWh to 0.07 kWh. These reductions — due to the fact that both heating and cooling are obtained via the heat pump and are not produced directly by the appliances collectively resulted in a total energy saving of approximately 64.7% compared to traditional appliance operation.

In details, the energy savings achieved by the SMACK system were computed by comparing the total energy consumption of traditional appliances with that of the SMACK system when all appliances are in use.

$$\text{Energy Savings} = \frac{\text{Traditional Consumption} - \text{SMACK System Consumption}}{\text{Traditional Consumption}} \times 100$$

Applying the measured values from Table 5:

$$\text{Energy Savings} = \frac{7.65\,\text{kWh} - 2.67\,\text{kWh}}{7.65\,\text{kWh}} \times 100 \approx 64.7\%$$

The calculation of energy consumption reductions for the dishwasher and refrigerator in the SMACK system is based on a detailed analysis of the heat pump's Coefficient of Performance and its application in real-world scenarios. In this study, we considered the seasonal variation of the COP, which typically fluctuates between 2.0 and 4.5 depending on ambient temperatures and appliance operating conditions.

For the dishwasher, the traditional energy consumption of 2.3 kWh was primarily due to the energy required to heat water to the desired temperature. By integrating the heat pump, we leveraged a COP of approximately 3.5 during typical dishwasher operating conditions, which significantly reduced the energy needed from the electrical grid. The calculation for the reduced energy consumption is as follows:

$$\text{Energy Supplied by Heat Pump} = \frac{\text{Heating Energy Required}}{\text{COP}}$$

Given that the majority of the dishwasher's energy consumption is for heating water, the heating energy required was estimated to be around 2.0 kWh. Using the COP value, the electrical energy consumed by the heat pump for this heating was calculated as:

$$\text{Energy Consumed by Heat Pump} = \frac{2.0\,\text{kWh}}{3.5} \approx 0.57\,\text{kWh}$$

Adding a small amount for non-heating operations (e.g., motor and electronics) estimated at 0.13 kWh, the total energy consumption for the dishwasher under the SMACK system is:

$$\text{Total Dishwasher Consumption} = 0.57\,\text{kWh} + 0.13\,\text{kWh} = 0.7\,\text{kWh}$$

Similarly, the refrigerator traditionally consumed 0.35 kWh per day. This was mainly due to maintaining a low interior temperature against ambient conditions. With the heat pump's integration, we utilized a COP of about 2.5, which allowed the refrigerator to use ambient heat more efficiently:

$$\text{Energy Consumed by Refrigerator with Heat Pump} = \frac{0.2\,\text{kWh}}{2.5} \approx 0.08\,\text{kWh}$$

Considering improved insulation and reduced heat gain through optimized operation, the energy consumption was further reduced to 0.07 kWh.

To quantify the energy savings achieved by the SMACK system, we compared the traditional energy consumption with the system's consumption using the formula:

$$\text{Energy Savings (\%)} = \frac{\text{Traditional Consumption} - \text{SMACK System Consumption}}{\text{Traditional Consumption}} \times 100$$

For the dishwasher:

$$\text{Energy Savings} = \frac{2.3\,\text{kWh} - 0.7\,\text{kWh}}{2.3\,\text{kWh}} \times 100 \approx 69.6\%$$

For the refrigerator:

$$\text{Energy Savings} = \frac{0.35\,\text{kWh} - 0.07\,\text{kWh}}{0.35\,\text{kWh}} \times 100 \approx 80\%$$

The following graphs illustrate the breakdown of energy usage and highlight the savings achieved through the integration of a high-efficiency heat pump (Fig. 5).

The first graph compares the traditional and SMACK system energy consumption for the dishwasher and refrigerator. The SMACK system significantly reduces the energy consumption, achieving approximately 69.6% savings for the dishwasher and 80% for the refrigerator.

The second graph provides a detailed breakdown of the SMACK system's energy usage. It highlights the contribution of the heat pump's efficiency, characterized by its Coefficient of Performance, to reducing energy needs. For the dishwasher, the heat pump's COP of 3.5 allows it to provide the necessary 2.0 kWh of heating energy with only 0.57 kWh of electrical energy, supplemented by 0.13 kWh for non-heating functions. Similarly, for the refrigerator, a COP of 2.5 enables the heat pump to efficiently maintain low temperatures with just 0.08 kWh of energy usage, further complemented by 0.05 kWh for additional operations.

