RES4CITY
renewable energies system for cities

Deliverable D2.1

Circularity and Sustainability Roadmap for the Urban Context

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Table of contents

List of Tables

List of Figures

List of Acronyms

Acronym	Meaning
CSP	Concentrated Solar Power
LCOE	Levelized Cost of Energy
M	Month
PACE	Property Assessed Clean Energy
PV	Photovoltaic
RE	Renewable Energy
RES	Renewable Energy Sources
RES-T	Renewable Energy Sources Thermal
RF	Renewable Fuel
SDGs	Sustainable Development Goals
WP	Work Package

Executive Summary

The present report analyses a set of renewable technologies, fuels, and strategies to enhance the uptake of renewable and sustainable solutions in cities. 33 items are preliminarily scrutinized along six dimensions, namely technical feasibility, economic feasibility, circularity, environmental impact, social acceptance, and gender issues. Out of the 33 items, 11 are analysed in detail in order to understand the potential to be readily applied in urban context.

Solar PV Panels. PV panels can now be considered as a standard technology with a substantial deployment in urban contexts. It can be said that the main driver for further development is the regulatory context which can evolve to further support the installations. From the economic point of view, PV panels reached grid parity in many cases and the Capital Expenditure (CAPEX) sharply decreases. The main challenge is linked to the circularity and in the organization of the *end-of-life* phase for the recycling and reutilization of the materials and components.

Solar Thermal Collectors. Low temperature solar thermal collectors can be considered a mature technology diffused in many EU cities, especially where the solar radiation conditions are convenient (e.g., South Europe). They are mainly used to produce domestic hot water, but new applications are also developed for industrial processes (e.g., food processing). From the economic point of view the feasibility depends on the alternative fossil fuel supply, but with the rising natural gas prices their convenience is quite easy to achieve. CAPEX considerably decreased thus large-scale deployments can be achievable.

Green Walls/Roofs. Green Walls/Roofs are not a renewable energy solution, but they are an impactful solution for increasing sustainability in cities by mitigating, among others, the heat island effect. The concept is very easy and consists in integrating vegetation in buildings. Despite its simplicity, it is only implemented in a few buildings and infrastructures, most of which became iconic. From the economic point of view the feasibility of the solution depends on the cooling and heating cost since it can contribute to reduce them substantially.

Heat Pumps. Heat pump is a pivotal technology for supporting the energy transition. It is the fundamental technology for enabling the electrification of heat generation. Its role in cities is relevant because it allows to switch the building heating demand from the fossil fuels to the power market, thus it permits to exploit the increasing renewable power generation. Different options are available on the market and they are also cost-competitive. The main issue is linked to the environmental sustainability of the refrigerants. However, the environmental impact is only ascribed to refrigerant leakage, while there are no issues during the normal operation. More and more sustainable refrigerants are object of research worldwide.

Thermal Energy Storage Technologies. Thermal storages serve to decouple the thermal energy consumption from its generation to ensure the continuity of supply. The scale of thermal storage systems can be different depending on the application. Large scale high temperature solar plants need large storages whereas individual thermal storage systems for domestic applications can be simple and very small (e.g., water-based storage in well insulated tanks). Small thermal storage systems are already feasible from the economic point of view. New systems with increased performances (e.g., in terms of improved insulation for longer storage) are continuously delivered to the market in combination with low temperature solar collectors, in order to provide *plug and play solutions*. Furthermore, the environmental impact of the domestic solutions is very limited because only

standard materials are used. If they are properly recycled and reused (e.g., circulation pumps), a virtuous circle can be activated.

Biofuels. Biofuels gained a relevant importance in the last years because they can be easily integrated with the distribution of traditional fossil fuels (e.g., petrol, gasoil, fuel oil, etc.). In fact, blended fuels appeared on the market. 100% biofuel products are also available. On the other hand, biofuel posed a relevant environmental issue in terms of reduction of biodiversity and reduction of land devoted to the production of food products. The most interesting aspect of biofuels is their production starting from waste treatment, in particular organic wastes, such as exhausted vegetables oils. In such a case, a good example of circularity and industrial symbiosis (e.g., food industry and energy industry) would be implemented.

E-fuels. Electrofuels gained their popularity recently as possible substitute for conventional fossil fuels. They are produced by exploiting electricity from renewable sources in order to activate chemical reaction and make synthetic fuels (e.g., e-methanol, e-methane, e-ammonia, etc.). On the other hand, the combustion of such fuels determines the emissions of CO_2, thus its success depends on the carbon capture storage to implement. Economic aspects are still uncertain since the technology is under development. However, there are economic advantages in the distribution of these fuels because the existing network can be largely exploited.

Hydrogen. Hydrogen can be also considered an e-fuel, because through the electrolysis process it can be generated starting from water and electricity. The main advantage of the hydrogen is that a clean combustion can be achieved without pollutant and greenhouse gas emissions. Hydrogen would be a game changer in the transport sector, especially for heavy duty vehicles which have a relevant impact on city (e.g., in cities hosting large harbours for example or in large cities in general). On the other hand, there are still a lot of uncertainties on both technical (e.g., safety concerns, distribution network, storage, etc.) and economic side since the production cost via electrolysis is not yet competitive.

Green Financing. To support the energy transition and decarbonization, financial resources are necessary, but public finance is not enough, thus it is necessary to attract private capital for these investments. To this aim innovative forms of financing are to be introduced on the market. *On-bill mechanisms* are innovative source of financing through the energy bill. The energy utility provides the upfront capital for making sustainable investment and then the users repay the investment on the bill in a number of years. *On-tax financing* is a mechanism of energy efficiency financing linked to local taxes (e.g., PACE mechanism). Local administrations, e.g., municipalities, provide upfront cost for energy/environmental retrofitting. Users repay the investment cost through local taxes in a fixed number of instalments as given by the specific mechanism. Both on-bill and on-tax mechanisms can be also transferred to next users (e.g., next owner or tenant). Finally, *green mortgages* are mortgages with lower interest rates with respect to standard ones because they are conditioned to investments in sustainable buildings. Sources of financing for green mortgages are available for commercial banks on the secondary markets and made available by financial institutions such as World Bank, European Investment Bank, etc.

Roadmap for the Decarbonisation of Cities. Based on the analysed technologies, renewable fuels, and strategies a roadmap is defined. Main elements and motivation of the roadmap are highlighted, and it is concluded that buildings, transportation sector, and energy system integration are the main aspects to consider for cities decarbonisation.

1. Introduction

According to UN 68% of world population is projected to live in urban areas by 2050[1] with an increase of 13 percentage points with respect to the current level. In other words, the urban population is expected to increase of 2.5 billion of people. This impressive growth poses the attention on how to manage in a sustainable way the expansion of cities according to the Sustainable Development Goals (SDGs).

On the other hand, the increase of the urbanization rate also offers important opportunities for enhancing the sustainability of cities by promoting stricter standards in terms of buildings energy performance, sustainable transportation, and a quick transition towards RES (Perea-Moreno, et al., 2018).

The development of RES technologies, fuels, and strategies is becoming an imperative to sustain both the increasing urbanization and the energy transition. Many cities have already expressed their commitment to be 100% renewables based and carbon neutral. For example, Copenhagen has a carbon neutrality target for 2025, similarly Sonderborg has its carbon neutrality target for 2029, whereas Aalborg has a view for a local 100% RES system by 2050 (Thellufsen & Lund, 2016).

Such efforts should consider different aspects of urban areas including the conventional energy supply, the grid, the RES techno-economic potential, and the possible alternative energy solutions (Hachem-Vermette & Singh, 2021). The development of high energy performance districts will depend on the integration of RES and alternative energy solutions with the existing energy system. RES systems include both electricity generating (e.g., solar PV, hydro, etc.) and heat generating (e.g., solar collectors, PV/T systems, etc.) technologies. Alternative energy systems include technologies with low environmental impact such as biomass, waste to energy (e.g., biomethane production), cogeneration/trigeneration, etc. The optimal combination of all these options will support the energy transition and carbon neutrality of cities.

In parallel with the technological development, it is necessary to develop adequate approaches for the management of the upcoming energy system, both in terms of its technical operation and business sustainability. New logics such as the demand side management, the energy flexibility management, etc. will be pivotal for the appropriate system operation (Kathirgamanathan, et al., 2021).

At the same time, it is necessary to develop innovative business models capable to support the development of sustainable energy systems to make them profitable and self-sustaining from the financial point of view by attracting private financing (Bianco & Sonvilla, 2021). Public financing is limited and can support the development at a limited extent only in the initial phases. The public support has the role of starting-up the process that then needs to become self-sustainable by generating a market participated by both public and private actors.

Based on all this, it is of paramount importance to develop a classification and analysis of the most relevant RES technologies, fuels, and strategies to achieve the full energy and carbon transition in cities.

The present report will offer an analysis of 33 technologies, fuels, and strategies based on six dimensions, namely technical feasibility, economic feasibility, circularity, environmental impact, social

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[1] https://www.un.org/sw/desa/68-world-population-projected-live-urban-areas-2050-says-un

acceptance, and gender issue. Furthermore, the ten most attractive approaches for cities will be selected based on stakeholders' consultation, literature analysis, workshops, etc.

The subgroup of the most attractive RES technologies, fuels, and strategies will be further investigated to gain a better acquaintance on the possible application and integration in city contexts.

2. Overview of Relevant Technologies and Strategies

In the last years an intensive research and development effort has been deployed to propose innovative solutions aimed at supporting the energy transition and carbon neutrality by developing RES based solutions, energy efficiency measures, innovative strategies for the management of energy systems and out-of-the-box business models to support the re-shaping of energy systems.

Literature is rich of many inspiring examples, applications, and concrete pilot cases demonstrating how the application of innovative technologies and strategies can support the transition and decarbonization of the energy system (Oduro & Taylor, 2023).

This section proposes a short analysis of 33 RES technologies, fuels, and strategies with possible applications in cities/urban contexts. The analysis is developed encompassing six dimensions, namely:

- **Technical feasibility** is related to the possibility to have a practical deployment of the considered technology/fuel/strategy in an urban context. A quick assessment of possible constraints or limiting factors is proposed.
- **Economic feasibility** attains the sustainability of the initiative in economic or financial terms also in comparison with alternative measures. Usually, the considered parameter is the LCOE.
- **Circularity** refers to the possible implementation of the circular economy principles to minimize wastes and to extract the maximum value of a device during its entire lifecycle as well as during the after-life cycle by re-using working components, recover primary material sources with some treatment, etc.
- **Environmental Impact** considers the possible harmful impact that the implementation of RES technologies/fuel/strategies may have on the environment and how it can be mitigated.
- **Social Acceptance** focuses on how the RES technologies/fuels/strategies are perceived by the society at large. It is common that the perception is different according to the considered RES technology/fuel/strategy based on the opinion of the public often influenced by claims of opinion leaders, social media, etc.
- **Gender Issues** is related to possible gender-based discriminations that can arise often when data collection is necessary (e.g., for implementation of certain strategies). This could lead to user profiling and habits monitoring and it could pose discriminatory issues based on the gender.

The following technology matrix proposes an analysis to gain a quick overview on a set of 33 RES technologies/fuel/strategies suitable for applications in city/urban contexts.

#	RES Technology & RF Strategy in Urban Environment	TRL	Type	Technical Feasibility	Economic Feasibility	Circularity	Environmental Impact	Social Acceptance	Gender Issues
1	Solar PV	9	RES T	- Consolidated Technology - Easily Integration in urban context - No relevant maintenance	- Attractive LCOE - Grid Parity reached or close to be reached - Well established supply chain	- Possibility to sell on secondary markets (e.g., spare parts) - High quality recycled materials to feed PV module production process - Low quality recycled materials downcycled in processes with less stringent standard	- Land utilization - Visual impact - Utilization of hazardous materials - Mining of critical raw materials	- General positive consensus for local installation - Possible opposition to large ground installation	N.A.
2	Thermal Solar	9	RES T	- Well established technology - Easy integration in urban context - Relevant for buildings refurbishment	- Pay-back period between 3-5 years depending on the location - Attractive LCOH - Well established supply chain	- Recycled material used for their manufacturing - 90% of glass, polyurethane, and steel components to be collected and recycled	- Hazardous and chemical materials impact during the manufacturing process	- Positive consensus for small domestic installation - Possible opposition for large scale high temperature plants	N.A.
3	Wind OnShore	9	RES T	- Difficult to consider in urban context (possibilities available in industrial areas)	- Attractive LCOE - Grid Parity reached or close to be reached - Well established supply chain	- Re-utilization of blades in cement co-processing - Repurposing by using blades as furniture in the	- Visual Impact - Noise - Bird strikes - Lubricants leakage	- High support to wind energy as a technology - Declining acceptance of	N.A.

15

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#	RES Technology & RF Strategy in Urban Environment	TRL	Type	Technical Feasibility	Economic Feasibility	Circularity	Environmental Impact	Social Acceptance	Gender Issues
				- Existing examples of integration in buildings for small horizontal turbines - Developments in the field of vertical axial turbines		urban environment (e.g., playground, bikes shelters, etc.) - Recycling and recovery for producing fibers to reinforce concrete, to re-use the composite material for producing new objects, etc.		local wind projects	
?4	Wind OffShore	9	RES T	- Possible application in cities with adequate coastal conditions - Possible issues in cities with large port facilities - Specific climatic conditions required	- Attractive LCOE - Grid Parity reached or close to be reached - Well established supply chain	- Re-utilization of blades in cement co-processing - Repurposing by using blades as furniture in the urban environment (e.g., playground, bikes shelters, etc.) - Recycling and recovery for producing fibers to reinforce concrete, to re-use the composite material for producing new objects, etc.	- Bird life (e.g., affecting migration routes) - Marine mammals (e.g., affecting movements and migration) - Ecosystem structure, functions, and processes (e.g., physical, hydrogeological, and physical characteristics)	- High support to wind energy as a technology - Ownership changes the acceptance level (e.g., local cooperative vs. large corporations) - If far from the coastline, higher acceptance	N.A.
5	Geothermal	8-9	RES T	- High temperature geothermal possible only in specific locations	- Geothermal energy at 90-150 °C competitive with	- Hybridization with other RES to reduce the need for geothermal	- Possible hydraulic and thermal changes in the deep underground	- Controversial cases available in the literature	N.A.

#	RES Technology & RF Strategy in Urban Environment	TRL	Type	Technical Feasibility	Economic Feasibility	Circularity	Environmental Impact	Social Acceptance	Gender Issues
				- Low temperature geothermal convenient in cities with Low external temperature - Possible issues connected with local geo-morphological conditions of the soil	respect to natural gas - Direct electricity production not competitive - High initial capital cost for low temperature geothermal coupled with heat pumps	- Reuse of some components (e.g., heat exchangers, pumps, etc.) for other applications - Repurposing abandoned coal mines or oil&gas wells for geothermal applications	- Geological interaction	- Acceptance limited by doubts linked to the security	
6	Tidal	6-8	RES T	- Exploitable only in specific locations - Scale between 0.1 and 2 MW - Predictable energy supply with possible applications in grid balancing	- Reliable supply chain to be developed - LCOE in 2030 is estimated in about 100 €/MWh - Economic feasibility achievable in the long period	- Technology is not mature enough for the elaboration of specific circular strategies. Anyhow the typical Reuse, Repurpose and Recycling approaches can be considered.	- Habitat loss - Animal-infrastructure interaction - Location specific issues	- General support towards the technology - Positive attitude to local project development	N.A.
7	Wave	7-8	RES T	- Specific wave conditions necessary - Only experimental prototypes available - Adequate for Oceanic coasts	- Reliable supply chain to be developed - LCOE in 2030 is estimated in about 150 €/MWh - Economic feasibility achievable in the long period	- Technology is not enough developed for the elaboration of specific circular strategies. Anyhow the typical Reuse, Repurpose and Recycling approaches can be considered.	- Habitat loss - Animal-infrastructure interaction - Location specific issues	- General support towards the technology - Positive attitude to local project development	N.A.

#	RES Technology & RF Strategy in Urban Environment	TRL	Type	Technical Feasibility	Economic Feasibility	Circularity	Environmental Impact	Social Acceptance	Gender Issues
8	Solar CSP	7-8	RES T	- Useful for industrial areas with medium temperature processes - Possible combination with absorption heat pumps - Possible integration in urban context	- Less competitive with respect to PV and wind for electricity generation - LCOE around 200 €/MWh depending on the location - CAPEX reduction opportunities from learning curve development	- Possibility to sell on secondary markets (e.g., spare parts) - High quality recycled materials to feed PV module production process - Low quality recycled materials downcycled in processes with less stringent standard	- Land occupation - Water consumption - Leakage of thermal fluids	- Limited information available - A few studies in Morocco show a support towards large scale CSP projects	N.A.
9	Fuell Cells	6-7	RES Technology	- Support the decarbonization of transport sector (e.g., heavy duty vehicles) - Necessity of a distribution infrastructure of hydrogen to support their diffusion - Existing technical and safety issues	- High CAPEX in short medium term - Technology at very early market stage	- Recovering of non-critically damaged Fuel Cells - Disassembly of non-recoverable Fuel Cells and selection of components for direct re-use on secondary markets - Waste management for the non-recoverable parts through mechanical and chemical treatments to recover valuable material	- Difficulties in obtaining green hydrogen - High Environmental impact in the manufacturing phase, especially the electrocatalyst production - Utilization of critical raw material such as nickel, platinum, etc.	- Safety concerns especially in mobility applications	N.A.

#	RES Technology & RF Strategy in Urban Environment	TRL	Type	Technical Feasibility	Economic Feasibility	Circularity	Environmental Impact	Social Acceptance	Gender Issues
10	Solar PV/T	8-9	RES Technology	- High level of integration in urban contexts - Maximization of the efficiency in relation to the occupied surface - Easy installation and maintenance	- Attractive LCOE/LCOH - Short pay-back period - Well established supply chain	- Possibility to sell on secondary markets (e.g., spare parts) - High quality recycled materials to feed PV module production process - 90% of glass, polyurethane, and steel components to be collected and recycled	- Visual impact - Hazardous and chemical materials impact during the manufacturing process	- Positive consensus for small domestic installation	N.A.
11	Biomass	9	Renewable Fuel Technology	- Availability of local sources - Monitoring of soot emissions - Energy-Food Nexus	- Attractive economics if resources are locally available - Supply chain must be reliable - Possibility to develop local economy	- Possibility to integrate with wood industry - Utilization of wood waste to produce pellets	- Trade-off between land for food or biomass in case of dedicated cultivation - Soot emissions can be a problem - Ash management can be problematic in case of massive use	- Controversial attitude on local projects - Fear to sustain negative externalities	N.A.
12	Biogas	9	Renewable Fuel Technology	- Potential availability in urban environment through anaerobic digestion of organic fraction of municipal waste - Well established production process	- Economically viable since it is primary conceived for waste treatment - Stable supply chain - Possible synergies between urban and rural areas if	- Integration between waste management and energy generation - Value extraction from farming organic waste - Opportunities related to the	- Possibility of biogas leakage - Imperfect production could lead to more emissions than expected	- Controversial attitude on local projects - Fear to sustain negative externalities	N.A.

#	RES Technology & RF Strategy in Urban Environment	TRL	Type	Technical Feasibility	Economic Feasibility	Circularity	Environmental Impact	Social Acceptance	Gender Issues
				- Synergic approach with municipal waste management services	biogas from farming is considered	production of char (fertiliser) for agriculture			
13	Hydrogen	7-8	Renewable Fuel Technology	- Renewable fuel for decarbonizing complex sectors (e.g., high temperature heat demand) - Technical complexities related to its distribution and storage - Potential large availability irrespectively from the location	- High investment costs - Supply chain to be built - Uncertain business model	- Recycled water from other processes can be used as input in the hydrogen production	- Low or close to zero environmental impact if produced via electrolysis and RES	- Positive attitude toward the technology - Decreasing level of support for infrastructure development	N.A.
14	Syngas	8-9	Renewable Fuel Technology	- Established technology, can be used for both electricity and thermal energy production - It requires wood feedstock (low moisture content) - Low TRL syngas technologies are being developed for expanding the usable feedstock	- High investment costs - To guarantee a reliable supply chain for the operation - Uncertain business model	- Circularity opportunities related to the production of char (fertiliser) for agriculture	- Closely linked to the biomass used in the process	- Difficult to assess due to the limited impact and small nature of these plants	N.A.

#	RES Technology & RF Strategy in Urban Environment	TRL	Type	Technical Feasibility	Economic Feasibility	Circularity	Environmental Impact	Social Acceptance	Gender Issues
				- It needs to be used locally (injection of biogas in natural gas pipelines not possible)					
15	Liquid Biofuels	8-9	Renewable Fuel Technology	- Availability of local sources, e.g., local exhausted vegetable oils - Blending with other liquid fuels - Energy-Food Nexus	- Attractive economics if resources are locally available - Supply chain must be reliable - Possibility to develop local economy	- Possibility to integrate with waste treatment industry (i.e., organic waste) and food industry - Recycling of exhausted vegetable oils	- Trade-off between land for food or biofuel in case of dedicated cultivation	- Controversial attitude on local projects - Fear to sustain negative externalities	N.A.
16	Heat Pumps	7-9	Technology	- Coupling of electricity and thermal sectors - Consolidated technology - Possibility to couple with many different RES	- Market growing at a high pace - CAPEX of 600 €/kW - Well established supply chain and developed EU industrial system	- Recycling of metal materials - Re-utilization of refrigerants - Modular design and better repairability as drivers for improving circularity	- Approximately equal to traditional system - Possible reduction of NOx emissions - Toxicity of refrigerants can be an issue	- Visual impact and space requirements as possible barriers for acceptance - Premium property value as a driver to overcome acceptance issues	N.A.
17	Green Roofs/Green Walls	8-9	Technology	- Positive integration with urban environment - Not complicated to implement	- CAPEX of around 100 €/m^2 - Substantial non-energy benefits	- Higher lifecycle of green roofs/walls protects the supporting infrastructure	- Positive environmental impact - Reduction of urban heat island	- Positive consensus for local projects	N.A.

#	RES Technology & RF Strategy in Urban Environment	TRL	Type	Technical Feasibility	Economic Feasibility	Circularity	Environmental Impact	Social Acceptance	Gender Issues
				- Beneficial micro-climatic impact - Lack of common standards	- Established supply chain	determining less replacement - Gray water recovery - Easy management of the components at end of life	- Reduction of water run-off from buildings - Reduction of carbon emissions		
18	Special Glazing	9	Technology	- Easy to apply - Very large potential - Passive method to reduce energy consumption	- Viable solutions available on the market	- Recycling cycle to be implemented at the end of life	- Reduced energy consumption for air conditioning	- Positive consensus for local projects	N.A.
19	Building Facade	9	Technology	- Passive method to reduce energy consumption - Easy to implement - Extensive impact	- Viable solutions available on the market	- Recycling cycle to be implemented at the end of life	- Reduced energy consumption for air conditioning/heating - Better ventilation opportunities	- Positive consensus local projects	N.A.
20	ORC	8-9	Technology	- Recovering of low temperature energy sources for electricity production - Well developed technology for medium/large system sizes - Low conversion efficiency	- High investment costs which make small-size systems not economically feasible	- Recycling of metal materials - Utilization of spare parts on secondary markets - Modular design and better repairability as drivers for improving circularity	- It depends on the fluids used in the cycle - Sustainable fluids are constantly under development	- Difficult to assess due to the limited impact and small nature of these plants	N.A.
21	Thermal Storage	7-9	Technology	- Decoupling of thermal energy production and consumption	- Quick pay-back period for small systems for	- Recycling of metal materials	- Very low for domestic water-based systems	- High level of support for domestic system	N.A.

#	RES Technology & RF Strategy in Urban Environment	TRL	Type	Technical Feasibility	Economic Feasibility	Circularity	Environmental Impact	Social Acceptance	Gender Issues
				- Integration with other technologies (e.g., solar thermal, heat pumps, etc.) - Scalable solutions available	domestic application - High level of uncertainties for large systems	- Utilization of spare parts on secondary markets - Modular design and better repairability as drivers for improving circularity in large systems	- Linked to the accumulation medium for large systems	- Decreasing support for large installations as for all the technologies	
22	Phase Change Materials	6-8	Technology	- Option to increase the performance of thermal storage systems - Most of them derived from hydrocarbons, some bio-based solutions available - Easy applicable	- Low installation cost during the construction phase - Very variable CAPEX depending on the type of PCM	- Recycling at the end of life - Different strategies depending on PCM typologies - Possible symbiosis with organic waste treatment	- Low impact for PCM deriving from food waste	- No substantial data available for a comprehensive evaluation	N.A.
23	Energy Excess recovery	N.A.	Technology	- Possible integration with existing DH network - Combination with absorption heat pumps - Energy recovery through ORC	- It can be very convenient depending on the temperature level of the source - Possibility for industrial symbiosis	- Example of circularity since waste heat is used to feed another process - Steel used for the infrastructures (e.g., pipes) can be recycled at the end of life	- Usually very limited since it is implemented in industrial areas - Often it implies only the installations of heat exchangers and pipes	- Closely linked to the infrastructure to build	N.A.