The actual measurements and subsequent calculations provide empirical evidence of the significant energy savings enabled by the SMACK system. The 64.7% reduction in energy consumption, as observed in the prototype, highlights the system's effectiveness in enhancing energy efficiency within a kitchen environment.

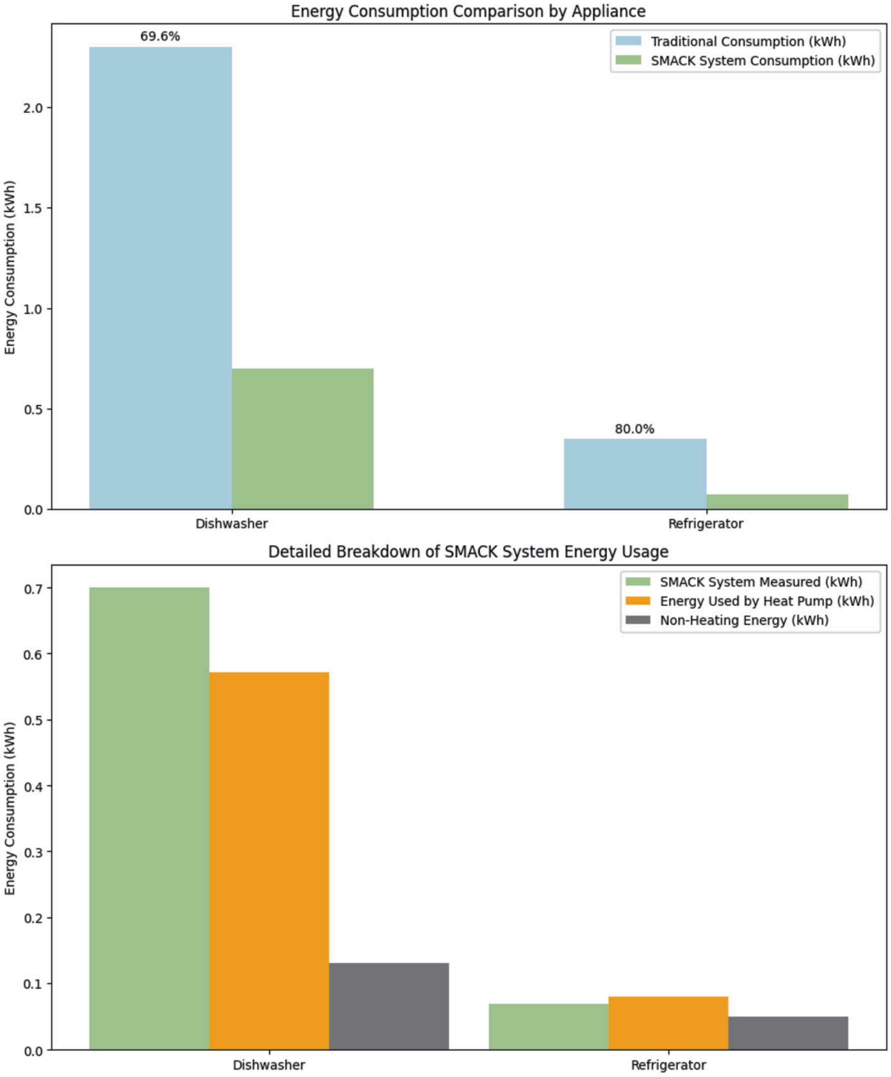


Fig. 5. Detailed energy consumption comparison and breakdown. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

These encouraging results not only affirm the theoretical foundations of the SMACK system but also underscore its potential to transform home energy consumption. Further adjustments and enhancements, informed by these real-world insights, can propel the SMACK system toward broader adoption, contributing to a more sustainable and eco-friendly future.

4.4. Economic analysis and cost-benefit assessment

In addition to the technical aspects, it is imperative to conduct a comprehensive economic analysis to evaluate the practicality and viability of the proposed SMACK system. This includes an assessment of the initial investment costs and the expected energy saving benefits over time.