#	RES Technology & RF Strategy in Urban Environment	TRL	Type	Technical Feasibility	Economic Feasibility	Circularity	Environmental Impact	Social Acceptance	Gender Issues
24	Low Temperature DH	8-9	Technology	- Integration with high available low temperature energy sources - Reduction of energy losses - Possibility to develop 100% RES systems	- Profitability depending on the location of installation - Possibility to retrofit existing high temperature network - Competitiveness of the possible tariffs depending on fossil fuel market	- Linked to the different technologies integrated in the community	- Reduction of fossil fuel consumption - Reduction of wasted energy - Resource optimization	- Overall high acceptance - If it is a retrofit, strong support is expected - Possible opposition in case of a new infrastructure development	N.A.
25	Absorption Heat Pumps	8-9	Technology	- Exploitation of heat/waste heat source for cold production - Integration with thermal RES	- Market availability of some devices - OPEX can be more convenient with respect to vapour compression heat pumps	- Recycling of metal materials - Utilization of spare parts on secondary markets	- It is mainly linked to the working fluids of the considered absorption heat pump	- Overall positive support	N.A.
26	Smart Grids	8-9	Technology	- Fundamental for the management of a large number of power injection and consumption points - Management of volatility issues in RES - Support to the electrification of consumption	- Continuous decrease in CAPEX - In many cases Investment profitability is secured by Regulatory Asset Base (RAB)	- Recycling of metal materials - Utilization of spare parts on secondary markets	- Positive contribution to environmental impact by allowing a higher penetration of RES in the energy system	- Overall positive support	N.A.

#	RES Technology & RF Strategy in Urban Environment	TRL	Type	Technical Feasibility	Economic Feasibility	Circularity	Environmental Impact	Social Acceptance	Gender Issues
27	Energy Communities	N.A.	Strategy	- Integration of different demand and supply sources - Better demand and supply balance	- Optimization of the supply cost - Origination of new business opportunities	- Linked to the different technologies integrated in the community	- Reduction of wasted energy - Resource optimization	- Overall positive support	N.A.
28	OnBill Schemes	N.A.	Strategy	- Stimulation to the implementation of energy efficiency measures and RES development - Involvement of energy utilities in the process - Large scale interventions	- Attraction of private financing in the renovation and RES market - Development of Energy Efficiency as a service - Implementation of cost-effective measures	- On bill programs possibly designed to support circularity	- Possibility to support measures with a balanced environmental impact	- Perceived as a commercial offer - Free option to consider it or not	- Issues linked to the different income level of males and females existent in some EU countries
29	Green Mortgage	N.A.	Strategy	- Support for retrofitting of small properties - Necessity to define clearly the “green projects” - Possibility to set requirements on the EPC level	- Attraction of private capital in the energy efficiency and green markets - Accession to capitals on secondary markets (e.g., from supra-national banks)	N.A	- Possibility to support only measures with a balanced environmental impact.	N.A	- Issues linked to the common prejudices existing for usual mortgages when required by minorities
30	On Tax Financing	N.A.	Strategy	- Stimulation to the implementation of energy efficiency measures and RES development	- Municipalities take the risk of non-payment - Accession to capitals on secondary markets	- On tax programs possibly designed to support circularity	- Possibility to support measures with a balanced environmental impact	- Possible perception as a support only directed to the upper-middle classes	- Being promoted by public administrations, no gender

#	RES Technology & RF Strategy in Urban Environment	TRL	Type	Technical Feasibility	Economic Feasibility	Circularity	Environmental Impact	Social Acceptance	Gender Issues
				- Involvement of municipalities in the process - Targeted interventions according to municipality's needs	(e.g., from supra-national banks)				issues should be foreseen
31	Demand Flexibility	N.A.	Strategy	- Implementation of DSM strategies to adjust the user electricity load on grid requirements - Requires demand side management and optimisation strategies deployed at building level - Schemes for of multiple loads aggregation required - Absence of established regulation and financial schemes limits their deployment - Medium stage development: pilot cases available	- Users' patterns strongly affect the economic turnout - Financial schemes for demand response programmes not yet established	N.A.	- It can reduce the peak load at network level, thus reducing carbon emissions - DSM programmes leverage on smart algorithms methods, thus optimising the users' energy consumption patterns and related carbon emissions	- It requires smart sensors and network systems to communicate consumption patterns (users' preferences) and system controls - Data protection must be respected - User perceived control on their consumption may be affected, thus reducing the social acceptance of the demand	- Possible issues linked to different energy demand profile due to different general habits between males and females

#	RES Technology & RF Strategy in Urban Environment	TRL	Type	Technical Feasibility	Economic Feasibility	Circularity	Environmental Impact	Social Acceptance	Gender Issues
								response strategies - Lack of established regulations schemes and contracts may affect the social trust	
32	Virtual Power Plant	N.A.	Strategy	- Optimization of RES generation - Reduction of generation volatility - Better management and integration of RES power plants	- More effective commercial operation of the power plants - Improved trading opportunities - Optimization of the strategic management	N.A.	N.A.	- Positive support due to the high support toward RES - The infrastructure is virtual then there is no local opposition	N.A.
33	Net Positive Energy District (PED)	N.A.	Strategy	- Challenges due to identification of spaces for installation - Adequate climate conditions for the installation of corresponding RES - Management of possible issues linked to grid stabilization	- Extensive investments required - Contribution to the reduction of energy poverty	- Recycling and re-utilization of the technologies included in the PED	- Reduction of carbon and pollutant emissions as a main target - Possible environmental impacts (e.g., visual impact) especially in historical city centres - Land occupation	- Positive reaction if created positive value for citizens	N.A.

3. Analysis of the Most Relevant Technologies, Fuel and Strategies

3.1 Solar PV Panels

3.1.1 Introduction

The history of PV solar energy begins in 1839. Edmund Becquerel discovered the photovoltaic effect, noting during his experiments that the platinum hit by the sun's rays produced a small electric current. After more than a century, in 1953, the first silicon solar cell was created which, after some developing by the Bell Labs, was able to transform 6% of the energy of solar radiation into electricity. Nowadays, efficiency of the best commercial PV modules reaches and surpass 24% (monocrystalline silicon) while thin film PV modules approach 20%.

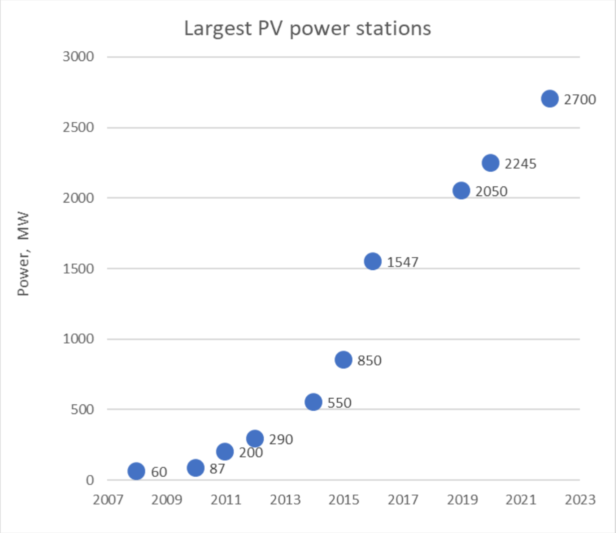

Figure 1 Evolution of the maximum dimension of PV power stations

Innovation in PV cells is mainly addressed to materials and to flexible thin-film solar. These lightweight devices can be manufactured in a variety of forms and can be twisted and shaped for easy incorporation into the built environment. Their efficiencies and device lifetimes are lower than those attained in silicon PV or thin films placed on glass. However, there are companies which are developing cell materials that are different from those used in conventional cells, such as perovskites and copper-indium-gallium-selenide (CIS, CIGS) and are also utilizing existing printing processes which have already shown success in other industries, with the potential of reducing manufacturing costs. Now, efficiencies are around 15% and roadmaps exist to go up to 20% (Amelia, et al., 2016). Global energy efficiency is gained by combining PV with thermal solar (Gaur & Tiwari, 2010). This technology fusion, often coupled to heat pump heating and storage, could be a key step toward the “zero bills home”.

Innovation in materials diverges from silicon toward CIS and Cadmium telluride (CdTe) (Tabassum, et al., 2017). The first is advantageous in terms of efficiency power generation (also under cloudy skies) and low environmental impact. CdTe has high efficiency and low cost since Cadmium and Tellurium are waste materials, deriving from the extraction of non-ferrous minerals, but pose some environmental doubt as cadmium is extremely toxic.

Figure 2. PV panels integrated in buildings within an urban context (credit: pexels-amar-preciado-13047564)

Speaking about more conventional PV application, the technology has reached a stage of consolidated maturity and it has expressed plants of large capacity especially in India and China which host 80% of the over 1000MW plants, see Figure 1, being the most powerful represented by the Bhadia Solar Park (India) featuring a power of 2700 MW. The largest European solar farm, with a power 850MW, is found in Spain. The above figure shows the timeline of largest PV power stations in the world lasting from year 2005. Very large plants are not usually located near big cities since they are often found in desertic zones, with lower land prices compared to city neighbouring land prices, sometimes hundreds of miles from the nearest big city. In fact, communities are forced to make choices in land use accounting for limited available roof space. From this perspective, small medium cities have more room for PV panel since they are often horizontally developed, with less shadowing and more roof space. PV façade system can be used as building cladding to attain visual appeal and energy efficiency. Transparent solar cells for windows may prove useful too. Net-zero cities will be built around small energy efficient buildings. This concept of decentralized and disjointed production and distribution is completely different from the previous and poses different challenges.

If the urban settlement is locatet near a lake or an inland see, PV technology can be deployed also according to a different concept. Among the world's largest floating solar farms, the Singapore 60 megawatt peak (MWp) floating solar photovoltaic system comprises 122,000 solar panels spanning 45 hectares. Other projects aim at creating connected artificial islands supporting thousands of solar PV panels across a field with the size ranging up to one or more football pitch.

Figure 3. Largest Germany Floating PV solar field in Ruhrgebiet, North Rhine-Westphalia (credit: Dietmar Rabich / Wikimedia Commons / "Haltern am See, Silbersee III, Solaranlage -- 2022 -- 0818-25" / CC BY-SA 4.0)

The cost of solar energy is falling. New concepts and technologies suggest PV solar will soon overwhelm fossil fuels. The future looks bright for PV solar.

3.1.2 Technical Analysis

Urban based PV system are represented by a number of different technologies and are implemented in different contexts with reference to both the grid interconnection and the installation site typology. Each kind of installation poses different challenges and constraints. Regulation is one of the most important factors that determine PV system viability (Salgado, et al., 2022). Near city systems divide in ground-mounted PV arrays, Figure 4, and lake/sea installations. Unlike large-scale, decentralized photovoltaic plants, these small solar farms produce electricity directly and for immediate use, within their hinterland. These PV systems can have small to medium power in the range 500kW to 5MW, they can be fixed or can automatically align to the sun, at a cost, exploiting at best the sunlight. They are usually owned by private individuals who have benefited of grants, but complete autonomy and grid parity will soon be achieved.

Figure 4. Ground mounted PV arrays (credit: andreas-gucklhorn-Ilpf2eUPpUE-unsplash)

Within city residential PV implementations mainly depend on the particular city structure. Semi-detached and single-family small houses, maybe located in the city surroundings, can have small ground mounted PV panels in the backyard or roof mounted fixed systems, see Figure 5. 10kW systems usually produce enough electricity for the average household, depending on the location and the family habits.

Figure 5. Residential photovoltaic roof (credit: pixabay - renewable-g1567af2c0_640)

These are classic implementations, but under an ever-increasing push towards electrification and the need of pollution reduction, cities will evolve in more efficient structures relying on renewable sources where neighbourhood energy services generate heat and energy right where people need it. In this context, solar panel will evolve in flexible surfaces which can be bent and directly incorporated into every part of the built environment.

According to the trend of recent years, the presence of photovoltaic systems on buildings has become normal and cannot constitute an automatic denial of landscape authorization. Environmental regulations framework is changing. The favourable season to install renewable energy sources had already taken hold in the administrative field. And this season has been reaffirmed by the recent simplification measures towards photovoltaics on buildings, also in line with the national interest in accordance with Community law. This is because the production of electricity from solar sources is itself an activity that contributes, though indirectly, to the protection of landscape values.

Technical analysis of a PV installation is founded on the designed plant power, utilization, and specific components for the orientation of the panels. The power generated by a PV plant is affected by the solar radiation at the selected site, the angle and direction of the solar collectors, the temperature, and the performance of various components.

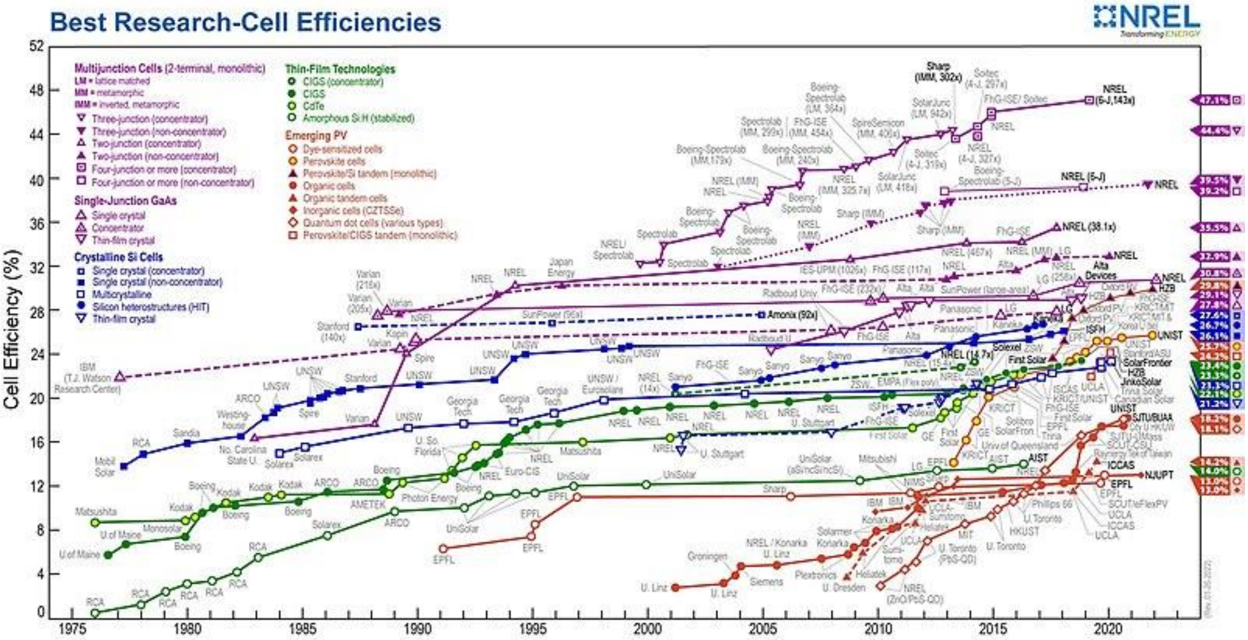

Figure 6. Best research PV cell efficiencies (credit: National Renewable Energy Laboratory, Golden, CO, CC0, via Wikimedia Commons)

During the lifetime of a PV system, power will decrease due to the degradation of panels and other components. The performance ratio (PR) measures of the quality of a PV plant. It is location independent, and it is expressed as the ratio between actual system power and the theoretical output when the system is operating in Standard test conditions (STC). It shows the fraction of energy that is actually available to the grid after deduction of energy losses also including:

- Collector conversion efficiency
- Inverter efficiency (if alternating current is needed)
- Storage efficiency (off grid systems)
- Shading
- other thermal losses

Ultimately, the development of solar photovoltaics, whatever it may be, will be bound by technical-economic rather than purely technical considerations as its spread is based on widely consolidated technology.

3.1.3 Economic Analysis

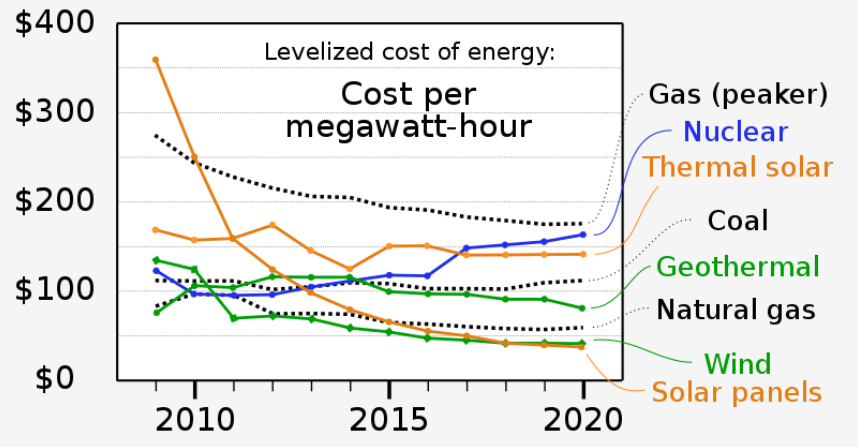

Figure 7. Levelized cost of energy (starting with LCOE 14.0, October 2020) for various energy sources as a function of year, derived from LCOE data from Lazard (credit: RCraig09, CC BY-SA 4.0, via Wikimedia Commons)

Economic feasibility and sustainability of PV technology depends on numerous factors, also technical, like conversion efficiency, system losses, energy storage, location (including shading), temperature, mounting context, and the selected tracking system. All these elements must be evaluated by an in deep simulation phase before any decision on the installation process is carried out (Windarta, et al., 2021).

The financial analysis of the engineering investment usually aims to compare the feasibility of a handful of different investment options between them and to some alternative existing measures (e.g., a comparison of the economic performance of the PV plant with that of the most efficient GCC (gas combined cycle) in the network). The “opportunity cost”, benefits that are lost when choosing one option over another, must be also assessed to better decision making. PV technological investments have a long economic life. Currency values, however, do not remain the same over time so the NPV (net present value) is often used to assist in the analysis, calculated as the difference between PWB and PWC (present worth benefit and cost).

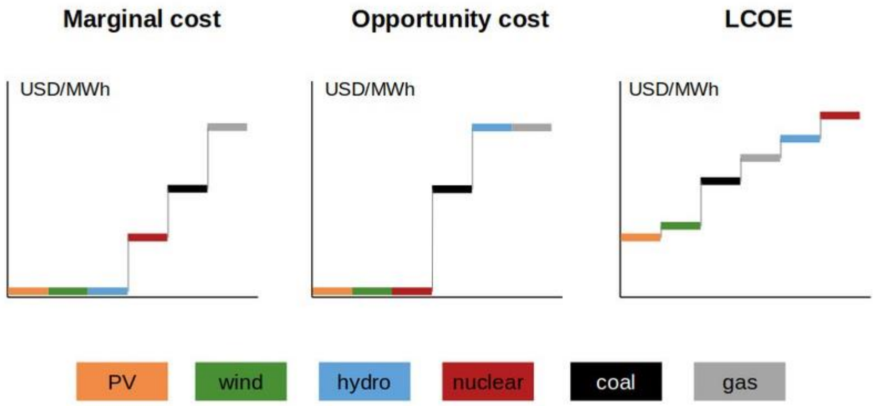

Figure 8. Qualitative representation of marginal cost, opportunity cost and LCOE for different generation technologies (credit: Cristóbal J. Gallego, CC BY-SA 4.0, via Wikimedia Commons)

The Levelized Cost of Electricity (LCOE), Figure 7, is frequently used to appraise a power system and to compare the cost of energy achieved from different sources. The LCOE estimates the income necessary to develop and run a generator over a particular cost recovery time (e.g., the useful lifetime of the asset). The LCOE computation account for several costs: capital, decommissioning, fuel, fixed and variable operations and maintenance, finance costs, and an expected utilisation rate (Alashqar, et al., 2022).

In the last decade, renewable energy (RE) experienced a remarkable cost decrease. The considerable declines in solar and wind are due to the drop in capital costs. Indeed, RE systems need direct financial obligations similar to thermal or nuclear power plants. However, the operational marginal costs are much lower, as illustrated. The reason for this is primarily that fuel costs dominate the marginal cost of generation for conventional generators while, for renewable generation, the fuel is essentially free, and the operations and maintenance (O&M) costs dominate. These significant LCOE reductions encourage countries to implement renewable energy resources.

Figure 9 shows an exemplificatory scheme of Technical/Economical feasibility analysis of an off-grid PV system with comparison to Diesel generation (Chaurasia, et al., 2022).

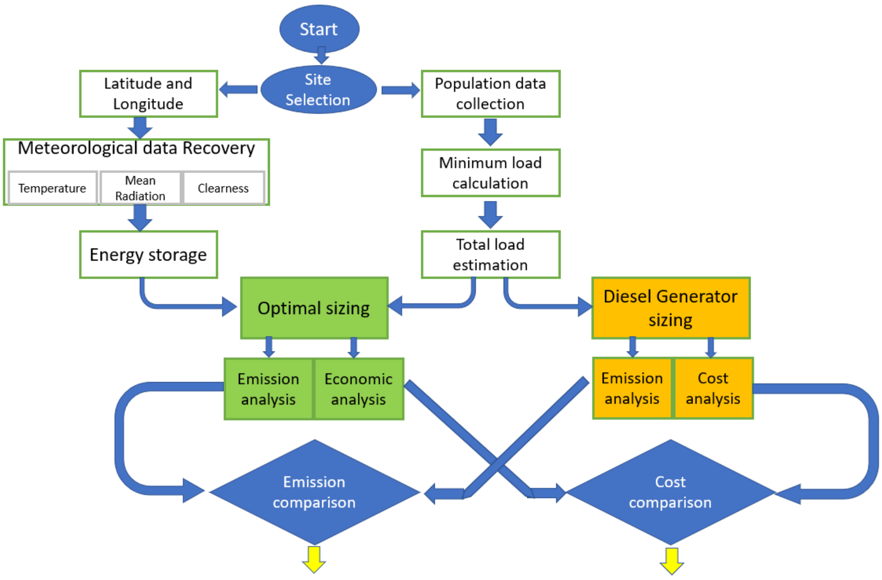

Figure 9. Feasibility analysis process. Off-grid PV vs. Diesel generator

Social acceptance or public perception is an important factor to consider when implementing a solar PV system. Social acceptance of a PV system can have a significant impact on its overall success and feasibility (Peñaloza, et al., 2022). Some people may object to the appearance of PV panels on buildings or in public spaces, especially in historic or landmarked areas. While the technology has advanced greatly, it may still not be considered efficient enough to generate the energy needed to power a building or home. People may be concerned about the safety of PV panels. Some people simply lack the knowledge and understanding of the benefits of PV panel systems and how they work. To increase community acceptance, it is important to address these concerns and educate the public about the benefits of solar PV panels, such as their environmental and financial advantages, as well as their safety and reliability. When it comes to complex systems, it's crucial to involve the general public in decision-making by hosting public forums or consultations to solicit opinion and address problems.

Promoting the advantages of PV systems in terms of energy grid independence and resilience to power outages is another strategy to raise social acceptance. To lessen the influence of PV panels on aesthetics and any potential noise or safety concerns, it's also crucial to think carefully about the design and placement of these solar energy systems.

3.1.4 Environmental Analysis and Circularity

A very important part of all energy consumption in the World comes from the production of electricity supplying homes and businesses. Much of this energy use pollutes the air and water and creates hazardous waste that must be disposed of. Solar panels help eliminate this pollution by capturing the energy of the sun and using that energy to power common household devices such as lights, heaters, and coolers. However, also the PV technology poses some pollution threat. Some types of PV cell technologies use heavy metals, and these types of cells and PV panels may require special processing when they reach the end of their operative life. In case of hybrid PVT (PV-thermal), some systems may use possibly harmful fluids to transfer heat, and leaks of these materials could be toxic to the environment. Fortunately, from a balance between environmental pros e cons, PV technology, if well managed during all the life span of a PV installation, can represent a value opportunity. As a consequence, it is important that the economic analysis of a PV plant can only be conducted in

conjunction with an assessment of the environmental impact and the economic feasibility of end-of-life (EoL) measures. Photovoltaic technology is one the main renewable electric source and due to the recent advances in the production technology, PV panels have become more cost-effective and profitable. Still, the operational life of these device is about 25-30 years on average, and then they move into the EoL waste electrical and electronic equipment (WEEE) stream.
Thus, EoL management is expected to enter its significant stage in many countries from the early 2030s owing to the wide spread of PV panels in the past decades (Mahmoudi, et al., 2020). The potential EoL of discarded photovoltaic panel is, currently, of the order of hundreds of thousands tons/year and will be of tens of millions tons/year in 2040. This partly valuable raw material presents a new environmental challenge, but also unique opportunities to create value.

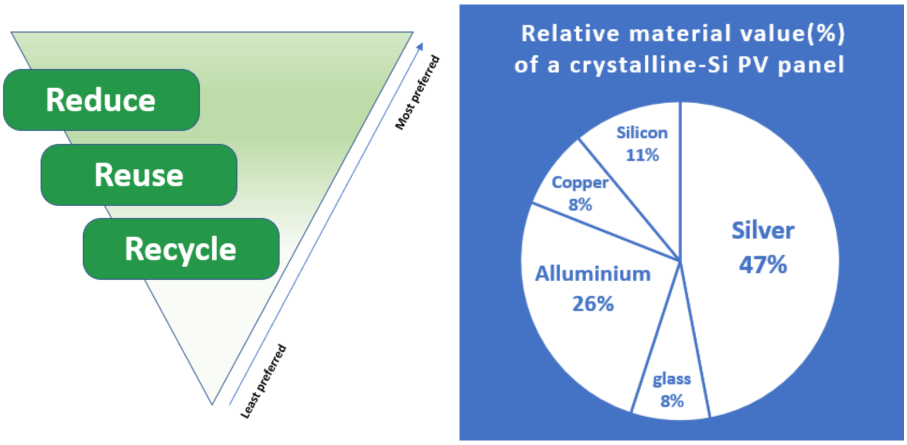

Figure 10. Recycle viewpoint. Relative material value (average) of a crystalline PV panel

The common options for PV panel waste management are summarized by the 3Rs: reduce, reuse, and recycle (IRENA & IEA-PVPS, 2016). Each segment of the PV value chain, including end-of-life, offers opportunities for value creation related to the reduction of material usage, the possibilities of repair and reuse, as well as the recycling and treating any waste produced from PV panels.

Reduce – PV panel composition is currently changing. materials savings and even replacements have been and are continuing to be researched for lead, cadmium and selenium so that the volume of harmful materials can be reduced. Since total consumption of rare and valuable materials will increase as the PV market grows, availability and prices will drive reduction and substitution efforts. Furthermore, considerable R&D is focused on new materials and material replacements: Indium will be reduced, glass front panel will be lighter, and research is looking at reducing or replacing polymers parts since they are not recyclable, thinner cells will reduce the amount of silicon and a reduction of silver is in view due to new progresses in inkjet and screen-printing technologies. Silver is most expensive material per unit mass of a PV panel (a typical panel contains up to 10 gr of silver, see Figure 10).

Repair – Most defective panels are normally returned to a producer service partner, or the producer itself for check and repair. To recoup some value from a returned panel by way of reselling, quality tests have to be made testing electrical, safety, and power output. The restored PV panels can be resold as replacements. Otherwise, they can be resold as used panels at a lower market price of around 70% of the original price. Panels remained effective after 30 years of life can be checked, refurbished, and reused with the creation of a secondary market of used panels. Panels that cannot be repaired are dismantled and forwarded to waste treatment companies.

Recycle – Disassembly and dismantling PV panels is strongly affected by the size of the installation. Waste management of large utility-scale installations (>100kW) is considerably easier than treating rooftop systems. Remote areas such as islands and rural areas can have high logistics costs for PV panel recycling programs. Currently, due to the small PV waste quantities there are not economic reasons to create dedicated PV panels recycling plants and End of Life panels are handled in general recycling factory. In the near future, things will rapidly change, and each type of PV panels will find dedicated waste recycling structures. By now, only the European Union (EU) has implemented PV-specific waste regulations (IRENA & IEA-PVPS, 2016). Pioneering PV electronic waste (e-waste) regulations, which cover PV-specific collection, recovery, and recycling targets, (WEEE) directive establishes that all companies that supply PV panels to the EU market (wherever they may be located) are responsible for the cost of collecting and recycling end-of-life PV panels put on the market in the EU.

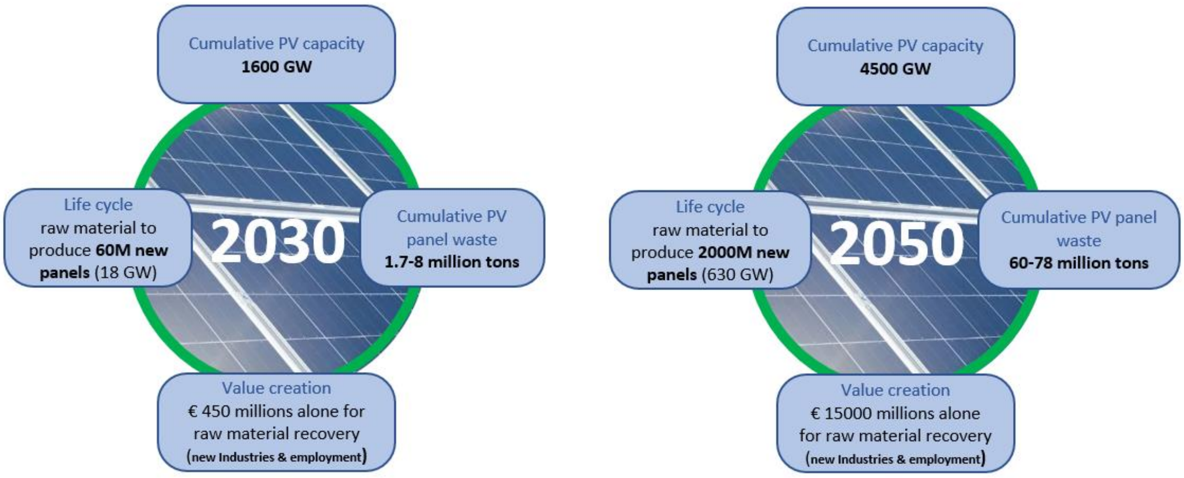

Figure 11. PV system lifecycle data. 2030 vs 2050 comparison

As usual, low quality recycled materials can be used to produce lower-grade PV modules, such as those used for off-grid or non-critical applications. They may also be used to produce other products, such as construction materials or insulation. High quality recycled materials are typically used to feed PV module production processes. This is because these materials meet the same level of quality and performance as the original PV modules, and thus can be used for the same applications.

Figure 12 shows a possible mass-flow diagram showing PV life cycle stages, processes, and decisions (Ovaitt, et al., 2022). Arrows represent the mass flow, circles the process efficiencies, hexagons symbolize decisions, and rhombuses are final dispositions.

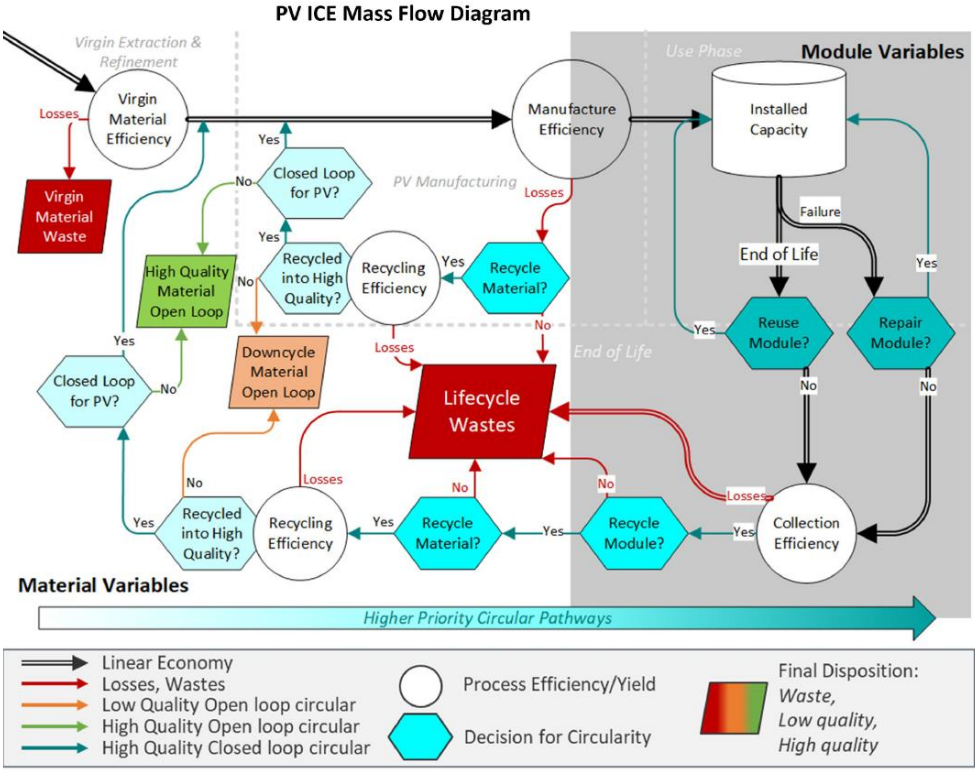

Figure 12. Mass-flow diagram showing PV life cycle stages, processes, and decisions (credit: Elsevier-ScienceDirect, creative commons CC BY-NC-ND 4.0)

3.2 Solar Thermal Collectors

3.2.1 Introduction

Earth's major source of energy is solar energy. Indeed, more than 175000 terawatts of solar energy hits the Earth in the form of light radiation, which is more much more the world's total energy demand. It seems obvious to try to exploit this endless energy source to our scope and the ancient Romans, just before the Common Era, were the first to develop systems to heat homes and water using solar energy and the greenhouse effect through glass. in 1767, Horace-Bénédict de Saussure, naturalist, and physicist from Geneve, conceived and built the first incarnation of solar panel, called "heliometer. In the mid-1800s, the Frenchman Auguste Mouchot thought of exploiting solar energy to produce mechanical energy, with the aim of reducing the dependence of his country's industry on coal. The low price of coal, however, overshadowed the great technical advances made. These two examples represent the roots of the two directions of development undertaken in the exploitation of solar thermal (ST) energy: that of indirect heating of environments through the circulation of fluids and that of the production of electricity from ST sources.

The first type of application (Figure 13) developed starting from the patent of the first commercial system to produce hot water by Clarence Kemp, in 1891. The system soon spread to Florida and California and, starting in the 1950s, to the rest of the world. The oil crisis of the early 1970s gave a new strong impetus to the development of this technology. The solar thermal industry has experienced significant growth in the last decade as a result of the improvement in efficiency of these plants, environmental maturity achieved in many industrialized countries, and the fundamental aids of their governments in supporting the development of this technology during the past decade.

Figure 13.On roof thermal collector system for DHW (credit: Chixoy, CC BY-SA 3.0 <http://creativecommons.org/licenses/by-sa/3.0/>, via Wikimedia Commons)

Figure 14. 50 MW high temperature molten-salt power tower in Hami, China (credit: Csp.guru, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons)

The other type of utilizing the solar heat consists in developing a high temperature generator, or some other gas heater, usually fed by a field of mirrors concentrating the solar irradiation as in Figure 14. This type of solar plant is usually placed in large open space, also in desertic areas. In analogy to PV panels, great plants for electric energy production are built outside the cities, maybe in the outskirts, and in contrast, in the city body, a myriad of local heating systems, equipped with thermal panels, are spreading on the roofs of buildings. A mid temperature concentrated solar power (CSP) system in form of parabolic arrays is shown in Figure 15.

Buildings are also the main target of the so called “passive solar technology” which use sunlight to heat living space and move air without the use of mechanical and electrical means. Thermal mass - brick, concrete, stone - is used throughout a passive solar building to store heat collected from the sun through south-facing windows and use it when needed. Moreover, some method using conduction, convection, and radiation is essential to transfer heat from where it is collected to other zones of the building. Recent "hybrid" applications warm the heat transfer fluid using the back of photovoltaic panels, also obtaining the result of lowering the temperature of the latter, with benefit for their collector efficiency which can be furthermore increased by coupling the system to a heat pump for increased flexibility and performance (Kalogirou, 2004).

Figure 15.Mid Temperature parabolic trough arrays (credit: ArséniureDeGallium, Public domain, via Wikimedia Commons)

Systems for domestic single-family use have an average size of 4-6 m^2, with a 150-300 litres tank, which make it possible to produce hot water at a "low" temperature (55-65 °C, something more with vacuum tubes), however suitable for use in the kitchen, bathrooms, and warm up. The energy available to users in 24 hours generally spreads from less than 1.0 kWh up to 3.5 kWh for each m^2 of collector surface, respectively in winter and in summer with clear skies, also depending on latitude. In some countries, in addition to single-family type plants, centralized flat-plate solar collector plants have been built for demonstration purposes or as part of funded programs. In Germany, systems of up to 3500 m^2, with hot water tanks of several hundred m^3, have been installed for heating apartments, hotels, sports facilities, and manufacturing companies.

The availability of advanced technologies in the construction of buildings (for example new thermally insulating and light-transparent materials) is opening the possibility of using solar panels for winter and summer air conditioning of homes and buildings. In Freiburg, the Fraunhofer Institute for Solar Energy Systems has been experimenting for years with a new type of house that is air-conditioned all year round using only solar energy.

When it comes to Solar District Heating (SDH) system, the first ST plants for SDH date back to the late 1970s in Sweden. Since then, other plants have been installed mainly in Denmark, Germany, Austria, and Sweden. A comprehensive set of guidelines and a website have been developed through the EU projects SDHtakeoff, SDHplus, and SDHp2m since 2009. There are several examples of successful solar district heating systems in urban areas in Europe, such as:

In Denmark, the city of Silkeborg has one of the largest solar district heating systems in the world. The 156,694 m^2 (110 MWth) SDH plant was completed in about seven months, on schedule, in December 2016. Municipal utility Silkeborg plans to use the solar energy it has captured to fulfill 20% of the yearly heating needs of 21,000 users connected to the plant's.

In Germany, the Black Forest city of Freiburg has an extensive solar district heating network that serves more than 9000 buildings. This city (population: 230000) describes itself as the environmental capital of Germany. This community in the southwest actively promotes solar energy thanks to its 1800 hours of sunshine every year.

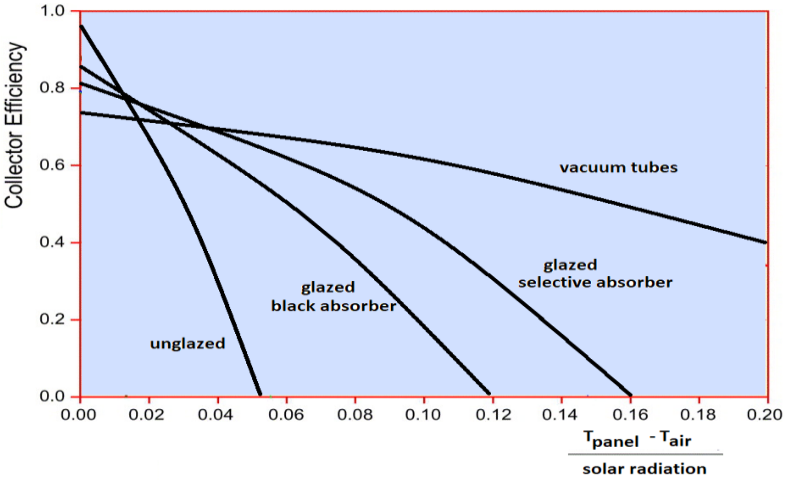

Figure 16. Collector efficiency for various panel typologies as a function of solar radiation and temperatures

3.2.2 Technical Analysis

Within cities Solar thermal is commonly used for water heating. Basically, it's a simple system: the solar panels on your roof collect solar energy, which is used to heat up the liquid in tubes, which is then transported into your storage cylinder.

However, ST panels have evolved according to different directions which have led to embodiments characterize by various levels of performances and tuned to distinct employments and contexts.

- ***Bare, unglazed, solar panels*** are usually employed as swimming pool heaters. Generally, these panels are made of heavy-duty rubber or plastic and are coated with an ultraviolet light inhibitor to enhance their life span. the black surface of the heater captures solar energy and transmits it to the water passing through the mat's network of pipes. The heated water gradually increases the temperature of the pool after a few days of sunny weather. These relatively inexpensive panels are often integrated with other heating means, sometimes a heat pump, and a pool insulating cover is advisable to reduce water overnight cooling due to evaporative and radiation losses. Beside pool heating, this panel type is also suitable for very low-cost systems, such as showers in hotels and summer campsites and in bathing establishments. Moreover, for productions such as washing water in the food industry and tannery, and hydroponic cultures in greenhouses.

- ***Glazed flat-plate solar panels***, are the classic ones made up of the real panel protected by a glass.The heat absorber inserted in the panel is thermally insulated from the outside air temperature by means of a tempered glass, above, and a layer of insulation below (rear body). They can produce hot water all year round.

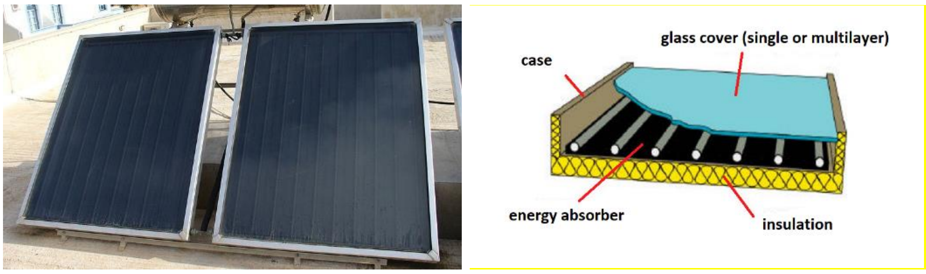

Figure 17. Flat plate solar collector (left) (credit: 23x2, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons). Illustrative view of the internal means (right) (

For these reasons they are more expensive than uncovered panels, but they are the most common in the traditional domestic sector. The collector efficiency is higher than the one of the unglazed panel since, a part from the rear insulation, the glass cover is transparent to the sunlight that enters it, but it is opaque to infrared rays that are retained inside (greenhouse effect). In this way the fraction of the incident energy that is re-emitted to the outside is much smaller. To enhance the greenhous e affect, multiglazed glass cover is often employed. Both glazed and unglazed collectors must include an antifreeze system in cold climates.

- ***Vacuum tube solar panels*** are the natural evolution of glazed panels and are suitable for cold climates and higher temperature heating. Much more expensive, they are able to provide very high performances. Evacuated tube collectors are made up of a single or multiple rows of parallel, transparent glass tubes supported on a frame. Unlike flat panel collectors, evacuated tube collectors do not heat the water directly within the tubes.

Figure 18. Vacuum tube collectors (right) (credit: Kgbo, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons) and tube schematic (right) (credit: Ilijanasov, Public domain, via Wikimedia Commons)

Each tube consists of a thick evacuated glass outer tube and a thinner glass inner tube, containing a proper heat transfer fluid, which is covered with a special coating that absorbs solar energy but inhibits heat loss. Inside each glass tube, a flat or curved aluminium or copper fin is attached to a metal heat pipe running through the inner tube. This sealed copper heat pipe transfers the solar heat to its internal heat transfer fluid which evaporates and rises by convection to the top, to a "hot bulb" that indirectly heats a copper manifold within the header tank. At the hot bulb, the vapor releases heat and condenses descending the heat pipe. The insulation properties of the vacuum are so good that while the inner tube may be as high as 150°C, the outer tube is cool enough to touch.

Both flat-plate and evacuated tube solar collectors can be found with integrated water tank. Usually in small size system. They are easy to transport and to install and have a relatively low cost. The flat plate type is not suitable for use in very cold locations because the water contained in the tank could freeze and ruin the panel.

Figure 19. Evacuated tube collector with auxiliary tank (credit: RanjithSiji, CC BY 3.0 <https://creativecommons.org/licenses/by/3.0>, via Wikimedia Commons)

- ***Solar assisted heat pumps (SAHP).*** In a simple solar thermal system, the temperature of the panel is linked to that of the reservoir. If I need hot water, I have to feed the reservoir with hotter water. Thus, the panel temperatures will have to be higher, and a significant amount of the sun's energy will be wasted in the ambient air. The collector efficiency decreases with increased temperature. To avoid these losses, double glazing and evacuated tubes are implemented.

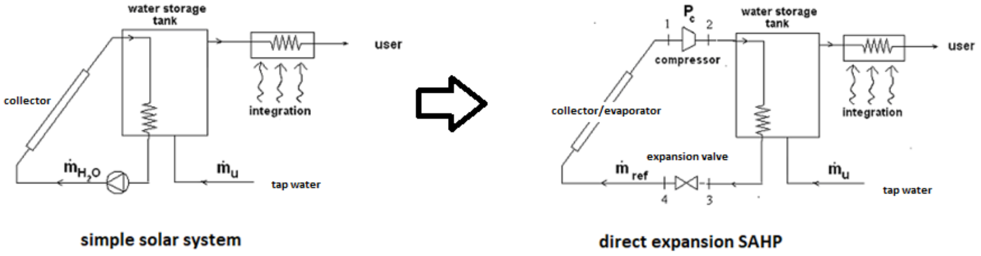

Figure 20. Solar assister heat pump schema. Comparison to a simple solar heater loop

Another approach is to break the link between panel and tank temperatures by means of a heat pump (Scarpa, et al., 2011). The panel is put in direct or indirect thermal contact with the HP evaporator while the reservoir water is heated by the HP condenser. In this way the panel remains cold, losses are minimized, and the panel surface can be strongly reduced for the same user demand. This technology fusion, often reported as “thermodynamic solar”, add the cost of the HP, but the technology is similar to that for geothermal heat pumps and quite consolidated. At the same time, savings are possible on the collector side since panels will be smaller and simpler (they are similar to the roll bond panel used for refrigeration).

- ***Integrated PV/T solar collector***. In this system, photovoltaic and thermal technologies are combined in a single compact device referred to as Photovoltaic/Thermal (PV/T) which consists of a PV module and a heat exchanger capable of generating both electricity and heat (Charalambous, et al., 2007). As the efficiency of a PV panel decreases at higher temperatures, removing heat by flowing a fluid through the collector mitigates this loss of efficiency. In addition, the combination of these technologies allows a significant saving of roof space in respect to the separate solution.
  PV/T collectors can be effectively used in conjunction to a solar assisted heat pump (SAHP) system which, if required, can be designed as a self-sufficient device.

Figure 21. Integrated photovoltaic/Thermal (PV/T) collectors (PV/SAHP system). University of Genoa Campus, Italy

The design of a simple solar thermal roof system to provide domestic hot water (DHW) to a single-family consists in a straigddthforard procedure followed by the panel installer. A procedure that shares some points with the installation procedure of PV panels. The usual target is to achieve a degree of autonomy between 60% and 80%. After the choice of the system type, the sizing involves the evaluation of:

- the solar resource in the specific location
- the user needs, that is the family hot water consumption habits
- the house characteristics and the roof conformation and exposition

Figure 22. District heating by a solar thermal collector field of 18300 m^2. Marstal, Denmark (credit: Erik Christensen, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons)

The evaluation of these and other parameters, after inspection by an installer technician, will allow to determine the number of panels, the volume of the accumulation and to proceed with the operational project. If the system is conceived to integrate a traditional source and feeds a low temperature heating system, e.g. underfloor heating, the surface of the panels must be increased, as well as the size of the tank which can even reach 1500 litres for homes exceeding 100 m^2.

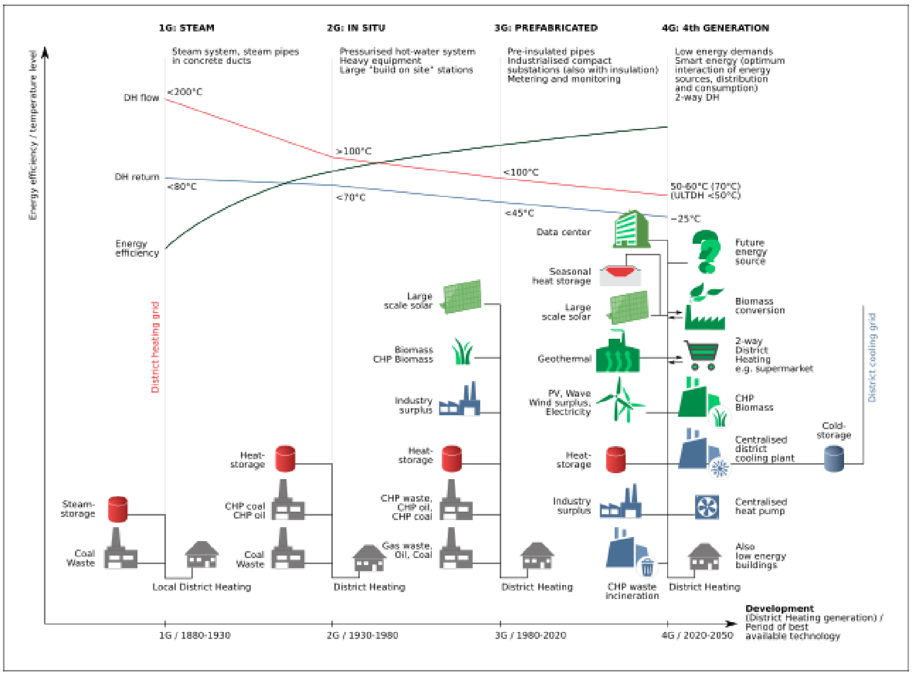

Figure 23. Generations of district heating systems (credit: MrmwAndol, CC0, via Wikimedia Commons)

The evolution of district heating (DH) systems can be divided into four generations, with each generation characterized by different technologies and methods of heat generation and distribution (Figure 23). Since the 3rd generation (1980-2020), large scale solar energy systems are included as a source. This generation of DH systems is characterized by the increasing use of renewable energy sources, such as geothermal, solar, and biomass, as well as the integration of smart grid technologies to improve the efficiency and flexibility of the systems.