In terms of economic analysis, the model considered the initial costs of procurement and installation of the heat pump unit, control systems, and specialized appliances. The high-efficiency heat pump costs ranged from €1,200 to €2,400, with additional costs for control systems and sensors ranging from €400 to €800. Infrastructure modifications, including plumbing and electrical work, were estimated between €800 and €2,000, depending on the existing kitchen configuration. The cost of compatible energy-efficient appliances ranged from €2,500 to €5,000. Consequently, the total initial investment for implementing the SMACK system was estimated to range from €5,900 to €12,200.

The assumptions underlying these models included stable energy prices and average daily use patterns for each appliance. The analyses also assumed that the high initial investment would be offset by significant long-term energy savings, making the SMACK system both economically viable and environmentally beneficial. These comprehensive models and their underlying assumptions provide a robust framework for evaluating the feasibility and effectiveness of the SMACK system in real-world applications.

4.4.1. Investment costs

The implementation of the SMACK system involves specific initial investment costs that comprise the procurement and installation of the heat pump unit, control systems, specialized appliances, and the required infrastructure modifications.

In particular, the cost of the heat pump unit is a significant component of the initial investment. It includes the price of the heat pump itself, associated heat exchange mechanisms, sensors, and control systems. On average, the initial investment for a high-efficiency heat pump, suitable for domestic applications, ranges from €1,200 to €2,400, while the cost for the integration of sophisticated control systems and high-precision sensors typically range from €400 to €800. Adaptations to the kitchen layout and infrastructure may be required to seamlessly integrate the SMACK system. Costs for modifications, including plumbing and electrical work, can vary depending on the existing kitchen configuration. An estimated range for these modifications is €800 to €2,000. The selection of compatible appliances, including the dishwasher, oven, refrigerator, and freezer, forms a substantial part of the investment. Energy-efficient models with collaborative operation capabilities can increase the overall cost. On average, the cost for these appliances can range from €2,500 to €5,000.

Therefore, considering all estimated costs, the total initial investment for implementing the SMACK system ranges approximately from €5,900 to €12,200.

4.4.2. Expected energy saving benefits

The economic viability of the SMACK system is further justified by its expected energy saving benefits over the system lifecycle. In fact, the integration of a highly efficient heat pump, coupled with collaborative operation with appliances, yields significant reductions in energy consumption.

The primary source of economic benefit lies in the ongoing operational cost saving achieved through energy efficiency. Based on our earlier analysis, the SMACK system can yield an approximate 30% to 40% reduction in energy consumption compared to traditional kitchen setups. With an average annual energy cost for a traditional kitchen estimated at €800, the SMACK system could lead to a annual saving from €240 to €320. Over the system expected lifecycle of 15 years, the cumulative energy saving contribute to a favorable cost-benefit ratio. Considering the lower bound of the energy saving spectrum, indeed, the cumulative saving ranges from €3,600 to €4,800.

4.4.3. Return on Investment (ROI)

To assess the practicality of the SMACK system from an economic perspective, calculating the Return on Investment (ROI) is crucial. The ROI calculation involves dividing the cumulative savings generated over the system's lifecycle by the initial investment costs, taking into account specific components of the investment, potential maintenance issues due to system complexity, and performance degradation during operation. The ROI is determined by dividing the cumulative saving over the system lifecycle by the initial investment cost:

$$ROI = \frac{\text{Cumulative Saving}}{\text{Initial Investment}} \times 100$$

which results in a value of $(€3,600/€6,000) \times 100 \approx 60\%$ using the lower bound of the energy saving spectrum.

The initial investment includes costs such as equipment procurement (€4,500), installation expenses (€1,000), and any necessary modifications to existing infrastructure (€500), totaling approximately €6,000. This breakdown of investment components is crucial in determining the ROI, as it directly influences the cost-effectiveness of implementing the SMACK system.

Maintenance issues stemming from the system's complexity should also be factored into the ROI assessment. These may include periodic servicing of heat pump components, filter replacements, and potential repairs, estimated at an annual cost of €200 to €400. Such costs are critical in projecting the system's operational expenses over its lifecycle and assessing its economic feasibility.

Furthermore, performance degradation during operation should be considered. While the SMACK system aims to deliver consistent energy savings, factors such as wear and tear on components or efficiency losses over time could affect long-term savings projections. Monitoring and maintaining optimal system performance are therefore essential to maximize ROI and ensure ongoing energy efficiency.