When including a ST system in a *district heating network*, three main elements are usually considered: the solar system – its integration into the network and – the flow regulation means. The solar source supplies a variable portion of the total DH demand. Regardless of the system typology, the system integration is simple if the ST system can only meet a tiny portion of the DH requirement. No additional storage for the solar heat is needed when the solar portion is so low, about 50% of the daily summer demand in the DH network on a day without clouds. Higher solar percentages necessitate for storage someplace in the system. The decision between centralized and distributed storage results in several system typologies and the requirement for a comprehensive plan for the entire DH network. Three type of system topology are usually found.

- central solar collector field with central storage
- distributed collector field with central storage
- distributed collector field without storage (feed-in)

From a technical perspective, solar district heating is a feasible option in areas with sufficient sunlight and a suitable layout for the installation of the solar panels. The solar panels are more frequently installed on the ground. Solar district heating systems are also low maintenance and have a long lifespan, making them a reliable source of heat for communities.

3.2.3 Economic Analysis

Economical and technical feasibility of the solar thermal technology at large, requires a preliminary distinction

- *Solar district heating*

Solar district heating is a renewable energy system that uses solar panels to provide heat for multiple buildings or households in a specific area. This system has both economic and technical feasibility, making it a viable option for communities looking to reduce their carbon footprint and energy costs. From an economic standpoint, solar district heating can be a cost-effective solution in the long term. While the initial investment in the installation of the solar panels and the necessary infrastructure may be significant, the savings on energy costs can be substantial. Solar district heating systems can also take advantage of government incentives and subsidies, further reducing the financial burden of the initial investment. However, the cost of solar thermal systems has been declining in recent years, making them increasingly competitive with traditional heating methods. Renewable resources have grown more affordable to produce as technology has advanced so that their growth accelerates. Governments are consequently beginning to abandon funding programs. Either they can't keep up with funding or they don't think incentives are necessary anymore. Investors in renewable energy have been severely impacted by the market move from subsidized projects to open markets, hence alternative securities, for instance the power purchase agreement (PPA, which can cover an existing asset previously under a feed-in tariff), must now be produced to replace government subsidies (Bruck, et al., 2018).

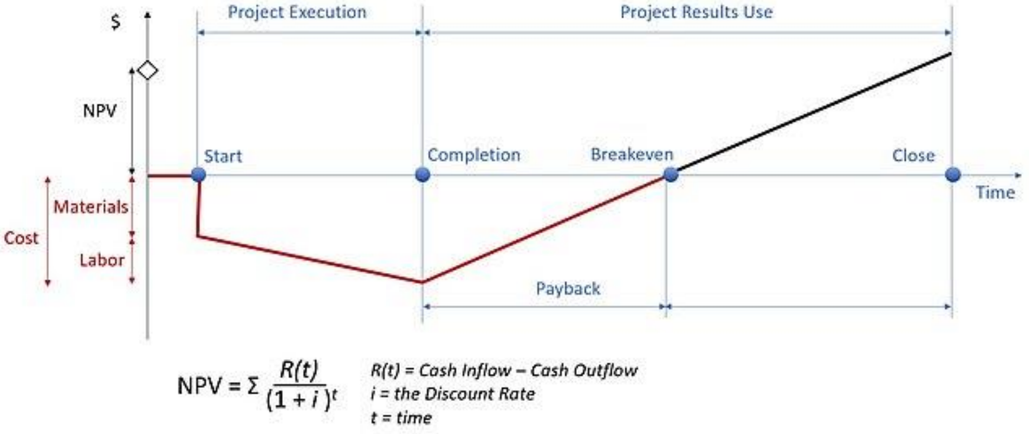

Figure 24. NPV- Payback representation (credit: Kokcharov, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons)

Apart from that, one challenge in implementing this technology is the need for sufficient space to install the solar thermal collectors. In urban areas, the availability of suitable land may be limited and the cost of acquiring and developing it can be high so that, in some cases, the cost of implementing a solar district heating system may be higher than traditional heating methods, particularly in cases where land availability, zoning and regulations are challenging. In this scenario, the feasibility of solar district heating systems should be considered on a case-by-case basis, considering the specific economic and energy market conditions of the area under consideration. The tools that can be used to perform an economic feasibility analysis of solar district heating are as usual: Life Cycle Cost Analysis (LCCA) (Naves, et al., 2019). This method evaluates the total cost of a solar district heating system over its entire lifecycle, considering the initial investment costs, operating costs, and maintenance costs and can provide a comprehensive understanding of the long-term economic viability of a solar district heating system. Net Present Value (NPV), which calculates the present value of future cash flows (and/or savings) generated by a solar district heating system, accounting for the time value of money (Figure 24). NPV can be used to compare the financial attractiveness of solar district heating to other investment options (Volkova, et al., 2019). The Payback Period calculates the length of time it takes for the benefits of a solar district heating system to pay back the initial investment costs. Internal Rate of Return (IRR) determines the rate of return on an investment in a solar district heating system. An IRR above a certain threshold is considered acceptable for a project to be profitable. The LCOH, levelized cost of heat, derived from LCOE, is used to evaluate the solar heat from the solar district heating plants various study (Tian, et al., 2018). The LCOH concept can be used as a tool to help to make decisions on systems planning and design.

- *On roof solar thermal panels*

On-roof solar thermal panel systems (Figure 25) are a renewable energy solution that uses solar panels installed on roof tops to provide domestic hot water and low temperature heat for buildings (Abd Alla, et al., 2020). These systems have both economic and technical feasibility, making them a viable option for individuals and businesses looking to reduce their energy costs and carbon footprint. The opportunity of design and install a thermal solar system devoted to single or multifamily use for DHW or low temperature heating is a task usually performed by the installer and it is quite consolidated.

Figure 25. On-roof solar thermal (credit: Bête spatio-temporelle, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons)

Currently, the cost of solar thermal systems is declining, making them increasingly affordable for homeowners and building owners. Additionally, government incentives such as feed-in tariffs and tax credits can help to offset the initial investment costs of a roof thermal solar panel system. However, it is important to note that the installation cost and maintenance cost are dependent on the panel size, the roof size and its condition, the location, the local labour cost and the chosen installer. To determine the most cost-effective solution, it's recommended to perform a detailed cost-benefit analysis, considering the specific economic conditions of the area under consideration, before making any decision (Martinopoulos & Tsalikis, 2014). With a combination of economic and technical feasibility, these renewable energy systems can provide a reliable source of heat while also helping to protect the environment. Anyway, regardless of all recommendations, it must be said that accurate economic analyses are rarely done when the investor is a family or even a condominium. Usually, one relies on the manufacturer/installer company which, being involved, would not be particularly suitable for this type of task.

From the Social acceptance viewpoint, there are some challenges associated with large solar district heating systems as they require a significant amount of land and can be expensive to install. Additionally, there can be concerns about the environmental impact of these systems, as well as potential issues with noise and visual pollution. Despite this, many communities have embraced large solar DH systems, particularly in Europe where solar thermal is more established. On the other hand, On-roof solar collectors have a small footprint and are generally well accepted by homeowners and communities since they represent a simple and cost-effective to reduce energy bill costs. Some concerns may involve the social/architectural acceptance of façade integrated solar-thermal but novel solutions are under way (Visa, et al., 2014).

3.2.4 Environmental Analysis and Circularity

Solar thermal technology represents a viable option to contribute to the fight against climate change, the reduction of the carbon footprint, and the protection of the environment. Thanks to the possibility of reducing, reusing, and recycling the materials used in its production and operation, this technology is able to provide a clean and renewable energy source in a sustainable manner. The challenge of collecting and utilizing solar energy for a house need, involves the use of a substantial portion of the roof area for the collectors, plus the fact that solar energy is only available from 5 to 8 hours during the day when the sun is up. The new technologies available today help us overcome these challenges. In selecting these new technologies, we must understand that their production in and of themselves involves extraction and utilization of certain resources taken from the earth. Therefore, it is our responsibility to make this selection well, so that the energy needed in their manufacture, for example, does not exceed the energy these solar technologies produce. To this aim a “life cycle analysis” (LCA) is performed. Solar thermal panel technology harnesses the power of the sun to heat water or air. This technology is particularly interesting from a circularity perspective as it allows for the reduction, reuse and recycling of the materials used in its production and operation.

The lifecycle of solar thermal panel technology encompasses all stages of this technology's existence, from the extraction of raw materials needed for its production to its final disposal (Koroneos & Nanaki, 2012). In the raw material extraction stage, materials such as glass and aluminium are mined and transported to the production facility. The environmental impact of this stage depends on the efficiency of the mining and transportation processes and the location of the resources. The production involves the processing of raw materials and the creation of the solar thermal panels. The environmental impact of this stage depends on the efficiency of the production processes and the energy used in the production facility. Moreover, the manufacturing process of both flat plate and evacuated tube collectors, may involve the use of harmful and chemical materials that can have a significant impact on the environment and human health. Indeed, the production of the collectors involves the use of glass, aluminium, and other materials, also toxic adhesives that must be properly managed not to pose a threat to the environment and human health. So manufacturers of thermal solar collectors must adopt sustainable and responsible manufacturing practices to minimize the impact of such materials on the environment and human health also using eco-friendly materials and production processes. By doing so, the industry can help ensure that the benefits of solar thermal technology can be enjoyed by future generations.

The installation stage involves the transportation and placement of the solar thermal panels in their final location. The impact of this stage depends on the transportation methods used and the location of the installation. The operative phase involves the operation of the solar thermal panels to heat water or air. Solar thermal panels have a minimal environmental impact during this stage, as they do not emit greenhouse gases or other harmful substances into the atmosphere.

The disposal involves the removal of the solar thermal panels at the end of their useful life. The materials used in their production, such as glass and aluminium, can be recycled and used to produce new panels or other products. But the design of solar panels must be improved to make them more easily recyclable, repairable, and reusable in the future. It is advised that companies join in bigger recycling initiatives because the economic viability of small-scale recycling may be constrained (El-Khawad, et al., 2022). This helps to reduce the environmental impact and protect natural resources. From the environmental impact standpoint, it contributes to reducing the dependence on non-renewable energy sources, such as oil or coal, which are responsible for greenhouse gas emissions and climate change. By using solar energy for heating, it's possible to reduce carbon dioxide emissions and protect the environment. The panels can be operated for many years, ensuring a very long lifespan, around 20-25 years, with very little maintenance so that waste reduced. The disposal of a large solar thermal field and that of on-roof collectors likely have significant differences in terms of scale and logistics. In particular, the disposal of a thermal field may involve the decommissioning and dismantling of several acres of equipment and infrastructure, while on-roof collectors can typically be removed relatively easily but with a possible loss of economies of scale. Indeed, economies of scale can lead to lower costs and increased efficiency in the dismantling of a district heating network, making it more economical for the company and potentially more cost-effective leading to lower costs (per unit) for materials and labour. In any case, a deep analysis on three systems (thermal SHC, conventional and PV assisted system) to identify the one characterized by the best life-cycle performances revealed that the impacts of PV assisted system are about 60% lower than those of the others, highlighting the advantage of using renewable electricity for building air-conditioning in locations with high solar radiation availability (Longo, et al., 2020). This option appears preferable in respect to the use of solar thermal heating and (absorption) cooling. A detailed study on LCA of a simple solar collector, accounting for production process, installation, maintenance, transports and disposal is reported in (Ardente, et al., 2005). The analysis also considers embodied energy consumption and conclude emphasizing the great environmental convenience of this technology.

Solar thermal technology can play an important role in the circular economy by reducing waste, extending the lifetime of equipment, and minimizing pollution while providing a sustainable source of energy.

3.3 Green Roofs/Walls

3.3.1 Introduction

Green roofs/walls (GRs/Ws) do not represent a direct source of energy but sustainable building features that provide a range of benefits in the urban context. They represent an important component of a city green infrastructure which refers to the integration of natural and semi-natural features into the built environment, providing ecological and other benefits to urban areas. Beyond GRs/Ws, some potential components of a green infrastructure are: street trees, community gardens, rain garden, bioswales (landscape areas that are designed to capture and filter stormwater runoff) and, in general, parks, green spaces, and urban forests.

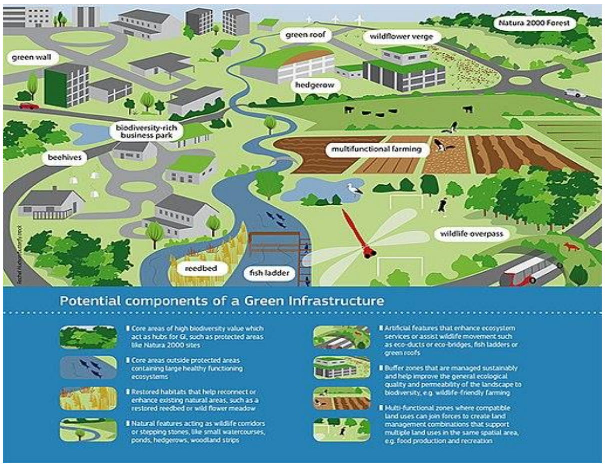

Figure 26. The forms and functions of green infrastructure (credit: Directorate-General for Environment, European Commission, CC BY-SA 4.0, via Wikimedia Commons)

In ancient times, people built green roofs on rooftops to provide insulation and to mitigate the negative effects of urbanization. The Hanging Gardens of Babylon, built around 500 BCE, was one of the most famous ancient green roofs. Early in the 1960s, with the energy shortages, contemporary green roofs first appeared in Germany.

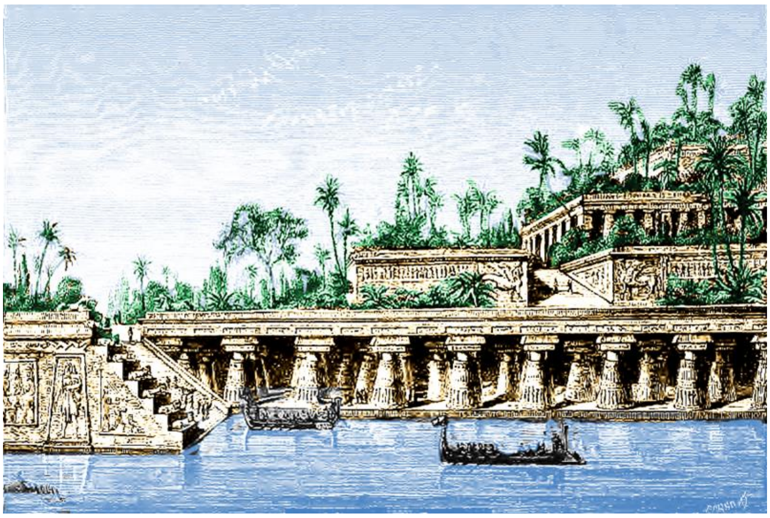

Figure 27. Jardins suspendus de Babylone (credit: Stella maris, CC BY-SA 4.0 via Wikimedia Commons)

Green roofs/walls have gained considerable attention in the domains of urban planning, architecture, and environmental science due to their growing popularity. GRs/Ws may be retrofitted onto existing structures, they give urban wildlife a biodiverse habitat, and can make public places more interesting for city dwellers to enjoy. Green roofs can also provide a new outdoor space for office employees and make previously unattractive locations appealing. Indeed, they provide a natural and pleasing environment that reduces stress and improves well-being, improves air quality, regulates temperature reducing the urban heat island effect, and reduces noise levels, making it a more peaceful and relaxing environment for office workers.

The increasing popularity of green roofs/walls has made them a topic of interest in the fields of urban planning, architecture, and environmental science. GRs/Ws have been implemented in cities of all sizes around the world. Some examples of cities that have implemented these structures include:

New York City, *Figure 28*, has a number of GRs/Ws, including the High Line (*Figure 28*), a public park built on a disused, elevated freight rail line 2.33 km long, first opened in 2009. It is considered one of the finest examples globally and has come to represent the excellence of American contemporary landscape architecture. The Greenbelt Native Plant Center, a green roof on a public works facility.

Japan, Osaka Namba Park has an 8-Level Roof Garden with waterfalls. It consists of a high-rise office building called Parks Tower and a 120-tenant shopping mall with rooftop garden. It was conceived as a large park, a natural intervention in Osaka's dense urban condition (*Figure 29*).

Toronto, Canada: Toronto has a number of GRs/Ws, including the Green Roof Innovation Testing Lab, a research facility that studies the performance of different green roof systems.

Figure 28. New York High Line (credit: U.S. Department of Agriculture, Public domain, via Wikimedia Commons)

Figure 29. Namba Park views (credit: 663highland, CC BY-SA 3.0, via Wikimedia Commons)

GRs/Ws have been clearly implemented also in cities throughout Europe.
Berlin has a long history of GRs/Ws, and the city has implemented a number of initiatives to promote their use. One example is the Green Roofs Program, which provides funding and technical assistance for the development of GRs/Ws.

Paris has implemented many green roofs/walls structures, including the Promenade Plantée (*Figure 30*), a public park built on an elevated railway line, and the Toits de Paris, a program that provides funding for the development of green roofs/walls on public buildings.

London has a number of green roofs/walls, including the Thames Barrier Park, *Figure 31*, a green roof/wall project that includes a park, playground, and community garden

Stockholm has a strong tradition of green roofs/walls, and the city has a number of initiatives to promote their use. One example is the Green Roofs for Healthy Cities program, which provides funding and technical assistance for the development of green roofs/walls.

Vienna has implemented several green roofs/walls projects, such as the Green Roofs Initiative. This initiative offers financial support and technical guidance to promote the establishment of green roofs/walls on public buildings.

Figure 30. Promenade plantée, Paris, France (Coulée Verte René-Dumont) (credit left: jean-louis Zimmermann from Moulins, FRANCE, CC BY 2.0, via Wikimedia Commons)(credit right: Guilhem Vellut from Paris, France, CC BY 2.0 via Wikimedia Commons)

Figure 31. The Green Dock, London Borough of Newham (The Green Dock, Thames Barrier Park by David Martin, CC BY-SA 2.0, via Wikimedia Commons)

Milan won the *2015 Best Tall Building Worldwide Award* and the *Award of Royal Institute of British Architects (RIBA) 2018 for International Excellence*, for the Vertical Forest, Figure 32, a residential complex in the Porta Nuova district (Stefano Boeri Arch.). The two towers, named *Bosco Verticale*, are covered in by over 20,000 trees, shrubs, and plants, making them some of the most iconic and recognizable green buildings in the world. The towers are designed to maximize the use of green spaces, with each floor featuring a different selection of vegetation.

In general, green roofs/walls can significantly enhance the urban environment by expanding green spaces, regardless of the city's size. This section primarily aims to examine the advantages and obstacles associated with implementing green roofs/walls in urban areas, considering their technical, economic, environmental, and social aspects. The benefits and challenges of implementing GRs/Ws in the urban context are complex and multifaceted (Shafique et al.,2018). From a technical standpoint, these building features require careful planning and consideration of barriers, standards, policies, incentives, and strategies. From an economic viewpoint, GRs/Ws can offer significant benefits, but they also come with initial and ongoing costs.

Figure 32. Milan, Italy. The vertical forest (credit left: Oliver Wendel c_ow, CC0, via Wikimedia Commons) (credit right: Patrick Bombaert pbombaert@skynet.be, CC BY 2.0, Flickr)

Looking at the environment, green roofs/walls provide numerous advantages. These include lower greenhouse gas emissions, better air quality, noise reduction, substantial energy savings, and enhanced biodiversity. Moreover, GRs/Ws can improve mental health, increase community engagement, and enhance urban aesthetics. To make the most of the advantages and overcome the obstacles of green roofs/walls, it is crucial to take into account all these factors and involve the community throughout the planning and execution phases. In general, GRs/Ws represent a promising sustainable building option that can contribute to a more liveable and resilient urban environment. Public policies implementation may play a substantial role in encouraging Green Roofs/Walls installation.

3.3.2 Technical Analysis

One of the technical challenges of implementing and maintain GRs/Ws in the urban context is the need to rethink future urbanization scenarios This includes ensuring that there is adequate space for vegetation and that the surrounding environment supports the growth of green roofs and walls. Siting &design / Load-Bearing capacity/ Water management/ Maintenance. These all present significant technical challenges requiring careful planning and consideration. Such planning involves identifying and overcoming obstacles to their adoption, such as lack of awareness or knowledge, lack of standards and regulations, and limited availability of funding. It also involves setting standards and establishing policies, incentives, and strategies to encourage the adoption of GRs/Ws. Furthermore, efforts to promote and disseminate information about green roofs, as well as investments in education and training, can help increase their adoption. Challenges associated with installing green roofs on new or existing buildings, if not properly reviewed or addressed, can increase costs and deter owners from installing such roofs. More in details, challenges and issues refer to all the phase of the life of GRs/Ws

Siting and design

Siting and designing involve considering the structural capacity of the building and the additional weight and load that the green roof/wall system will add. The dead load of a green roof assembly should be determined on a project-specific basis, because growth medium composition varies from job to job and the results can only be regarded as a prediction, not as the true weight of the green roof system (Weiler & Scholz-Barth, 2009). Variations in actual green roof dead loads result from normal variations in material thickness and density. There are other load implications. Roof landscaping may change snow drift patterns, seismic loads, and ponding from rain accumulation; these changes may be in excess of typical or previous design allowances.

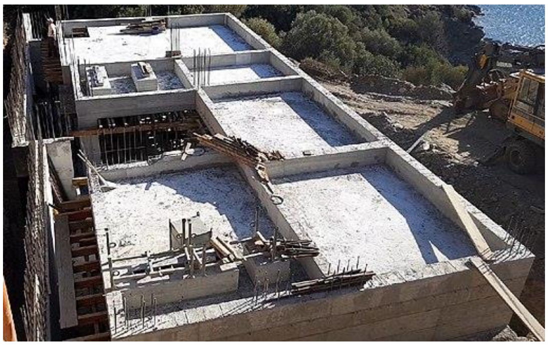

Figure 33. Construction of an extensive green roof in Likorema (Euboea, Greece) (Etan J. Tal, CC BY-SA 4.0, via Wikimedia Commons)

Figure 34. Lower Manhattan (credit: Alyson Hurt from Alexandria, Va., USA, CC BY 2.0 <https://creativecommons.org/licenses/by/2.0>, via Wikimedia Commons)

Depending on the type of construction, the climate, and the proposed system. In case of retrofitting, a feasibility study should be conducted on an existing structure to determine the capacity of a building to accept the weight of a green roof. A roof may have enough structural capacity built in to support a green roof of a given depth, or reinforcement may be needed.

Historic buildings create an opportunity for green roofs. However, this requires special consideration of the historic building's architectural and structural features. The design must be compatible with the building's original materials and must not alter the building's historical appearance Low-growing, ground cover plantings (e.g., sedum) should be planted behind existing parapets so that vegetation is not visible from the public right-of-way.

The preservation office will review permits to ensure that alterations are “compatible” with historic building character. A flat roof should not conflict a new green roof, as compared with the installation of solar panels, which stick up and alter the building’s outline or façade. Furthermore, various countries have adopted codes and standards pertinent to green roof installations which must accounted for. These codes and standards can vary depending on the location and jurisdiction, and may include guidelines for insulation, fire safety, structural loads, and waterproofing

Installation

One of the challenges of installing green roofs/walls is the lack of experience among contractors. Choosing a contractor with expertise in installing green roofs/walls is vital to ensure the project is executed accurately and within the specified timeframe. Another challenge is the proper handling of plants during the installation process. Green roofs/walls require a specific type of substrate, irrigation and drainage systems, as well as specific plants that are suited to the local climate and environment. If plants are mishandled, they can die, leading to expensive repairs or the need for an entire system replacement. Liability and warranty can also be an issue when installing green roofs/walls. Make sure the contract includes a thorough warranty that covers the installation and any potential defects. Additionally, prioritize safety as a crucial consideration.

Figure 35. Roof layers (credit: thingermejig, CC BY-SA 2.0 via Wikimedia Commons)

The must comply with all occupational safety and Health requirements that pertain to green roof installation. It is essential to provide training for workers regarding the appropriate safety protocols for rooftop work, as well as proper handling of materials and equipment utilized during the installation process. Once the GR/W is installed, it's important to establish the plants properly by keeping them adequately hydrated and nourished, this can take some time, and it is essential that the establishment period is properly planned and managed. Additionally, it might be necessary to conduct routine monitoring and maintenance during the initial months to guarantee the survival of the plants.

Maintenance and operations

Maintaining and operating green roofs/walls involves many challenges, such as leaks, plant loss, wind scour and uplift, and roof penetration. These challenges must be carefully monitored and addressed in order to ensure the longevity and effectiveness of the green roof/wall system. Since one of the main challenges of maintaining GRs/Ws is preventing leaks (Tolderlund, 2010), they are designed to retain water in the soil, so if there are any leaks in the roof or wall, it can cause water damage and can compromise the integrity of the green roof system. It's important to monitor and maintain the roof or wall's waterproofing system to prevent leaks. Another issue occurring is the loss of plants. This can happen due to a variety of factors such as improper irrigation, lack of sunlight, over-compaction of the substrate, or pest infestations so that a regular monitoring of the vegetation is crucial to prevent plant loss. Also, wind scour and uplift can be a problem on GRs/Ws, as the added weight and height of the green roof/wall system can make it more susceptible to wind damage. As said, it's important to consider wind loads and design the GRs/Ws system accordingly to prevent any damage.

Figure 36. AMA Plaza (Chicago) Green Roof Maintenance (credit: Flickr, Attribution-ShareAlike 2.0 Generic, CC BY-SA 2.0)

Green roofs/walls can be vulnerable to damage from roof penetrations, such as skylights, vents, or HVAC equipment penetrations which can create a potential for leaks and damage to the green roof/wall system. A study by (Silva et Al.,2015) addresses the upkeep of green roofs in Mediterranean regions. The building and roof systems of eleven case studies in Portugal are described in a field survey, together with any irregularities, underlying reasons, and maintenance procedures. The characterization of the actual in-service requirements benefits greatly from in-situ surveys. The study suggests a maintenance strategy to improve the upkeep of green roofs based on a discussion of the survey results and the general suggestions that are already accessible. The recommended maintenance schedule is broken down by maintenance source element, accounting for all system layers and additional green roof components like irrigation or drainage systems. It's important to maintain and repair roof penetrations to prevent leaks and assure the integrity of the GRs/Ws system.

Finally, it should be noted that the greater part of green roof research has been undertaken on a theoretical foundation, or with practical measurements on green roof test beds or isolated components, according to a survey of about 100 papers of particular interest for Nordic climates (Andenæs, et al., 2018). There isn't much literature on the operation of fully functional green roofs that have been installed on buildings, and no publications on the building technical performance of aged green roofs could be located. Given that the performance and integrity of green roofs over time have not been studied, these knowledge gaps point to a significant risk factor in their operation. Even though green roofs have been installed and utilized worldwide for many years, this fact remains true.

3.3.3 Economic Analysis

The economic feasibility and sustainability of green roofs/walls depend on a combination of factors, including initial costs, maintenance costs, energy savings, property value, stormwater management, and environmental credits.

The initial cost of installation can be significant, particularly if the roof or wall requires structural modifications to support the weight of the vegetation and substrate. It is important to evaluate the long-term cost-effectiveness of the project, accounting for factors as material and labour expenses, along with any required structural upgrades. GRs/Ws require regular maintenance, including watering, fertilization, and pruning, which can add to the overall costs. Any repairs or replacements that may be required must also be estimated and it is important for building owners and developers to carefully consider these costs and assess the potential return on investment before committing to a green roof/wall project. But Green roofs/walls can provide energy savings in buildings through various mechanisms:

1. Insulation: The vegetation on green roofs and walls act as insulation, helping to reduce heat loss in the winter and heat gain in the summer. This can result in lower heating and cooling costs for the building.

2. Temperature Regulation: Green roofs and walls help regulate temperature by reducing the urban heat island effect. This means that the surrounding air temperature is kept cooler, reducing the need for air conditioning in the building (Ascione, et al., 2013),

3. Rainwater Harvesting: Some green roof systems (blue-green roofs) can also be designed to collect and store rainwater for irrigation or non-potable uses, reducing the building's water consumption and the energy required to pump and treat water.

Saving energy and costs in the long term will lead to lower energy bills for dwelling owners. As they are seen as a desirable feature by potential buyers and renters, GRs/Ws can also make a building more attractive with an increase of the property value. Reducing stormwater runoff costs by capturing and retaining water, which can save money on infrastructure and maintenance (Carter & Jackson, 2007).

All these data can used to quantify the economic feasibility of a green roof/wall system by indices like the simple payback period (SPP), net present value (NPV), internal rate of return (IRR), Return on Investment (RoI), and others (Ma'bdeh, et al., 2022). NPV helps determine how much money an investment will make or lose over time, accounting for the time value of money. The NPV method is considered to be a standard method for evaluating long-term investments. SPP is a metric that expresses the period of time it takes to recover the initial investment through savings or revenues generated by the investment. A shorter SPP means that the investment will pay off sooner and is thus more economically feasible. It is a common method to evaluate simple and short-term investments. Both NPV and SPP methods are useful tools when evaluating the economic feasibility of green roofs/walls, as they provide a way to determine the return on investment over time and can be used in conjunction with other analysis methods. It's important to note that while they can provide valuable information, they do not consider environmental and social benefits as well as externalities (Bianchini & Hewage, 2012), neither any legal nor regulatory aspects, thus other factors should be taken into account as well.

More advanced financial feasibility studies (Mahdiyar, et al., 2021) involve the use of probabilistic approaches including:

- Design and evaluation of different analysis scenarios
- NPV (*Figure 37*) and DPBP (discounted payback period) evaluation in stochastic context by means of Monte Carlo simulation
- Short- and long-term costs and benefits of GRs/Ws installation assessment
- Sensitivity analyses

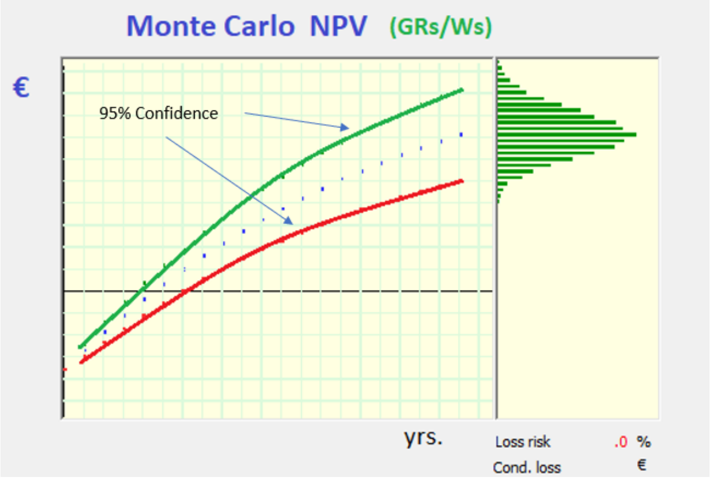

Figure 37. NPV calculation example in stochastic regime

Most studies on this subject conclude by underlying that the implementation of these green structures is cost-effective over the long term, providing a range of benefits including energy savings, increased property values, reduced maintenance costs, and improved stormwater management.

From a community standpoint, GRs/Ws can create sustainable jobs in a transformed green economy, as they require skilled professionals for installation, maintenance, and management.

3.3.4 Environmental Analysis and Circularity

Cities continue to be a substantial environmental burden despite significant efforts to manage their resources in a more sustainable manner (Langergraber, et al., 2021). The demand for fresh resources (water, food, energy, and materials), together with high pollution levels and ecological deterioration, rises in tandem with the urban population growth. Although many cities have endorsed policies for resource efficiency and sustainable development, the bulk of urban areas still have a significant negative impact on the environment. Few existing frameworks present urban difficulties from the perspective of strengthening the circularity of resources management in cities and ensuring a sustainable urban development. In terms of the potential of nature-based solutions to enhance resource efficiency, the green economy, and circularity, the EU research project Nature4Cities (Grant ID: 730468) fosters a set of urban challenges (Ramusino, et al., 2017). Vertical Greening Systems and Green Roofs are among the Nature-Based Solutions Units that are acknowledged as having significant potential in this area.

Environmental benefits

Green Roofs/Walls offer a range of environmental benefits in the urban context. One of the main benefits is the reduction of greenhouse gas emissions, as GRs/Ws can help to reduce energy consumption for heating and cooling. Using evapotranspiration and simply covering the roof with a less absorbent surface can lower temperatures. Green roofs will translate into significant economic gains by reducing the energy costs associated with cooling buildings. GRs/Ws can also improve air quality by removing pollutants from the air and releasing oxygen (Yang, et al., 2008). In addition, these green structures can increase biodiversity by providing habitat for plants, insects, and animals in urban areas.

By understanding the full environmental impact of GRs/Ws, it is possible to design and implement these systems in a more sustainable manner. One approach to achieve this is by considering the principles of a circular economy, which focuses on minimizing waste and optimizing resource utilization through recycling and reusing. GRs/Ws can contribute to a circular economy (Calheiros & Stefanakis, 2021) by using recycled materials, such as recycled rubber or plastic, in their construction and by allowing the reuse of materials at the end of their lifespan. Green roofs/walls use natural materials such as soil, plants, and rock, which are renewable resources that can be replenished. In addition, they can be constructed with recycled materials such as crushed concrete, glass bottles, or reclaimed wood. This reduces the need for virgin materials and helps to close the material loop. By reducing the volume of rainwater excess, it is possible to lessen the strain on municipal stormwater systems. GRs/Ws also reduce the urban heat island effect (Susca, et al., 2011), which can decrease the need for air conditioning, thus reducing energy consumption and waste, and decreasing carbon emissions (Žuvela-Aloise, et al., 2016). Green roofs/walls can help to sequester carbon by removing carbon dioxide from the air through photosynthesis.

Long-lasting products and closed loop: green roofs/walls are designed to last for many years, which means they can continue to provide benefits long after they are installed. Their maintenance and end-of-life plan also play an important role.

Social benefits:

Figure 38. Nomura International plc roof garden, London (Photo © David Hawgood,cc-by-sa/2.0)

Beyond economic and environmental benefits, GRs/Ws can have a range of social benefits in the urban context as the improvement of mental health and well-being (Ode Sang, et al., 2022). Research showed that being exposed to nature, also green roofs, can have positive effects on mental health by reducing stress and anxiety. GRs/Ws can also increase community engagement by providing spaces for social interaction and recreation (Williams, et al., 2019). In addition, green roofs can enhance urban aesthetics and can contribute to a sense of place and community identity. So, it is important to consider the social acceptance of GRs/Ws when implementing these systems in the urban context. Engaging with the community and stakeholders is crucial in order to grasp their needs, preferences, and concerns. This engagement is vital for designing and implementing green roofs/walls in a manner that aligns with the community's expectations and requirements. It is also critical to consider the temporal cycles of vegetation, as green roofs may not always be green or in bloom. This can affect the perceived value of GRs/Ws by members of the community and the installation and maintenance of green roofs/walls can create jobs in the green economy, supporting local businesses and communities and contributing to the social acceptance of the technology. (Zambrano-Prado, et al., 2021) provide an intriguing study on a different but related topic, agri-green roofs (UAGR), and examine the opportunities and perceived challenges associated with its deployment in urban areas. They reviewed the five categories of potential and limitations (social, environmental, legal/administrative, technological/architectural, and economic). The Mediterranean environment, a lack of specific norms and procedures, the initial investment, the pre-condition of the roof and its load bearing capacity, and a lack of knowledge and social cohesion related UAGR projects were the primary obstacles noted. Social cohesiveness, higher life quality, new particular legislation, money made from UAGR initiatives, and aesthetic advancement were the key opportunities.

To conclude, as cities have worked to improve their sustainability and liveability there have been a substantial increase in the acceptance of this technology and green roofs and walls are now recognised as an important technique for enriching the urban environment, offering a number of benefits. The initial expense of installation and the requirement for ongoing care are two obstacles that still stand in the way of the widespread use of GRs/Ws. Nevertheless, the technology has gained widespread recognition as a valuable asset for establishing sustainable and livable urban environments. With cities confronting ongoing challenges like climate change, urbanization, and environmental degradation, green roofs and walls are expected to assume a progressively vital role in shaping the cities of tomorrow.

3.4 Heat Pumps

3.4.1 Introduction

Heat pumps (HPs) are gaining recognition as a crucial technology for decarbonizing heat and have garnered substantial policy backing in various countries. In urban areas, HPs have become a prevalent and favoured option for heating and cooling buildings. Compared to traditional heating and cooling systems based on fossil fuels, they provide a more energy-efficient choice.

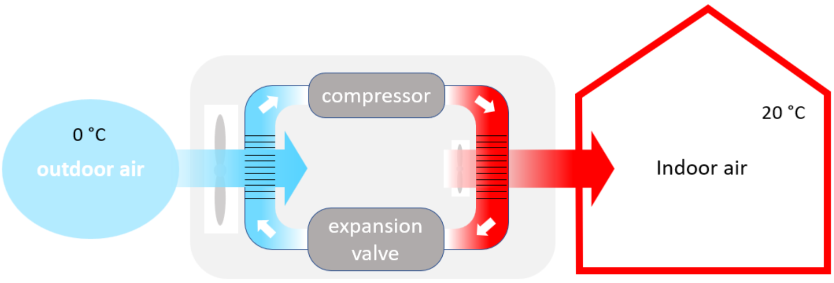

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Figure 39- Typical heat pump scheme for residential heating

The first heat pump wasn't created until the 19th century by British physicist Lord Kelvin that, using the principles of thermodynamics, conceived this device to extract heat from the air. Heat pumps were mostly utilized for industrial processes and refrigeration around the turn of the 20th century. In the 1950s, the first air-source heat pump for home heating was released, and it was initially well-liked in areas with mild winters. Heat pumps, however, didn't start to be widely used in North America for home and commercial heating and cooling until the energy crisis of the 1970s. Following the oil crisis, a large number of actors became involved in the heat pump sector, and the intense coopetition dynamics relating to heat pumps contributed to durable connections and synergies during the early stages of the transition. Large heat pumps were increasingly used in district heating systems in certain European nations during the 1980s, especially in Sweden. However, in the mid-1980s, oil prices returned to their previous low levels and this, combined with lifted subsidies and higher interest rates, created a stagnation for heat pump industry that underwent a 10-year period of low sales of small heat pumps while the market for large heat pumps practically vanished. Nevertheless, in conjunction with changes in company ownerships and governmental industry support, the HP sector maintained both production and service capacity and, by the mid-1990s, it became possible for it to offer more reliable and standardised heat pumps to the home heating market. Over the years, heat pump (HP) technology has undergone advancements and refinements through the introduction of new refrigerants, compressor designs, and control systems. Presently, heat pumps have gained popularity as an energy-efficient substitute for conventional heating and cooling systems. Their applications span across residential buildings, as well as large commercial and industrial facilities.

Sweden has played a significant role in the heat pump market due to its extensive use of district heating systems. This experience has led to the widespread adoption of heat pumps also in residential and commercial buildings. According to a report by the European Heat Pump Association, Sweden held the largest market share for heat pumps in space heating in 2020, accounting for over 38% of the total market. This is partly because of the nation's aggressive climate goals and dedication to lowering carbon emissions in the building industry. Many heat pump markets in other European countries are 10 years behind the Swedish market in development.

Anyway, legislative support for heat pumps as a crucial technology for heat decarbonization has also grown in a number of different nations over the course of the last few years. Over 190 million heat pump systems were in use in buildings worldwide in 2021. In recent years, the worldwide inventory of heat pumps has been consistently growing, with notable expansions in key heating markets such as North America, Europe, and northern and eastern Asia. The deployment of heat pumps in urban environments is important for reducing carbon emissions and enhancing air quality in densely populated areas. By employing electricity to capture ambient heat from the ground, sun, water, or air, heat pumps can produce useful heat with one-third to one-fifth the electricity used by traditional electric equipment. Currently, heat pumps are more cost-effective than oil and gas for heating over their lifetime in many countries.

More specifically, in an urban environment, heat pumps are crucial for their characteristics of efficiency, reduced emissions and adaptability. Heat pumps are more efficient compared to traditional systems, and may reduce the energy required for heating and cooling buildings up to 50%. This efficiency is particularly needed in urban areas where energy demand is high and space limited. Moreover, heat pumps generate fewer carbon emissions than conventional heating and cooling systems, especially when utilizing renewable energy sources. Heat pumps do not emit carbon monoxide and nitrogen oxides, which worsen air quality in densely populated urban areas. Lastly, heat pumps are versatile and adaptable, suitable for various building types ranging from small residential homes to large commercial and industrial facilities, making them an ideal technology for urban settings. So, heat pumps have become essential for attaining urban sustainability, enhancing air quality, and lowering building energy demand and this technology is becoming increasingly popular among architects, engineers, and urban planners.

According to the Net Zero Scenario, heat pumps will make up more than half of all heating sales by 2030. As stated by (IEA, 2022),doubling the amount of heat pump installations would accelerate the replacement of gas boilers in the EU and result in a 2 billion cubic meter reduction in gas consumption in the first year.

However, regardless of the many benefits of heat pumps, fewer than 10% of all heating equipment sold globally in 2021 was a heat pump; 45% of that equipment still used fossil fuels. In fact, several factors contribute to the relatively low adoption rate globally and the cost of installation, which may be higher than that of conventional heating and cooling systems, is the first severe obstacle. While heat pumps could lead to energy savings in the long run, this can make it difficult for households and building owners to justify the expense. Furthermore, the technology is still quite new to users, and many people may not completely comprehend how it operates or its potential advantages. In some nations, there may also be legal and administrative obstacles that make it challenging to install and utilize heat pumps, such as out-of-date building regulations or codes that favour conventional heating and cooling systems. Finally, the dominance of fossil fuels in the heating industry represents an important barrier to the widespread use of heat pumps because oil and natural gas-based heating systems are firmly established in the market.

Despite these challenges, the market for heat pumps is expanding steadily as knowledge of the technology grows, adoption-promoting policies and regulations are updated, and awareness of the technology itself rises.

3.4.2 Technical Analysis

Heat pumps operate by drawing heat from the air, ground, or water and transferring it into a building to provide warmth during winter. Conversely, during summer, they extract heat from the building to provide cooling. Heat pumps use electricity to move heat rather than generating it, making them highly efficient and sustainable.

According to the second principle of thermodynamics heat naturally flows from a warm region to a cooler one, but this flow can be inverted by applying energy according to both the first and second law. The mechanical heat pump is the most popular type of heat pump (1MW) among many that have been conceived. It has four main components: evaporator, compressor, condenser and expansion device.

Common heat pumps use a refrigerant that passes through all these components, a working fluid that can change from a liquid to a gas when absorbs heat and back to liquid when releases it between the indoor and outdoor environments.

This technology is like that found in a refrigerator. Heat pumps are by far more efficient than traditional boilers or electric heaters and can be less expensive to operate because most of the heat is only transferred rather than generated. So, the heat energy produced is typically many times more than the amount of electric energy needed to operate.

The fluid in a heat pump follows four main processes.

- When the refrigerant is in the outdoor environment, in the component named evaporator, it absorbs heat from the air, ground, or water and vaporizes into a gas.

-This gas is then compressed by the compressor and increases its temperature and pressure. The energy spent to augment gas temperature is little compared to the one absorbed during evaporation but allows for the subsequent release of heat.

-The compressed gas then flows through the condenser which is in thermal contact with the indoor environment to be heated. Into the condenser, the hot refrigerant releases the heat it absorbed from the outdoor environment and condenses back into a liquid.

-The liquid refrigerant is then passed through the expansion valve, where it expands and cools down before being cycled back to the evaporator to repeat the process.

Heat pumps provides heating for building, domestic hot water, swimming pools and other users.

They are usually differentiated according to their heat source, though multiple sources are frequently used in the same system.

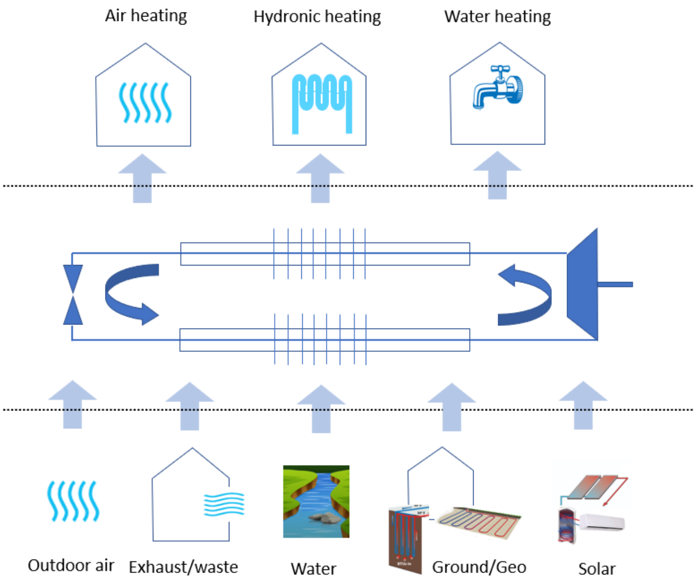

Figure 40- Heat pumps classification by source

Air-source heat pumps (ASHP):

These very common heat pumps extract heat from the outdoor air to heat indoor spaces. They work best in moderate climates. ASHPs are easy to install and cost-effective compared to other types of heat pumps. When installed properly, an air-source heat pump can provide a home with up to three times as much thermal energy as it consumes in electricity. All places, except those that regularly endured subfreezing conditions, have adopted air-source heat pumps. However, ASHP technology has improved recently, making it currently a viable alternative for space heating in colder climates (Zhang, et al., 2018).

There are various types of air source HPs. Packaged versus split. Most heat pumps are split systems, meaning they contain an inside coil and an exterior coil. The interior central fan is connected by supply and return ductwork. Conversely, coils and fans are typically located outdoors in packaged systems. A wall or roof-mounted ducting system distributes heated or cooled air to the inside.

Figure 41- Image 6209793 by HarmvdB <a href="https://pixabay.com/users/harmvdb-357255">

ASHP can also divided in Ductless vs. Ducted. Construction for ductless installations is minimal because all that is needed to connect the indoor heads and outdoor condenser is a three-inch hole through the wall. Just ductwork is used in ducted systems and can be convenient if the home already as a ventilation system. Also, single-zone and multi-zone systems can be found.

There are pros and cons to air source heat pumps. The main pros are low carbon footprint, good savings on energy bills, possible use for both heating and cooling, for both space and water heating, eligible for boiler upgrade scheme, easy installation, low maintenance, lifespan, no fuel storage. Among the cons we found lower heat supply than boilers, low efficiency below 0 °C, and they can be noisy. A systematic literature review of ASHP Field trials is found in (Carrol, et al., 2020).

Waste heat recovery heat pumps (WHRHP):

Heat pumps are a class of active heat-recovery equipment that allows the temperature of a waste-heat stream to be increased to a higher, more useful temperature. Usually, they recover heat from industrial processes or waste heat from buildings and use it to heat other spaces. They are highly efficient but require a reliable source of waste heat. The increase in temperature is achieved at the cost of an external mechanical or thermal (absorption HP) (Xu, et al., 2018) energy source, as in every HP (Van de Bor, et al., 2015).

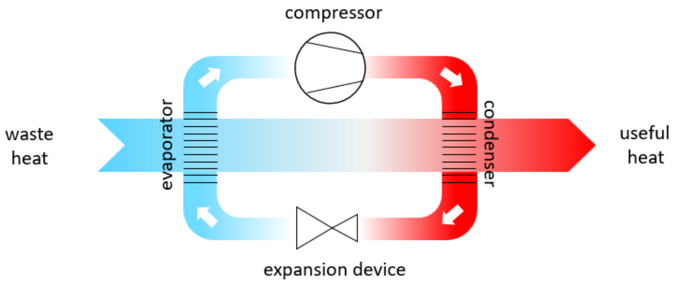

Figure 42- Schematics of waste recovery by Heat Pumps

High temperature heat pumps can be employed for a variety of tasks, including the production of hot water and the upgrading of waste energy for use in other systems. Integrability into the production process sector and matching the available heat source to the needed heat demand are two of the primary issues for high temperature heat pumps. The capacity of heat pumps to deliver process heat has recently attracted increased attention from a variety of industries in relation to energy efficiency, making use of surplus heat, and lowering greenhouse gas emissions associated with process heat generation.

Current conventional technology provides temperature up to 80 °C but key technology is commercially available up to 100 °C. On the other hand, in recent years, there has been a rapid advancement in research and prototypes are studied that reach 140 °C.

Water-source heat pumps (WSHP):

These heat pumps can extract heat from either a body of water, such a lake or river, or a ground loop system. They use water as their heat source. Despite being more effective than ASHPs, they can be more expensive to install because a water source is required. They are anyway less expensive than ground-source HPs. For commercial buildings, water-source heat pumps outperform alternative technologies in terms of energy efficiency. In order to function, a WSHP rejects heat to a water-pipe system (also known as a water loop) in the summer and absorbs heat from the same water loop in the winter. If several WSHP units are installed, a single water-loop system (or header) can service all of them. In comparison to ASHPs, the operation is quieter, and the system footprint is smaller because heat is more effectively removed from water than from air when it is transferred into a pipe carrying water via a heat exchanger. The low heat coefficient on the air side of an air-source system is the limiting factor of ASHPs; however, the forced convection heat-transfer coefficient on the water side is significantly larger, making WSHPs equipment more efficient and smaller.