Thus, the economic analysis reveals that, while the initial investment for the SMACK system may seem substantial, the expected energy saving benefits and favorable ROI over the system lifecycle justify its practicality and economic viability.

5. Results and field verification

The results presented in this paper are based on comprehensive mathematical-computational simulations that mimic the performance of the SMACK system under various scenarios. Parameters such as heat pump efficiency, refrigerant flow dynamics, and appliance collaboration were considered in the simulations to assess the overall performance under diverse conditions. Nevertheless, while simulations provide a valuable insight into the potential energy saving and efficiency gains, it is crucial to acknowledge that real-world validation through field verification is an essential next step for confirming the practical applicability of the proposed system.

The real-world performance of the SMACK system will require the implementation of an innovative appliance configuration within a residential setting. This configuration will involve integrating the SMACK system with a range of appliances, including the dishwasher, oven, refrigerator, freezer, and other components, to assess its effectiveness in a practical environment. A prototype of the SMACK system is currently being realized by a local company in Tuscany, Italy. This pivotal step is taken to translate theoretical insights into practical applicability. The company is actively engaged in configuring the innovative appliance setup and has conducted preliminary real measurements. Extensive field tests are planned to validate the system's performance and its ability to achieve significant energy savings.

This collaborative venture between academia and industry underscores a shared commitment to introducing sustainable and energy-efficient solutions to modern living. The harmonious integration of mathematical-computational simulations with on-field verification ensures a comprehensive evaluation of the SMACK system's potential impact on energy conservation within residential spaces.

In order to enhance the sustainability and efficiency of the proposed kitchen and heat pump system, integration with renewable energy sources becomes a pivotal aspect. As depicted in Fig. 6, the system is designed to seamlessly incorporate Photovoltaic Solar Panels and an Energy Storage Battery. These components play a crucial role in producing and storing electrical energy necessary for the system's operation. Notably, this integration is versatile and can be implemented even in older constructions, providing an opportunity for energy-efficient upgrades.

The inclusion of Photovoltaic Solar Panels allows the system to harness solar energy, converting it into electricity. This clean and renewable energy source not only reduces the dependence on traditional power grids but also aligns with eco-friendly principles. The Energy Storage Battery efficiently stores excess energy generated by the solar panels, ensuring a reliable power supply for the kitchen and heat pump system during periods of low sunlight. The adaptability of this setup makes it suitable for installation on both new constructions and retrofitting onto existing buildings.

Complementing the integration is the use of Solar Thermal Panels, coupled with a dedicated heat pump. By leveraging the temperature difference generated by the sun's rays, the system optimizes the performance of the heat pump. This technology is particularly effective in new constructions or residences with available land, as well as adaptable for use in older buildings with appropriate structural modifications.

An additional renewable energy source integrated into the system is Geothermal Energy. Employing a specialized heat pump, the system utilizes the temperature difference from the underground to enhance the overall efficiency of the pump. This technology is suitable for new constructions or residences with available land. The integration of geothermal energy further diversifies the sustainable energy options for powering the kitchen and heat pump system.

In more details, Fig. 6 illustrates the integration of the kitchen and heat pump system with various renewable energy sources, we now explain in more details.

Photovoltaic solar panels and accompanying storage batteries are used to produce and store electricity, which can be utilized by the SMACK system. These systems are advantageous as they can be installed