WSHPs can provide simultaneous heating and cooling. It is typical for some tenants in a multi-use location to need cooling while others demand heat at the same time, depending on the orientation of the buildings and the needs of different types of tenants. WSHPs have the ability to transfer heat from one place that rejects it to another location that needs it.

The use of water as the heat carrier fluid has another advantage. Low-quality heat is thrown into the atmosphere since it is not cost-effective for an ASHP to recover it. As a result, this energy is squandered. A WSHP rejects energy into a common water loop, which serves as a reserve and may be quickly transferred to the location that needs heat. Due to the high heat-transfer coefficients that water is capable of achieving and its high specific heat, thermal energy is also transferred where it is needed as water is pushed through a pump to various locations within a single structure or group of buildings. Now, the energy that would often be lost in an ASHP is recovered and put to use elsewhere. The overall energy use of the building is reduced. Waste (sewage) water can be profitably used as heat source, this approach being widely applied in North European countries like Sweden and Norway since the beginning of the 1980s (Hepbasli, et al., 2014) .

Ground-source heat pumps (GSHP):

These devices, also known as “low temperature geothermal heat pump”, use the constant temperature of the ground to heating or cooling purposes (Abdeen, 2008). They are more efficient than ASHPs and WSHPs but can be more expensive to install due to the need for underground piping. Geothermal heat pumps are highly effective air conditioning systems for commercial and industrial buildings for the standpoint of energy savings and greenhouse gas emissions reduction. Building heating accounts for 30% of all main energy use, making energy efficiency in this industry more crucial and advantageous than ever. The correct sizing of a system of underground heat exchangers (geothermal probes), connecting geothermal heat pumps to the ground, a thorough understanding of the thermal properties of the surrounding ground as well as an assessment of the thermal loads of the building are needed. When the probe field is properly sized the temperature around the single underground exchanger settles at a few degrees below the undisturbed value and the performance of the system remains high; on the other hand, if the sizing is incorrect and there is an excessive intensity of heat extraction, the ground may even freeze near the exchanger, leading to the fall of the COP.

One benefit of ground-source heat pumps is that they operate under relatively stable conditions because, starting at a depth of about 15 meters, the ground temperature is roughly constant over time and unaffected by daily and seasonal temperature variations. In contrast, air heat pumps are affected by changes in the outside air temperature. Furthermore, adopting water heating systems that operate at low temperatures (30-40°C), like radiant flooring, can result in COP values in winter operation of the order of 4 and even higher.

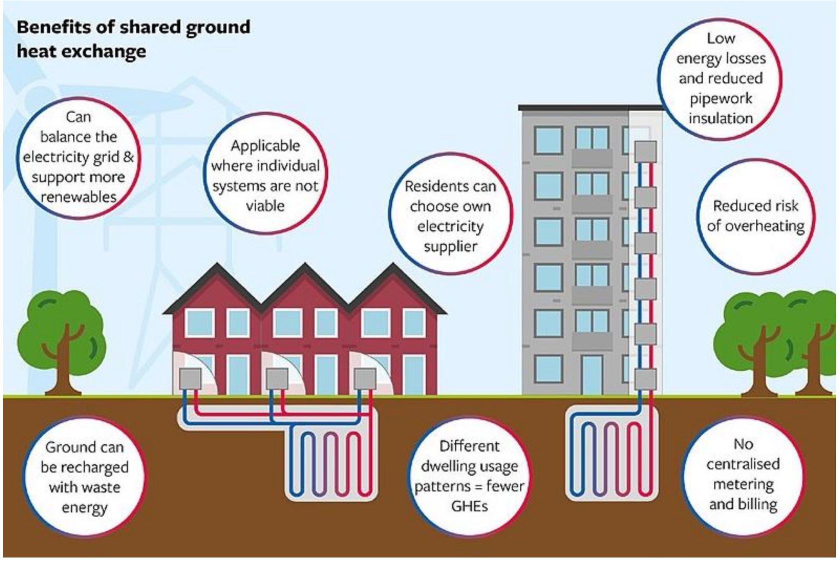

Figure 43- Catherine Bale, David Barns, Josh Turner, CC BY-SA 4.0, via Wikimedia Commons

Next to GSHP, higher temperature heat pumps are found. The term "geothermal energy" refers to a broad range of uses for geothermal heat extraction at various depths, temperatures, and technological foundations. Although all forms of geothermal energy originate below the Earth surface, the technologies' scope of use and conceptual underpinnings are very different. "Shallow" and "deep" geothermal are distinguished by depth, temperature, and capacity ranges. Shallow geothermal systems function between0 and 200 m, 0 and 30 degrees Celsius, which is equivalent to atmospheric ambient temperature; for this reason, it is often referred to as low temperature geothermal heat. Deep geothermal energy can be used directly or through high temp heat pumps (> 30 °C) can supply heat up to 140 °C, while shallow geothermal energy must be processed through a heat pump to be used for space heating (indirect thermal energy consumption). This kind of high temperature heat pumps can use both deep geothermal and waste heat coming from industrial process.

Solar assisted heat pumps (SAHP):

These heat pumps use solar energy to heat water or a refrigerant which is then used to heat a building or to provide domestic hot water. A heat pump is combined with a thermal solar collector (a series of panels that convert sunlight into heat). A solar assisted heat pump, in contrast to other varieties, may also absorb heat directly from the sun. Similar to solar hot water systems, it accomplishes this utilizing a solar collector.

In contrast to a solar hot water system, a solar aided heat pump uses a collector that can also draw heat from the air. As a result, the device may generate hot water even when the sun isn't out. They can be combined to photovoltaic panels for increased efficiency.

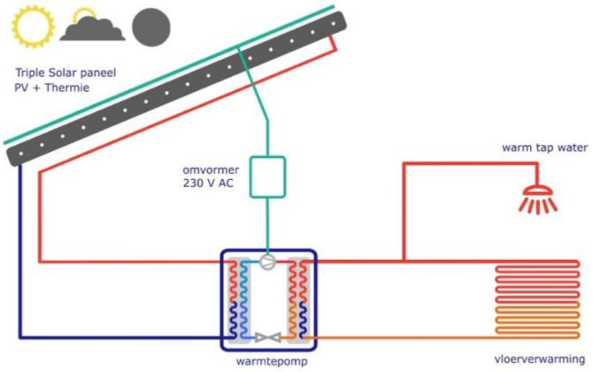

Figure 44- Cees Mager, CC BY-SA 4.0, via Wikimedia Commons

They are highly efficient and sustainable but require a significant initial investment in solar panels.

This technology fusion, often reported as “thermodynamic solar”, add the cost of the HP, but the technology is similar to that for geothermal heat pumps and quite consolidated. At the same time, savings are possible on the collector side since panels will be smaller and simpler (they are similar to the roll bond panel used for refrigeration).

Absorption heat pumps (AHP):

They use a two-component working fluid and the principles of boiling-point elevation and heat of absorption to achieve temperature lift and to deliver heat at higher temperatures. The operating principle is the same as that used in steam-heated absorption chillers that use a Lithium Bromide/water or water/Ammonia mixture as their working fluid. Key features of absorption systems are that they can deliver a much higher temperature lift than the other systems, their energy performance does not decline steeply at higher temperature lift, and they can be customized for combined heating and cooling applications.

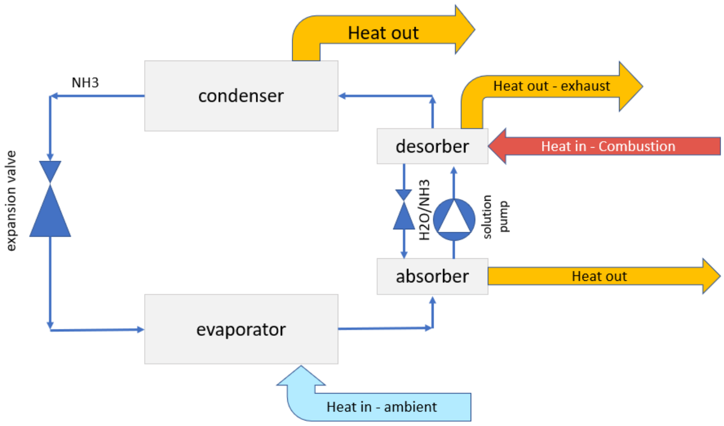

Figure 45 - Scheme of a Gas-fired AHP water heater

These systems can be used with a variety of delivery methods, including fan coils, air handlers, ceiling cassettes, high wall units, chilled beams, and radiant floors and they can be installed in both retrofit and new applications Absorption heat pumps are very quiet and offer very efficient gas heating, much lower electrical power consumption, and savings in operational costs. The units are reliable and durable and feature modular construction. Naturally, since there are no compressors or engines, absorption heat pumps need a high temperature source (e.g., gas-fired) to operate.

System Performance Metrics and evaluation

The performance of a heat pump system can be influenced by various elements, as the system's design, the installation, and the operating conditions. Different system key measures are used to assess the performance of a heat pump system. These indicators make it possible to evaluate the system's effectiveness and identify areas for development in order to increase performance. Coefficient of performance (COP), seasonal performance factor (SPF), and part-load performance are the three basic system performance indicators used to assess heat pump systems. Caution must be used since this technology generally underperforms in practice when compared to its rated performance (O'Hegarty, et al., 2022).

The COP measures how much heat a heat pump produces in relation to the energy input needed to achieve that heat output. It displays the effectiveness with which the heat pump transforms energy into heat. The SPF is comparable to the COP but considers the system's performance across the whole heating or cooling season as opposed to simply at one operating point.

The type of heat pump and the operating conditions can affect the COP and SPF values. An air-source heat pump, for instance, might have a COP of 3.0 in moderate weather, but that value might fall as the temperature rises. In contrast, a ground-source heat pump may have a more consistent COP across a wider range of temperatures, due to the stable temperature of the ground.

Overall system design, quality of the installation, and operating conditions: temperature, humidity, and airflow, have a great impact on the heat pump system performance. The kind, quantity, and quality of the refrigerant charge, the size and effectiveness of the heat exchangers, and the system's regulation method are other factors that can affect the heat pump system performance. Depending on the heat source and the application, a heat pump system must be built to work at the correct pressure and temperature levels in order to maximize its COP and SPF.

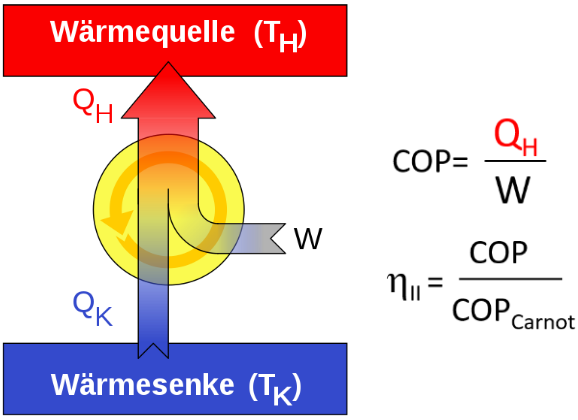

Figure 46- Coefficient of Performance definition. MikeRun, CC BY-SA 4.0, via Wikimedia Commons

The Analysis of so the called “second law” efficiencies helps to design better systems since they compare devices to their ideal counterpart. The use of advanced control strategies, such as variable-speed compressors and intelligent heat exchangers, are crucial in optimizing system performance.

Part-load performance is a measure of the efficiency and effectiveness of a heat pump system under partial load conditions, an off-design condition. A heat pump system is designed to operate efficiently at its maximum rated load. When a heat pump operates at partial load conditions the COP and SPF values may decrease.

Performance and efficiency also depend on the refrigerant charge. Incorrect refrigerant charge can lead to increased energy use and significant system damage.

The heat pump system won't be able to absorb or release heat as effectively if the refrigerant charge is too low since there won't be enough of it to adequately transport heat between the indoor and outdoor units. In order to reach the appropriate temperature, the system will have to run for longer periods of time, which may result in higher energy consumption.

On the other hand, if the refrigerant charge is too high, it can cause increased system pressure, reduced compressor efficiency, and potential damage to the compressor or other system components.

3.4.3 Economic Analysis

Due to the requirement for specialist equipment and indoor/outdoor units, heat pump systems often have higher upfront capital expenses than traditional heating systems. Indeed, the cost of an advanced heating system is not significantly lower than that of an air-to-air heat pump, but the situation changes when ground source heat pumps and other more complex types of heat pumps are concerned. Retrofitting heat pump systems into old buildings could also come with extra expenses for infrastructure improvements and alterations. Anyhow, spending money on heat pump systems can have long-term financial and environmental advantages. Indeed, heat pump systems generally have lower operational costs than conventional heating systems as they use electricity to move heat rather than generating heat themselves. The attained savings will depend on the effectiveness of the heat pump system, the cost of electric energy, and the efficiency of the current heating system. Use of heat pump systems may be especially beneficial in urban settings, where there may be greater electricity costs but also possibilities for fewer carbon emissions. Additionally, it's critical to keep in mind that operational savings may generate long-term financial advantages that will help to offset the higher initial investment expenses of a heat pump system. Single family installations usually are made without any kind of economic analysis other than the one suggested by the seller. More important installation, as those connected to district heating, require a deep life cycle assessment (Calise, et al., 2022). Life cycle cost analysis accounts for the capital costs, operational costs, and other factors such as maintenance and replacement costs over the lifespan of the heat pump system (Pratiwi & Trutnevyte, 2021). Other indices to account for are the Payback period, also in its discounted implementation, which refers to the amount of time it takes for the energy savings from a heat pump system to offset the initial capital costs, and the Net Present Value that is, the lifetime value of the financial investment, discounted to the present. Life cycle cost analysis and payback periods and NPV can vary depending on the specific heat pump system and the urban context but are important considerations in evaluating the economic feasibility of heat pump system adoption. Longer payback periods may still be justifiable if the life cycle cost analysis shows that the overall economic benefits over the lifespan of the system outweigh the upfront capital costs. Net present value considers the time value of money and calculates the present value of future cash flows associated with a heat pump system (Dusseault & Pasquier, 2021). Another method for financial analysis that measures an investment's profitability over time is internal rate of return (IRR). A heat pump system's long-term economic feasibility can be determined by NPV and IRR calculations, which can also assist stakeholders in weighing the costs and benefits of adoption. In these assessments, several scenarios may be studied to assess the economic viability of a heat pump system in various situations.

Sensitivity analysis examines how modifications to important variables like energy costs, equipment costs, and system efficiency impact the viability of a heat pump system economically (Alshehri, et al., 2021). The economic feasibility is assessed in terms of the likelihood and potential effects of risks such equipment failure, changes in energy prices, and regulatory changes. In order to help stakeholders in estimating the potential financial effects of changing circumstances, sensitivity analysis and risk assessment are crucial parts of economic analysis for heat pump systems in urban settings. By considering different scenarios and risks, stakeholders can make informed decisions about the long-term economic benefits of adopting a heat pump system (Garber, et al., 2013).

Policy Considerations

A number of heat pump market-supporting measures are now being established as a result of historically high energy prices and the expectation of forthcoming winter difficulties in the wake of Russia-Ukraine crisis. In the next five years, the REPowerEU wants to deploy 10 million hydronic heat pumps, which will be followed by other country-specific goals. In its Defense Production Act, the United States likewise emphasized heat pumps as a crucial technology (IEA, 2022). These laws mandate energy-efficient construction standards and provide tax incentives, rebates, and subsidies for renewable energy sources. Additionally, several nations have specific laws in place that mandate or promote the installation of heat pump systems in particular kinds of structures. For instance, the Energy efficiency of Buildings Directive in the European Union mandates that member states set minimum energy efficiency requirements for both new and existing structures. In order to achieve these requirements, the regulation also promotes the use of renewable energy sources, such as heat pump systems. Governments could also establish building codes and standards that require or encourage the use of heat pump systems in all types of buildings.

The economics of heat pump systems can be significantly impacted by the implementation of carbon pricing and other environmental policies. Heat pump systems become a more cost-effective substitute for conventional heating systems that rely on fossil fuels when carbon pricing is in effect. Many countries impose taxes on electricity that are substantially higher than those on fossil fuels, which inadvertently encourages the usage of oil and gas. Adjusting tax rates and including the cost of using fossil fuels into prices are two important steps.

Effective collaboration between stakeholders is essential to promoting the adoption of heat pump systems in urban contexts. Stakeholders include policymakers, utilities, building owners, installers, and manufacturers. There are several ways to collaborate. Heating and cooling as a service, which involves renting out heat pumps to customers and overseeing the technology's proper operation, is a promising business model with the potential to benefit both customers (by relieving them of the burden of high upfront costs) and businesses, which can gain from more stable and long-term revenue streams than by simply selling the heating equipment. By creating and marketing integrated heat pump systems with metering, active demand response protocols, heat storage, or even solar PV, as a set of appliances under one brand, businesses can further capitalize on the synergies between various technologies.

3.4.4 Environmental Analysis and Circularity

Heat pump technology typically has a lower environmental impact compared to traditional heating and cooling systems that rely on fossil fuels. Heat pumps are energy-efficient systems that utilize electric energy to transfer heat from a cold region to an indoor zone, rather than generating heat by burning fuel. Nevertheless, the life cycle climate performance (LCCP) study approach suggested by the International Institute of Refrigeration (IIR) can be used to thoroughly evaluate the environmental atmospheric impact of carbon production (Refrigeration, 2016). (Choe, et al., 2018) investigated how long-term GSHP operation affected the thermal condition of the ground beneath urban areas. After ten years of operation, the overall subsurface thermal state increased by 7 °C relative to the starting temperature. Thermal infiltration occurred at nearby construction sites as a result of this. A significant factor in the performance and operating life deterioration of GSHP systems is soil thermal imbalance, which also has negative environmental effects on the soil in the vicinity.

Furthermore, environmental effects may result from heat pump manufacturing and disposal. Energy and materials are used throughout the manufacturing process, and waste may be produced during the disposal of old or damaged heat pumps. Some heat pump systems also employ refrigerants, which, if discharged into the atmosphere, can be powerful greenhouse gases. To address these concerns, the heat pump industry has made efforts to improve the circularity of their products. This involves reducing waste and maximizing the reuse and recycling of materials by designing systems to be easily disassembled for recycling at the end of their life (Sevindik, et al., 2021).

The European Union has also implemented policies and regulations to encourage the circularity of heat pumps. The Circular Economy Action Plan (Commission, 2020), for example, aims to promote sustainable consumption and production by increasing the lifespan of products and reducing waste.

So, the heat pump industry is working to reduce its environmental effect and increase circularity. However, there is still potential for improvement, and to reach more sustainable and circular practices in the future, business and policymakers will need to continue to innovate and collaborate. It is not a trivial task to build a circular economy for the HP since most of the device and machinery in use or nearing the end of their useful lives in this industry were not made to be circular. Resource efficiency must be increased by design, extending product life and recycling and reusing materials, and rethinking part design toward circularity.

Urban Design and Planning

To ensure that heat pumps are successfully incorporated into the built environment, the growing usage of heat pumps in urban settings will necessitate careful planning and study. To create efficient deployment and management plans for heat pump systems, cooperation between building designers, utilities, and legislators will be necessary.

- Building designers and architects will need to consider the installation and integration of heat pumps into the overall building design as they become more prevalent. This entails considering the placement of the interior unit, its size and location, as well as the ductwork and pipes, as well as the outdoor unit's location (Sayegh, et al., 2018).
- Energy infrastructure in metropolitan areas will be impacted by the rising use of heat pumps. Utilities will need to prepare for the increasing electricity demand brought on by heat pump systems. Upgrades to current infrastructure, including transmission lines and substations, may be necessary to achieve this (Baeten, et al., 2017).
- The installation of geothermal loops may necessitate additional land if ground-source heat pumps are used. Urban land use planning may be impacted by this since new construction may need to take this extra space into consideration.
- By minimizing the heat produced by conventional heating systems, heat pumps can aid in lowering the urban heat island effect. In order to reduce the impact of the urban heat island effect, cities may need to take heat pumps into account while designing and planning their metropolitan areas.
- Building codes and standards will need to be modified to reflect the use of heat pumps as they become more widespread. Establishing installation and maintenance requirements as well as rules for noise and emissions are all part of this (Sun, et al., 2016).

3.5 Thermal Energy Storage (TES) Technology

3.5.1 Introduction

Thermal Energy Storage (TES) refers to the process of storing thermal energy in various forms such as heat or cold for later use. TES is an important technology as it can help manage peak energy demands, reduce energy costs, and increase the use of renewable energy sources. It is a cost-effective method for energy storage that consents the use of renewable energy sources, like solar and wind power, during their availability. The stored energy can be used during periods when these renewable sources are not accessible.

This technology has been developed and refined over many centuries, it has always been crucial for human comfort and survival and has changed over time to meet society's evolving needs. Because society is emphasizing sustainable energy solutions, TES is likely to play an increasingly important role in the future of energy storage and management.

The usage of ice storage in ancient civilizations was one of the oldest examples of TES, with people storing ice in pits during the winter months and using it to cool their homes and food during the hot summer months. This tradition persisted for centuries before being supplanted by the introduction of artificial refrigeration in the early twentieth century.

Figure 47 Ancient Advanced Technology: 2,400-Year-Old Yakhchals (Iran) ice storagein the Desert (Credit: Bockomet, CC BY-SA 4.0, via Wikimedia Commons)

Around the mid-19th century, residential heating began using hot water storage in Europe, followed by the United States. This was accomplished by storing hot water in huge reservoirs or subterranean storage facilities, which could then be utilized to heat homes during the winter. In the 20th century, new materials and methods and TES became a more efficient and cost-effective. In the 1930s, phase change materials like paraffin wax were utilized in TES in the form of ice packs and heat pads. Molten salt was later developed as a storage medium for concentrated solar power (CSP) systems in the 1950s.

Figure 48-The molten salt test loop (MSTL) at Sandia National Laboratories' National Solar Thermal Test Facility in Albuquerque, New Mexico (Credit: Randy Montoya, Flickr, 2.0 Generic (CC BY-NC-ND 2.0)

The oil crisis in the 1970s renewed interest in TES technology, and a number of research efforts to build new storage systems were undertaken. In those years, the development of sensible heat storage systems, which required the use of massive tanks filled with water, rocks, or other materials that could store heat and release it later when needed, was noted. In the 1980s, this technique was refined by the use of advanced materials as phase-change materials and ceramics.

Nowadays, TES approaches such as sensible heat storage, latent heat storage, and thermochemical storage are on the cutting edge. Sensible heat storage entails storing heat in temperature-changing materials such as water, rocks, or concrete. Latent heat storage is the process of storing energy by altering the phase of a material, such as melting or freezing. Thermochemical storage is the process of storing energy by changing the chemical state of a substance.

Thermal Energy Storage (TES) systems have several benefits, including energy savings, cost savings, and environmental advantages. On the other hand, TES also face the initial cost of installation and require careful design and operation to ensure optimal performance and efficiency.

Finally, TES technology is thought to have the highest level of security. The other storage methods are listed from highest to lowest level of security, starting with batteries, bulk gas/liquid storage, PHS (Pump Hydro Storage), and then comes batteries. The least secure energy storage technology is A-CAES (Adiabatic Compressed Air Energy Storage) (Azzuni & Breyer, 2018).

Notable embodiments

Implementations of TES include the use of underground aquifers for storing hot water, the use of phase-change materials in buildings to store heat, and the use of molten salts in concentrated solar power plants. Noteworthy plants include:

Figure 49- Salmisaari CHP power plants by sunset in Helsinki, Finland -– (credit: Pöllö, CC BY 3.0 , via Wikimedia Commons)

District Heating Systems: Finland's Salmisaari plant run by Helsinki Energy is one example of a district heating system that makes use of TES technology. More than 1,500 buildings in the Helsinki metropolitan region are heated and distributed by the facility using a mix of hot water storage tanks and a heat pump.

Solar Thermal Power Plants: A solar thermal power plant that makes use of TES technology is the Gemasolar project in Spain. The plant stores extra heat produced during the day in molten salt, which is subsequently used to produce electricity when there is less sunshine.

Figure 50- Gemasolar Thermosolar Plant – (credit: kallerna, CC BY-SA 4.0, via Wikimedia Commons)

Ice Storage Systems: During off-peak hours, these storage systems use energy to freeze water. During peak demand hours, the stored ice is then used to cool buildings. In San Francisco, the California Academy of Sciences is an example of a structure that uses an ice storage system for cooling. Up to 5.3 million pounds of ice can be stored in the building's ice storage system, which also lowers the peak electricity usage by 10%.

Underground Thermal Energy Storage (UTES): UTES systems store thermal energy in underground aquifers or rock formations, which can then be used as needed to heat or cool buildings. A residential community that makes use of UTES is the Drake Landing Solar Community in Canada.

During the summer, the community's UTES system stores extra solar energy, which is then used to heat homes in the winter. Energy (mechanical) can be also stored as compressed air (Borri, et al., 2022), even in underground air storage but it is not enumerated among the TES technologies.

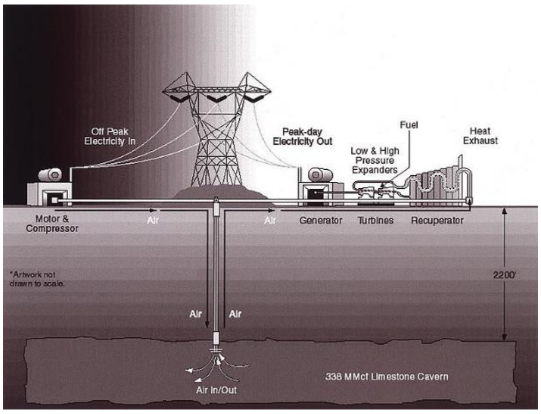

Figure 51- Compressed air energy storage, Sandia Test Facility – (Credit: U.S. Department of Energy from United States, Public domain, via Wikimedia Commons

Applications for TES technology range from district heating to renewable energy generation to building cooling and heating. Future developments in TES technology are expected to result in even more creative applications and deployments of this technology (Cabeza, et al., 2021).

3.5.2 Technical Analysis

Thermal storage facilities ensure a heat reservoir for optimally tackling dynamic characteristics of district heating systems: heat and electricity demand evolution, changes of energy prices, intermittent nature of renewable sources, extreme wheatear conditions, malfunctions in the systems. The implementation of thermal energy storage in district heating and cooling systems is advisable with reference to both short-term and long-term storages. Connections of sensible, latent (phase change material) and chemical heat storage are welcome considering the research maturity of each type of technology to grant the transition of current energy systems towards next generation district heating (Alva, et al., 2018).

Among the examples of Thermal Energy Storage (TES) systems, the storage of daytime heat for night-time heating and the storage of summer heat for winter heating are found. The storage of thermal energy results in a change in the internal energy of the material in the form of sensible heat, latent heat of phase change, thermochemical energy, or a combination of these phenomena (Gil, et al., 2010).

TES systems cover a wide range of temperatures and applications that will be discussed below in light of their application scenarios.

The most important characteristics of energy storage systems are (Ibrahim, et al., 2008):

- duration, which is the time during which energy can be stored with acceptable losses
- storage density, which is the amount of energy stored per unit volume
- energy efficiency, whose value is given by the ratio between the energy extracted during discharge and the energy stored during charging.

To improve efficiency, heat losses should be minimized, and the maximum possible energy recovery should be achieved when extracting energy from the storage system.

To ensure that thermal energy storage systems are profitably used to improve the efficiency of processes in which they can be integrated, some specific requirements must be met. It is essential that a TES system can operate stably within the temperature range required by the application, or ideally within a wider temperature range. Additionally, the storage materials used must be cost-effective and available in large quantities. Regarding the materials used for storage, different choices can be made depending on the storage system used, temperature range, and specific application so that the choice of a TES system depends on factors as the required storage period, operating conditions, economic feasibility, and environmental constraints.

The key parameters used for classifying TES systems are the storage period and the type of heat exchange.

Based on the required storage period, two main families of TES systems are distinguished, with some systems adopting mixed storage periods:

-Short-term thermal storage: This includes all systems with a daily cycle and storage capacities ranging from a few hours to a maximum of one week. Usually, in these systems, thermal energy is stored at a sufficiently high temperature to allow direct exchange with the user at the desired temperature.

-Long-term thermal storage: This type of storage includes all systems with storage capacities greater than three or four months. A typical system is one coupled with a thermal solar power plant that stores heat in the summer and redistributes it in the winter. This balances the imbalance between the high solar radiation in summer and the greater demand for heat in winter.

Depending on the heat transfer method, (TES) systems can be classified into three main categories: sensible heat systems, latent heat systems, and thermochemical systems as depicted in Figure 6.

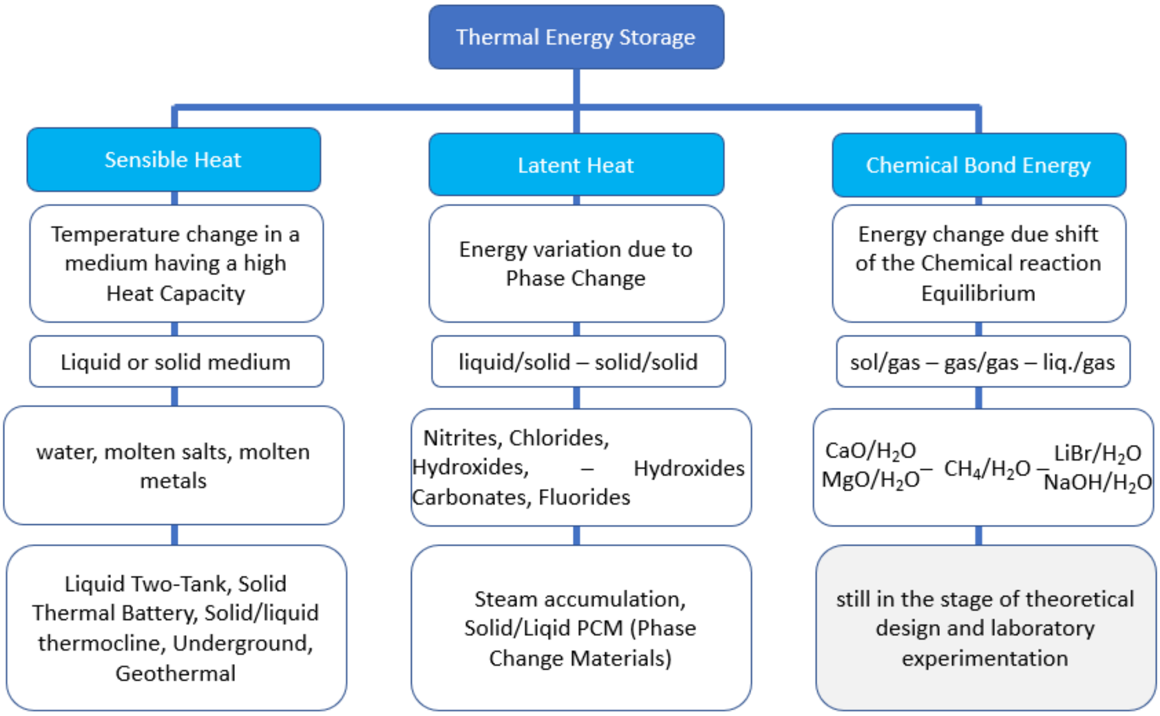

Figure 52- Heat storage types and methods

In **Sensible Heat Thermal Energy Storage** (SHTES) systems, energy is stored through the variation of the temperature of a liquid or solid medium without any phase change in the temperature range of the process (Gil, et al., 2010), (Sharma, et al., 2009).

Sensible heat build-up takes place in the storage material, the container and in the input/output devices.

The stored energy is proportional to the mass, to the specific heat of the medium and to the temperature variation. A good material to be defined as such must have a high thermal capacity, be cheap and easily available in large quantities. At low temperatures, water is the most suitable liquid for this type of storage as it has a high specific heat value of about 4.2 [kJ/ kg*K] and is cheap. Therefore, having a high value of the product $\rho * c_p$, water will provide the possibility of using temperature differences that are not too high and for this reason it is favoured in working in heating and cooling systems of buildings. The limit of water is represented by the low value of its evaporation temperature (100°C). When the temperature exceeds 100°C under normal pressure, oils, molten salts (Dunn, et al., 2012), and liquid metals are employed to transition to solid materials, which can be used up to 1000°C in some applications (Laube, et al., 2020). The advantage of employing sensible heat storage is that it is affordable and does not pose concerns associated with the use of poisonous chemicals; yet it requires huge quantities when compared to other kinds of storage due to the low energy density of the materials utilized.

Latent Heat Thermal Energy Storage (LHTES) systems are based on the absorption or release of heat that occurs during the phase change of a storage medium without significant temperature changes.

The most widely used state transitions are solid-liquid and solid-solid because they have restricted volume variations. Due to the substantial volume changes of the storage medium during the phase transition, the liquid-vapour transition is rarely used. The materials employed are concisely characterized by the abbreviation PCM (Phase Change Material) (de Gracia & Cabeza, 2015); they can withstand a wide temperature range. A latent heat storage system consists of the following components: a PCM material that undergoes a phase shift in the temperature range under consideration, where the heat supplied is stored as latent heat, a container, and a surface for exchange between the heat source and the storage medium, as well as between the latter and the thermal load. The stored energy is determined by the latent heat of fusion and the mass.

The most significant advantages of LHTES systems are their high storable energy density value, which is significantly higher than that of sensible storage (see Figure 53), as well as their minimized temperature changes. It should also be noted that LHTES systems are substantially smaller than SHTES systems with the same stored thermal energy.

A comprehensive review on heat transfer in LHTES systems can be found in (Sarbu & Dorca, 2019).

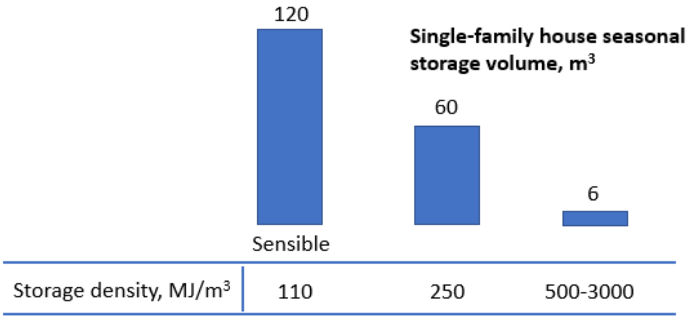

Figure 53 - Density values of sensible, latent, and thermochemical heat storage

Thermochemical energy storage involves reversible chemical reactions that entail energy storage in endothermic processes and energy release in reverse exothermic reactions. Theoretically, of all thermal storage systems, thermochemical energy storage has the largest energy storage density capability. Before making it commercially viable, however, a number of critical issues must be resolved, including the removal of heat from chemical reactors and the separation of components in both stages of reversible reactions (Angerer, et al., 2018). Theoretical design and laboratory testing are still the steps of thermochemical storage.

3.5.3 Economic Analysis

TES are very important in energy management since they are designed to store thermal energy during periods of low demand, as at night or during weekends, and release it during periods of high demand. This allows to manage more efficiently energy supply and demand and to reduce peak energy loads. Due to the importance of TES systems for district heating and cooling, building HVAC systems and industrial processes, economic analysis is central in assessing the feasibility and cost-effectiveness of their implementation. This kind of analysis helps in identifying the factors that affect their adoption and can also help decision-makers to determine the economic benefits and potential return on investment of TES designs (McKenna, et al., 2018).

TES systems can have higher initial capital costs compared to traditional HVAC systems due to the need for specialized equipment and materials. These costs can vary depending on the scale and complexity of the system. Costs depend only on the particular medium selected as storage since it is clear that a phase change material or a chemical medium will cost more than water. Operational costs are also important: TES systems require energy to charge and discharge the storage medium. Furthermore, this process always results in energy loss since Round-trip efficiency (RTE) is not one and physical losses are always resent.

RTE is the ratio of the output energy to the input energy in a charging/discharging cycle (Hameer & Van Niekerk, 2016). All these losses represent operational costs which anyway can be offset by energy savings during periods of lower energy demand. Maintenance and repair costs are to be accounted for. Usually, a cost analysis can be done to compare the lifetime costs of implementing TES systems versus traditional HVAC systems to determine the cost-effectiveness of implementing this technology. Naturally, the economic analysis depends on the particular type of TES and on its implementation. Concerning PCM TES applied to solar power plants see for instance (Prieto & Cabeza, 2021).

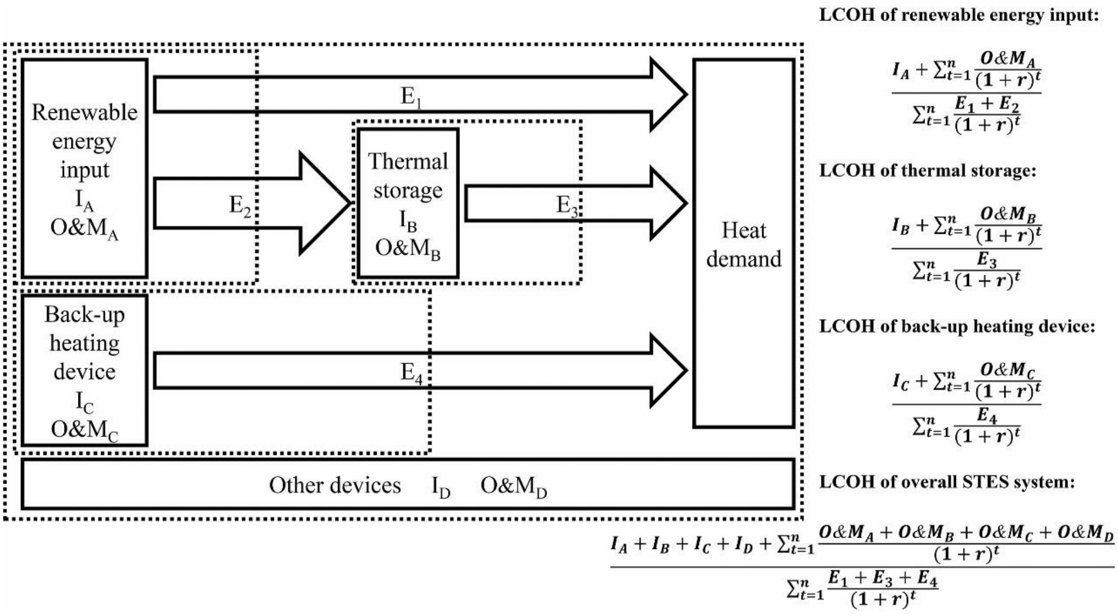

Figure 54 - Specific system boundaries for LCOH analysis (Credit: (Yang, T., et al., 2021), CC BY 4.0)

All the main financial indexes are used to evaluate the feasibility of a particular design

- Return on Investment (ROI), a measure of the profitability of an investment which can be calculated by dividing the net profit by the initial investment. A positive ROI indicates a profitable investment.
- Net Present Value (NPV), the sum of the present values of all cash inflows and outflows associated with an investment, adjusted (discounted) for the time value of money. A positive NPV indicates that the investment is expected to generate positive returns given a time horizon (Arslan & Arslan, 2022).
- Internal Rate of Return (IRR) analysis is the rate at which the net present value of all cash flows associated with an investment is equal to zero. A higher IRR indicates a more profitable investment.
- The levelized cost of heat (LCOH) approach is a useful tool for comparing the lifetime costs of various heat production methods.

Sensitivity analysis is also used in the economic study of TES systems to identify the key factors that affect their cost-effectiveness and the amount of uncertainty associated with these variables. This kind of analysis, for instance, may analyse the impact of changes in the cost of energy, in the cost of TES system components, and of the system performance on the overall economic feasibility of the TES system. Sensitivity analysis can assist in evaluating the robustness of the economic analysis.

The use of TES provides benefits in terms of reduced energy consumption during periods of high demand and peak loads management aid, resulting in energy savings and so, lower energy costs. Reduction of energy consumption and demand charges can result in cost savings for consumers and utilities. Moreover, by encouraging renewable energy sources use and boosting energy system efficiency, TES systems can help reduce greenhouse gas emissions.

Conversely, the implementation of TES system demands for high initial capital costs, careful design, and operation to ensure optimal performance and efficiency and to face the limited availability and reliability of renewable energy sources. Indeed, this can impact the performance and efficiency of TES systems.

Case studies can be used to analyse the economic benefits and challenges of TES implementations in various applications and can also provide insight into the cost and economic benefits in specific applications.

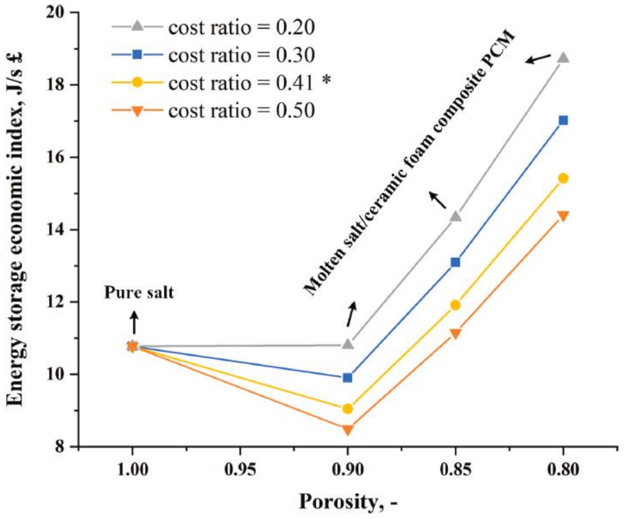

Figure 55- Comparison of energy storage economic indexes of pure molten salt and molten salt/ceramic foam CPCMs (Credit: (Zhang & Yan, 2023) , CC BY 4.0)

The regulatory and policy framework is an essential part of TES system economic analysis. Government laws and regulations can encourage or discourage the use of TES systems. Policies that promote renewable energy and energy efficiency, for example, can create favourable conditions for TES systems. Similarly, policies that encourage the use of TES systems, such as tax breaks or subsidies, can help to speed up their deployment. Conversely, policies that promote traditional energy sources, such as fossil fuels, can make it more difficult for TES systems to compete in the market. Regulations and standards imposing requirements on the design, installation, and operation of TES systems can also have an impact on their cost-effectiveness and acceptance.

The main operational and economic characteristics of a TES technology are listed below

- The highest electrical power output is known as the *power rating*. Higher power ratings typically result in greater size and more expensive energy converters that transform stored energy into different forms for the purpose of producing electricity. Additionally, because a bigger temperature gradient in the heat exchanger may be used to produce a higher power rating, more durable material may be required in this scenario, raising the cost.

- The entire cost of ES material, such as molten salt, concrete, firebricks, etc., is directly correlated to *nameplate capacity*. To build the liquid thermal energy storage medium containers with a higher capacity, additional material is also required.
- *DOD* stands for depth of discharge, or the proportion of the stored energy that is released. A fully charged energy storage device will discharge 90% of its energy according to a 90% depth of discharge (Ibrahim, et al., 2008).
- Cycle/Day and Days in a Year show how frequently a 100% DOD charging/discharging cycle is performed for a certain device. The annual cycle frequency varies depending on the circumstances and can be 250 to 750 (Sharma, et al., 2016).
- The ratio of the energy output to the energy input during a charging/discharging cycle is known as *round-trip efficiency* (RTE). The RTE for thermal energy storage systems can be between 70% and 100%.
- When the installed capacity varies over the course of the energy storing unit's service life, *storage degradation per year* refers to the degeneration of the storage system (Betancur-Arboleda, et al., 2021). The medium's ability to store energy diminishes with time for a variety of reasons, including harsh working conditions, storage medium leakage, etc. The cost of operation and maintenance will be influenced by the rate of capacity deterioration

3.5.4 Environmental Analysis and Circularity

TES technology can significantly reduce greenhouse gas emissions and increase the use of renewable energies. However, its possible environmental effects should be considered (Dincer, 2002), just like in any other technology. To understand the possible effects of TES systems on the environment requires a deep life cycle analysis (Bernal, D.C., et al., 2021).

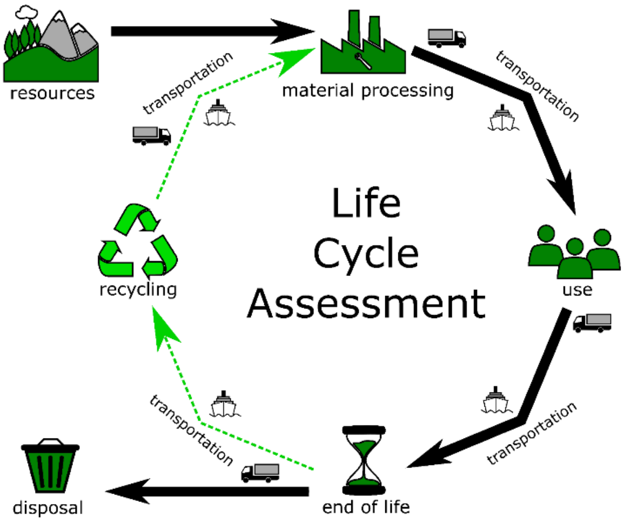

Figure 56- Simplified Life Cycle Assessment (Credit: (Scharrer, D., et al., 2020), MDPI Open Access)

Life cycle analysis (LCA)

Life cycle analysis or LCA (also known as life cycle assessment) is a methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or technology, from the extraction of raw materials through its eventual disposal. Insights into the environmental effects of Thermal Energy Storage (TES) technology are provided by the application of LCA, which can assist guide decision-making and highlight areas for improvement (David, et al., 2021).

A TES system's life cycle typically involves the following stages: obtaining raw materials, producing, shipping, installing, using, maintaining, and disposing of it at the end of its useful life. Each stage has the potential to have an influence on the environment by greenhouse gases emission, depleting resources depletion, and waste.

TES systems' effects on the environment differ depending on the particular technology and application. For instance, different materials, like concrete, steel, and plastic, and phase change materials (PCMs) (Vega, et al., 2022) each with varying environmental effects, are used in the production of TES systems. Additionally, emissions from equipment and trucks powered by fossil fuels may be produced during the installation and transportation of TES systems.

By minimizing the requirement for power generated using fossil fuels during the operational phase, TES systems can contribute to environmental advantages by lowering greenhouse gas emissions.

Another potential environmental impact of TES technology is its energy consumption during the charging and discharging cycles. The use of electric energy to charge and discharge TES systems may cause greenhouse gas emissions and other environmental concerns, especially if the electricity is from fossil fuels. To lessen the environmental impact of TES systems, it is important to enhance their charging and discharging cycles efficiency and to use renewable energy sources whenever possible

Additionally, the upkeep of TES systems may influence the environment, especially if hazardous materials are utilized. The end-of-life stage is another crucial one to think about because getting rid of TES system parts might lead to waste production and possible environmental damage (Abokersh, et al., 2021).

A complete picture of the technology's total environmental performance may be obtained using LCA, which can be used to measure the environmental effects of each stage of the life cycle of TES systems. LCA can guide the creation of more sustainable TES systems by pointing out problem areas and potential improvements.

Circularity

Another crucial factor in the environmental impact of TES technology is circularity. Reduce, reuse, and recycle are circular economy practices that can assist reduce the environmental effect of TES systems (Abokersh, et al., 2021). Principles and methods from the circular economy are increasingly being used in a variety of industries, including the energy industry, to increase resource efficiency and sustainability. A more dependable and effective energy storage system may result from the use of circularity into Thermal Energy Storage (TES) technology. Circularity and circular methods used in TES technology will be covered in this section.

In TES technology, the concept of circularity refers to the capacity to maximize material utilization, minimize waste production, and foster a circular flow of materials and energy. Utilizing circular methods can enhance TES systems' environmental performance and aid in the shift to a circular economy. The following are a few examples of circular techniques that can be used in TES technology:

1. Materials recycling and reuse: The TES system needs materials to build the storage tank, the insulation, and the heat transfer fluid. The demand for virgin materials can be decreased and waste production can be kept to a minimum through the use of recycled resources and the recycling of materials after their useful lives.
2. Modular design: A modular design can make it easier to replace individual TES system sections or components, decreasing the need for a complete replacement and lengthening the life of the system (Hoivik, N., et al., 2019).
3. Repurposing waste heat: The TES system can be charged using waste heat from industrial activities or the production of electricity. This can improve resource use while lowering energy use and greenhouse gas emissions.
4. Energy recovery: By integrating TES systems with other energy systems, wasted energy can be recovered. For instance, power plant waste heat can be used to charge the TES system, and the heat that is then stored can be used to produce electricity when demand is at its highest.

As said, a helpful method for assessing the environmental effects of TES systems throughout the course of their life cycle is life cycle analysis (LCA). The LCA of TES systems considers material creation, building, running, maintaining, and end-of-life management.