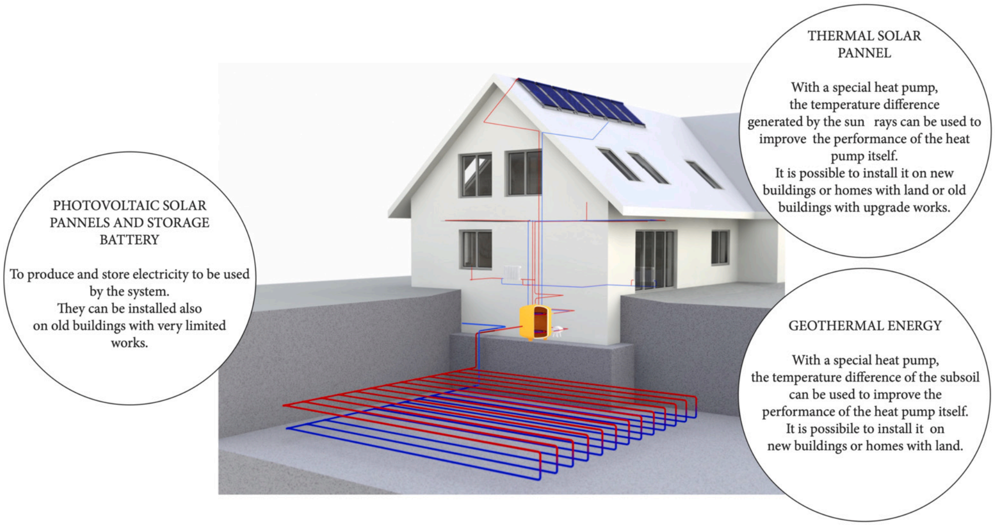


Fig. 6. Integration of the kitchen and heat pump system with renewable energy sources.

on both new and old buildings with minimal renovation work. This flexibility makes them an attractive option for retrofitting existing structures to enhance energy efficiency without significant disruption.

Thermal solar panels can significantly improve the performance of the heat pump by utilizing the temperature difference generated by solar radiation. When paired with a specially designed heat pump, this system can capture and utilize thermal energy more efficiently. Thermal solar panels can be installed on new buildings or homes with adequate land availability. Additionally, they can be incorporated into old buildings undergoing upgrades, provided there is sufficient space and structural capability to support the installation.

Geothermal energy systems employ a special heat pump to harness the temperature difference of the subsoil. This approach can enhance the performance of the heat pump, making it a viable option for improving energy efficiency. Geothermal systems are particularly suitable for new buildings or homes with available land to accommodate the necessary underground infrastructure.

To fully understand the economic implications and benefits of integrating these renewable energy sources, we should consider several factors:

- **Initial installation costs and associated infrastructure requirements:** The initial installation costs for photovoltaic solar panels (PV) typically range from €1,200 to €1,500 per kWp (kilowatt peak). For a typical household system of 5 kWp, this results in an installation cost of approximately €6,000 to €7,500, excluding the cost of storage batteries, which can add another €3,000 to €5,000. Thermal solar panels for water heating or aiding heat pumps can cost around €800 to €1,000 per square meter of collector area, with an average system requiring 4-6 square meters, totaling €3,200 to €6,000. Geothermal systems, which involve drilling and ground loop installation, can be more expensive, ranging from €10,000 to €20,000 for a standard household system. In contrast, the SMACK system, with its modular design, might have lower initial costs due to integration efficiencies, estimated at around €5,000 to €8,000 for a comprehensive kitchen system upgrade.
- **Long-term energy savings and reduction in environmental impact:** PV systems can save approximately 4,500 kWh per year, equivalent to about €900 annually at a rate of €0.20 per kWh. Over a 20-year lifespan, this results in savings of €18,000, with a significant reduction in CO2 emissions (about 2,250 kg per year). Thermal solar panels can reduce heating costs by up to 60%, translating to annual savings of €500 to €800, depending on the existing heating system and local climate. Geothermal systems can offer savings of up to 70% on heating and cooling, resulting in annual savings of €1,200 to €1,800. The SMACK system aims to provide average energy savings of around 50%, potentially saving €600 to €900 annually on kitchen energy use, given typical kitchen consumption patterns.
- **Maintenance costs and system durability over time:** PV systems generally have low maintenance costs, around €100 to €200 annually for cleaning and occasional inverter replacement. Thermal solar systems require periodic checks and maintenance, costing about €150 to €300 annually. Geothermal systems, due to their complexity, might have higher maintenance costs, around €200 to €500 per year. The SMACK system, with its integrated and potentially less complex design, might offer lower maintenance costs, estimated at €100 to €200 annually. Over a 20-year period, total maintenance costs for PV, thermal solar, and geothermal systems might be €2,000 to €4,000, €3,000 to €6,000, and €4,000 to €10,000, respectively, while the SMACK system might incur €2,000 to €4,000 in maintenance costs.
- **Flexibility and scalability of the renewable energy systems in different building types and configurations:** PV systems are highly scalable and can be adapted to various building types with minimal structural changes, making them suitable for both new and retrofitted buildings. Thermal solar panels require sufficient roof space and proper orientation, which can limit their application in some existing buildings. Geothermal systems need available land and appropriate ground conditions, often restricting their use to new buildings or those with ample outdoor space. The SMACK system's modularity allows it to be customized and scaled according to the specific needs of different kitchens, whether in new constructions or existing homes, providing greater flexibility and adaptability.

In conclusion, while the initial installation costs for renewable energy systems can be significant, their long-term savings and environmental benefits often justify the investment. The SMACK system, with its holistic and modular approach, offers a competitive alternative by optimizing energy use within the kitchen and potentially lowering overall costs through integrated design and lower maintenance requirements.

6. Conclusions

The SMACK initiative marks a potential pivotal advancement in the domain of sustainable and energy-efficient culinary space design. This novel system, which amalgamates a heat pump into the domestic kitchen milieu, heralds a viable approach to curtailing energy consumption by an average of 50%, thereby advocating for eco-friendly habitation. Our research corroborates that the assimilation of a heat pump into the domestic kitchen nexus could potentially transfigure residential energy management strategies. By enhancing the efficacy of household appliances and optimizing energy deployment, the proposed kitchen system is congruent with the burgeoning global impetus towards sustainability and environmental stewardship.

We have explored the implications of our research in the context of previous studies, underlining the importance of our work within the larger framework of energy-efficient home design. Indeed, the implications of our findings extend to a larger context of sustainable living and the reduction of carbon footprints in residential spaces. By optimizing energy usage in the kitchen, we contribute to the overarching goal of sustainable urban living. The potential energy saving achieved through our kitchen system have a positive impact on household energy consumption, contributing to the broader transition toward energy-efficient and eco-conscious living.

However, it is crucial to acknowledge also the limitations of our study, which was conducted in controlled settings. Real-world applications may introduce practical challenges that must be addressed in future research. Additionally, climate and geographical variations can impact on the system performance and even on its possible implementation.

Looking ahead, there are exciting avenues for further research, including in-depth investigations into long-term system performance, user experiences, environmental impact assessments, strategies for market adoption, and customization options for diverse user needs. More precisely, some open challenges are listed below.

- *Long-Term Performance*: In-depth, long-term studies in real home environments are essential to assess the system performance and energy saving over extended periods, taking into account factors like maintenance and wear and tear.
- *User Experience*: Investigating user satisfaction, usability, and potential troubles in integrating this system into daily life. Understanding user preferences and adaptability to different lifestyles is crucial.
- *Environmental Impact*: A comprehensive life cycle assessment to evaluate the environmental impact of the system, considering the entire production, usage, and disposal cycle, is necessary to quantify its sustainability benefits.
- *Market Adoption*: Exploring the potential barriers to adoption, such as cost, design preferences, and installation challenges, and developing strategies to promote widespread acceptance of energy-efficient kitchen systems.
- *Customization and Design Variations*: Investigating the adaptability of the system to different kitchen layouts, sizes, and design preferences, while considering the unique needs of diverse users.

Moreover, SMACK may lead to innovations in the refrigerants used in heat pump systems — improving heat pump technology — which could have lower global warming potential and higher efficiency.

In summation, the research delineated herein constitutes a considerable stride in the arena of sustainable architecture and interior design. SMACK does not represent a mere incremental enhancement; it symbolizes a fundamental transformation in kitchen design ethos, recalibrating the normative for intelligent, energy-preserving culinary spaces. By integrating avant-garde technology with environmentally conscious materials and modular design tenets, it challenges traditional paradigms, establishing new precedents for eco-sensitive living.

The modular design of SMACK not only underscores its adaptability to diverse needs but also positions it as a scalable model. This flexibility ensures that SMACK is not a one-size-fits-all solution; instead, it caters to the varied requirements of contemporary living, making it a practical and feasible choice for a wide range of households. The empirical foundation laid in this research goes beyond theoretical propositions. Through a concrete data-driven estimation of energy gains in various configurations, including or excluding household appliances, SMACK provides a practical guide for real-world implementations.

Finally, the future implications of SMACK integration into homes are vast, and further research can explore its long-term environmental impact, user satisfaction, and broader applications within the realm of sustainable design and technology.

CRediT authorship contribution statement

Gabriele Bartolozzi: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giulia Palma:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Antonio Rizzo:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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