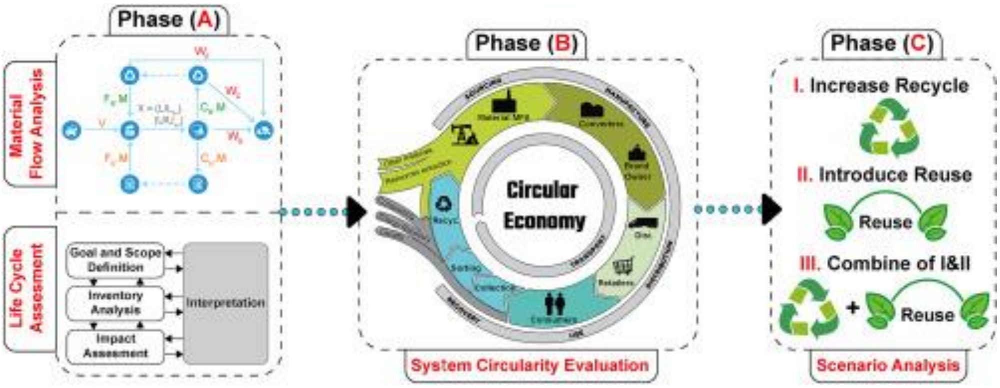

Figure 57- A framework for sustainable evaluation of thermal energy storage in circular economy (Credit: (Abokersh, et al., 2021), CC BY-NC-ND 4.0)

LCA can be used to find ways to make TES systems more environmentally friendly, like cutting back on the usage of non-renewable resources and cutting greenhouse gas emissions. According to the findings of LCA studies on TES systems, different TES system types, energy sources, and end-use applications have different environmental implications. For instance, TES systems powered by renewable energy sources like solar and wind power typically have lesser environmental implications than those powered by energy sources based on fossil fuels. The environmental effects of the system can be further diminished by TES technology's use of circular methods.

Circularity and circular methods can increase the TES systems' sustainability and effectiveness. The adoption of circularity in TES technology can aid in the shift to a circular economy and the accomplishment of the United Nations' Sustainable Development Goals. LCA is a practical tool for assessing the environmental effects of TES systems and pinpointing areas for development.

Acceptance and social impact

Thermal Energy Storage (TES) technology holds the promise of transforming energy storage and utilization methods. However, like any new technology, there are challenges associated to a variety of factors, including the economic, technical, regulatory, and cultural contexts in which it is being implemented (Zhang, X., et al., 2022). By addressing these challenges and promoting the benefits of TES technology, it may be possible to overcome these barriers and promote the widespread adoption of this promising technology.

One factor that can impact the acceptance of TES technology is the cost. While TES systems can help reduce energy costs in the long term, the initial investment can be significant. This can make it difficult for some consumers or businesses to justify the expense of implementing a TES system, particularly if they are operating on a tight budget. complexity of the systems can impact the acceptance of TES technology. TES systems operation may require specialized training or expertise. This can create a barrier to entry for some potential users, particularly those who do not have the technical knowledge or resources to manage and maintain the system. The regulatory and policy environment can also impact the acceptance of TES technology. In some cases, regulations or policies may be in place that favour traditional energy storage technologies over TES systems. This can create an uneven playing field for TES technology, making it more difficult for it to gain a foothold in the marketplace. Moreover, confusing regulation and poor coordination between administrators may generate issues among professionals in the sector and obstacles to a holistic view of stakeholders.

There may also be cultural and social barriers to the acceptance of TES technology (Simó-Solsona, et al., 2021). Some people may be resistant to change, particularly if they have grown accustomed to using traditional energy storage technologies. Others may simply need to be educated on its potential advantages. So, it is important to focus on educating consumers and businesses about the pros of TES technology. This can include highlighting the long-term cost savings, as well as the potential environmental advantages of reducing energy consumption. In addition, efforts can be made to simplify the technology and to create a proper regulatory and policy environment promoting the use of TES technology.

Technology for thermal energy storage (TES) has the potential to significantly affect society. The employment market will be affected most immediately since experienced people will be needed for TES system development, installation, and maintenance, opening up positions in the renewable energy industry. Increasing the production and storage of renewable energy can also result in greater energy security and independence, reducing reliance on erratic energy markets and foreign energy sources.

TES technology also offers a way to lessen greenhouse gas emissions and the carbon footprint of buildings and industry, which can assist to lessen the consequences of climate change. This may result in better public health, better air quality, and lower expenses for treating pollution-related illnesses.

By lessening the heat island effect, which is brought on by buildings and pavement absorbing heat, TES technology can also enhance the quality of life for those who live in urban areas. This effect raises temperatures in urban areas. To lower the urban heat island effect, TES systems can help cool buildings during the day to lessen the demand for air conditioning and release the heat at night when it is cooler.

It is important to remember that TES technology may not always have beneficial social impacts. In some circumstances, Communities may object to the installation of TES systems for to aesthetic issues, noise pollution, and potential effects on property values. Furthermore, lower-income areas might find it difficult to adopt TES systems owing to the cost of TES implementation. This represents a barrier which may create a potential social equity issue. When developing and marketing TES technology, governments and stakeholders must consider any potential social effects. Education and community involvement can help to address concerns and encourage acceptance of TES systems. In addition, laws and financial incentives can be implemented to guarantee that TES technology is available to everyone, irrespective of income level or geography.

3.6 Sustainable Fuels (Bio-fuels, E-fuels, Hydrogen)

3.6.1 Introduction

Biofuels have been used for cooking and heating since ancient times, while e-fuels have a shorter history behind. However, the modern biofuel business was born in the 1970s in response to worries about the environment and energy security whereas, e-fuels are a recent innovation that aims to transform renewable power into synthetic fuels. Both biofuels and electrofuels are attempts to attain energy independence and lessen their negative effects on the environment (Gaurav, et al., 2017). Hydrogen has gained significant attention as a sustainable fuel option due to its versatility and potential for zero-emission energy applications (Fayaz, et al., 2012).

Figure 58- Biofuels (Credit: Image by href=" https://www.vectorportal.com" Vectorportal.com , CC BY 4.0).

Nowadays, the world is facing an unprecedented challenge as climate change continues to threaten the planet (Adams, 2008). In response to this, many countries have implemented emissions legislation to reduce the amount of greenhouse gases in the atmosphere and the legislation action can be considered a key factor in driving innovation and uncertainty in the fuel market. So, a transformation is taking place in the automotive (Pearson & Turner, 2012) and power industry that is unprecedented in its history. As the demand for fuel increases and the volatility of the market becomes more pronounced Governments must be prepared to quickly respond to these changes to ensure that the environment is protected. Companies must also be prepared to develop new products and services that meet the changing needs of the market. So, a series of question arises on which energy/fuels will dominate in the future, and on how these technologies will impact industry infrastructures and customers' perception and choices in this rapidly changing landscape. Bio-fuels, made from plants like corn, soy, and other edible foods (previously) or, with more sophisticated processes, from waste (second generation) (Sims, et al., 2010)and e-fuels (synthetic hydrocarbon fuels), plus hydrogen, are on the verge of a full-scale war. Furthermore, speaking about transport and mobility sectors, they also have to deal with electric vehicles that seem to have some advantages (Pasini, et al., 2023).

Figure 59- E-fuels (Credit: Image by Shafin_Protic, CC0 via pixabay)

The debate on the future of heat engines in the European Union has been intense. Incorporating e-fuels and biofuels into European law was an attempt made by some Member States that was only partially successful, with the former gaining a pass and the latter receiving nothing. There may already have been a market response to Europe's worries, especially from the car industry. They have made it quite obvious that investments in electric cars (and hydrogen in the future) will take up the majority of their attention in the upcoming years. In fact, no one is developing new internal combustion engines in Europe; instead, all funding is going towards electric or hydrogen (fuel cell) technologies. Despite the potential benefits of renewable fuels, such as eliminating the need to establish a network of charging stations and reducing charging wait times, this alone is insufficient, and these green fuels may at best be viewed as niche solutions. Anyway, there is not only the automotive sector and sustainable fuels could be utilized in many applications like Heating, Off-Grid applications, energy storage systems and others.

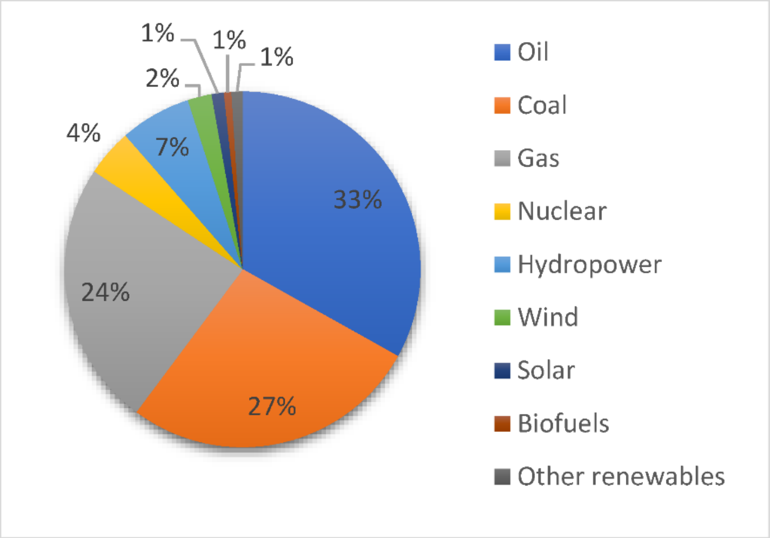

Figure 60- Global energy consumption by source in 2019 (Credit: (Khan, et al., 2021), CC BY 4.0 via MDPI)

Addressing serious environmental, economic, and social concerns requires a transition to sustainable energy.

The use of fossil fuels for both energy production and transportation has contributed to resource depletion, air pollution, and climate change. The transition to sustainable fuels is essential to addressing these problems and promoting a sustainable future. To follow, some key reasons for switching to sustainable fuels:

Climate Change Mitigation and air quality: Sustainable fuels, such as biofuels, e-fuels, and hydrogen produced from renewable sources, provide, to varying degrees, a solution to cut greenhouse gas emissions (Anderson, 2015), poor air quality and adverse health effects. These eco-friendly substitutes for fossil fuels can reduce climate change and the rise in global temperatures by displacing fossil fuels, according to the targets outlined in the Paris Agreement. Improved air quality will protect public health by reducing the prevalence of respiratory and cardiovascular diseases.

Energy Security and Independence: By lowering reliance on limited fossil fuel resources and broadening the energy mix, sustainable fuels can improve energy security, Countries' energy independence and lower the geopolitical risks associated with fossil fuel dependence (Gökgöz & Güvercin, 2018).

Rural Development and Job Creation. When it comes to biofuels, for instance, the cultivation of energy crops can boost rural economies by giving farmers new sources of revenue. In the same way, the expansion of the hydrogen and e-fuels industries has the potential to boost innovation, open up new employment opportunities, and propel economic growth (Ram, et al., 2020).

Technological Advancement and Innovation: The switch to sustainable fuels asks for and encourages innovation, which may result in scientific discoveries and advancements in productivity, affordability, and scalability. Research and development in the field of sustainable fuel technologies may have broader implications that will encourage innovation in a variety of industries and make the economy more resilient and sustainable.

The adoption of sustainable fuels aligns with the United Nations Sustainable Development Goals (SDG 7, 13). We can speed up this change and prepare the path for a more sustainable and resilient future by investing in research, putting supportive policies into place, and promoting stakeholder collaboration.

Bio-fuels can be profitably used as direct substitute of a plethora of fossil fuels. Anyway, also e-fuels, while primarily associated with the transport and mobility sectors, can be utilized in a number of applications:

- industrial processes requiring large amounts of heat and power
- replacing conventional fossil fuels in furnaces and combined heat and power (CHP) plants.
- energy storage systems (Tsiklios, et al., 2023)
- remote and Off-Grid Applications (Viteri, et al., 2023)
- transportation in aviation and maritime sectors (Gray, et al., 2021)

Anyway, the use of sustainable fuels will depend on the specific characteristics of the technology, the availability of renewable electricity (Graves, et al., 2011), and the compatibility with existing infrastructure

3.6.2 Technical challenges

Sustainable fuels show considerable promise In terms of lowering greenhouse gas emissions, improving energy security, and diversifying energy sources. However, they must overcome a number of obstacles in order to be widely adopted and to reach sustainable energy objectives. The creation and application of cutting-edge technologies to boost productivity, cut costs, and enhance overall performance present a substantial challenge. Moreover, the cost competitiveness of sustainable fuels is now a challenge due to their economic viability. Owing to feedstock availability, size of the production process, and the requirement for innovative technologies, the cost of producing sustainable fuels is now frequently greater that traditional. Furthermore, the lack of comprehensive laws, standards, and regulatory frameworks tailored to sustainable fuels is actually a major obstacle. Finally, the transition to sustainable fuel adoption requires the development of complex infrastructure for fuel production, storage, and distribution.

- Bio-fuels challenges

The idea that Municipal solid waste (MSW) is a reliable source of raw materials to extract and reuse has gained traction in recent years. As a result, the cycle of managing waste has undergone significant evolution, moving from "collection and landfill disposal" to "waste sorting and treatment in dedicate plants", with the goal to minimize the part to be sent to landfill. Given that this last have long stood as a symbol of an environmentally unsustainable model, this paradigm shift embraces the ideas of environmental sustainability as well as the circular economy, which is based on the recycling of materials and resources that must be reintroduced into the economic circuit.

A large amount of MSW, i.e. paper, glass, metals, and plastics, can be recycled to create new raw materials for use in production circuits. A similar conversion may be made for the organic waste component, which can be used in some processes to create compost for use in agriculture, energy, and bio-fuels (Sipra, et al., 2018). Biofuels are important because they provide a renewable and potentially sustainable alternative to traditional fossil fuels so that, they may lower greenhouse gas emissions, improve energy security, and encourage rural development. Biofuels can contribute to a more diverse and cleaner energy mix by utilising biomass feedstocks and cutting-edge conversion methods. Moreover, they may address issues like climate change, air pollution, and resource depletion related to the use of fossil fuels. By using organic waste and by-products to produce energy, biofuels also provide an important waste management method. Some challenges remain in any case, such as feedstock availability, land usage and assuring sustainable production methods.

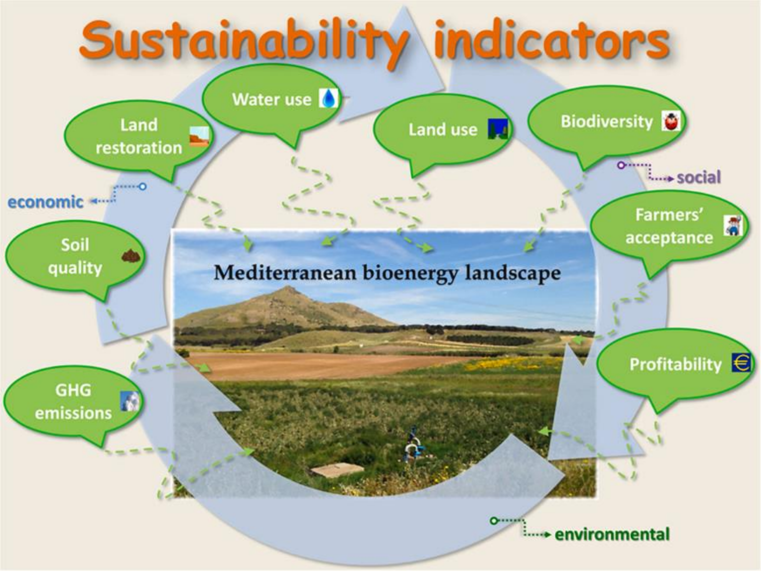

Figure 61- (Credit: (Pulighe, et al., 2019), *CC BY 4.0 via ScienceDirect)*

- *feedstock availability*

Various feedstocks, such as crops, agricultural leftovers, algae, or waste materials, are needed depending on the type of biofuel (Swain, 2017). Concerns relating to resource availability arise from the possibility of competition between the demand for these feedstocks and food production or other land uses. Additionally, the seasonality of particular feedstocks may limit their availability for reliable year-round biofuel production. Concerns relating to resource availability arise from the possibility of competition between the demand for these feedstocks and food production or other land uses. Additionally, the seasonality of particular feedstocks may limit their availability for reliable year-round biofuel production. To avoid damage to food security, ecosystems and biodiversity, a reliable and sustainable supply of raw materials is needed.

- *Land Use Concerns*

Biofuel production often requires considerable land area and this raises concerns about potential land use change and associated environmental impacts. Land conversion for the production of biofuel feedstocks can result in biodiversity loss (Wiens, et al., 2011), and deforestation (Gao, et al., 2011), especially if natural ecosystems are destroyed to make space for agricultural land. The carbon benefits of biofuels could be outweighed by changes in land use since these changes could cause carbon that has been stored in vegetation and soil to be released. Finding a balance between the demand for land for food production and biofuel crops is the real challenge.

- *Ensuring Sustainable Production Practices*

Making sure that bio-fuels production methods are sustainable is crucial. Along the whole production lifetime, from feedstock cultivation to fuel conversion and distribution, this involves reducing greenhouse gas emissions. It also entails dealing with potential environmental harms like pesticide use or water pollution from agricultural runoff. Resource efficiency, waste management, and the preservation of biodiversity and ecosystems are all parts of sustainable production methods. Strong certification programmes, guidelines, and standards may ensure that biofuel production adheres to sustainable practises and reduces any potential negative effects.

Second-generation biofuels, produced from non-food biomass and waste, offer potential advantages over first-generation biofuels as they are not in direct competition to the food industry. We consider in the second generation also biofuels derived from non-food feedstocks like algae, which can be grown in various aquatic environments. However, there are still some issues associated with their production among which:

- *Feedstock Availability, Composition and Variability*

The collection and handling of diverse waste streams can be logistically complex and costly, requiring proper infrastructure and collection systems. There is a wide range in the composition and quality of waste feedstocks. Processes for conversion that are reliable and efficient have difficulties because of this variability. The efficiency of conversion and the quality of the biofuel can be affected by a variety of feedstock properties, including moisture content, lignin content, and ash content. Moreover, waste feedstocks may contain contaminants including heavy metals, pesticides, and other substances and pre-treatment and purification steps are necessary to assure the quality of the biofuel and avoid any potential harmful environmental effects.

- *Energy and Water Requirements*

Significant energy inputs are frequently needed for processes like pre-treatment, hydrolysis, and fermentation when turning waste into biofuels, depending on the particular conversion method used. Water is also required at different phases of the production process. To reduce negative environmental effects and resource consumption, it's critical to guarantee the greatest energy and water efficiency of second-generation biofuel production (Yang, et al., 2009).

Although second-generation biofuels are generally considered more sustainable than first-generation ones, the entire production process must be evaluated for its overall sustainability (Mohr & Raman, 2013) and lifespan effects. This assessment must cover greenhouse gas emissions, changes in land use, water use, and evaluate potential effects on environments and biodiversity. The creation of sustainable second-generation biofuel production systems can be aided by a thorough lifecycle evaluation, which can also help identify areas for improvement.

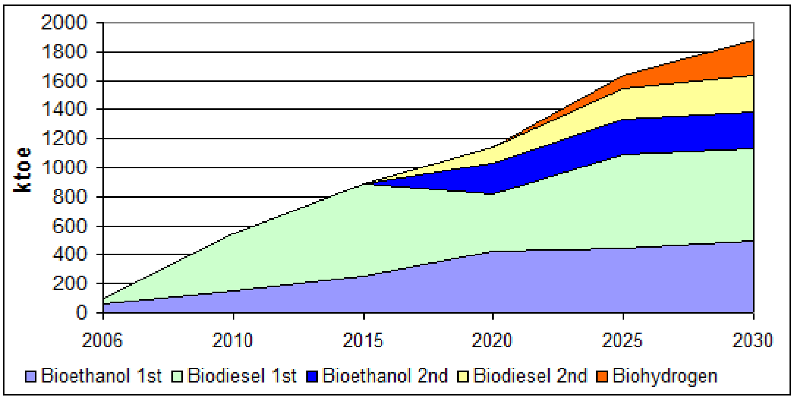

Figure 62- Production of transportation biofuels and prevision up to 2030 (Credit: SEBE2013, CC BY-SA 3.0, via Wikimedia Commons)

- E-fuels challenges

E-fuels, also known as synthetic fuels or electrofuels, have recently gained popularity as a possible substitute of conventional fossil fuels. These fuels are, or must be made using renewable energy sources, including solar or wind energy and hydrogen is the best known. It has and has aroused a lot of interest because it is a clean and flexible energy source. E-fuels, including hydrogen, are being studied to the aim of decarbonize a variety of sectors, including transportation, industry, and power generation, as the world works to transition to a more sustainable energy system (Ramirez, et al., 2020).

The primary benefit of e-fuels is that they often work with current cars, ships, and planes as well as existing liquid fuel supply and retail systems. With conventional fuels, 'drop-in' fuels like e-diesel, e-gasoline, and e-jet fuel can be totally fungible. The usage of drop-in e-fuels may be a necessary component in a portfolio of activities to decrease transportation-related GHG emissions given the lengthy lifespans of the current fleets of cars, ships, and aeroplanes and the urgency of tackling climate change. In general, new or modified vehicles and infrastructure are needed for other renewable transportation fuels (Brynolf, et al., 2022).

Low energy conversion efficiency from electricity to energy at the wheels and high manufacturing costs are e-fuels' key downsides. The future availability of e-fuels is now very uncertain due to these disadvantages and recent substantial advancements in electric vehicle technology (namely battery cost and performance).

E-fuels are of synthetic origin, composed of hydrogen combined or not with carbon dioxide. They are suitable for internal combustion engines but need to be produced using renewable energy sources to be considered clean (Nemmour, et al., 2023). Moreover, producing synthetic fuels requires a substantial amount of electricity. E-fuels are environmentally inefficient if there is no existing infrastructure network for their production. Additionally, the production costs are not as advantageous, which could ultimately impact, for instance, the price paid by purchasers of vehicles fuelled by e-fuels. In particular, the production of e-fuels faces several significant barriers that need to be overcome for widespread adoption. Some of these obstacles characterize the biofuel production too. Other are typical of e-fuels. Among the first we find the *Cost and Economic Viability since* the production of both biofuel and e-fuels is often more expensive compared to conventional fossil fuels and even other renewable energy sources (Ueckerdt , et al., 2021). Also, the requirement of dedicated infrastructure for production, storage, and distribution are common to both and the same regarding *Policy and Regulatory barriers* which ask for establishing clear and supportive policies that incentivize e-fuel production. However, the following are more specific to E-fuels:

- *Energy Efficiency:*

The conversion processes used to produce e-fuels often have lower energy efficiency compared to direct use of renewable energy sources. The main way to produce **hydrogen**, electrolysis, usually involves the following steps: (a) electricity generation, (b) electrolysis of water to yield hydrogen and oxygen, and (c) compression or liquefaction for transportation and storage. Energy is lost throughout each phase, resulting in a lower energy efficiency than with biofuels.

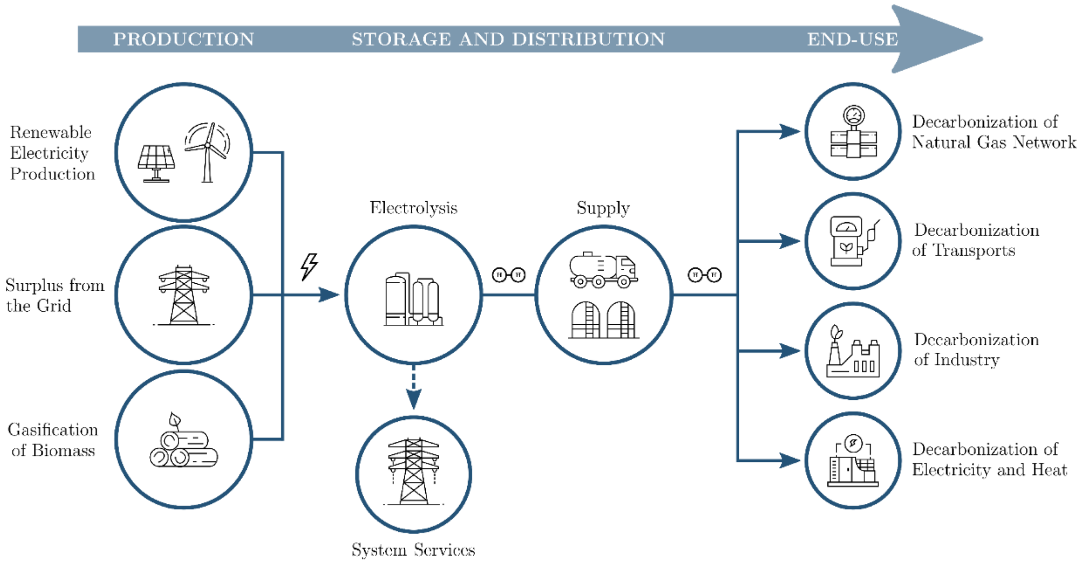

Figure 63- flowchart of hydrogen's value chain (Credit: (Vidas & Castro, 2021) *,* *CC BY 4.0**, via MDPI)*

a) Electricity Generation: The overall energy efficiency of hydrogen production is greatly influenced by the effectiveness of electricity generation systems but it may be better if the power used for electrolysis originates from sustainable resources like solar or wind. In any case, there is a reduction in energy efficiency because of conversion losses.

b) Electrolysis Efficiency: There are inherent efficiency restrictions with electrolysis since the process of converting electrical energy into hydrogen can lead to energy losses, which lower overall efficiency, depending on the method employed (e.g., alkaline electrolysis, proton exchange membrane electrolysis, or solid oxide electrolysis) (Vidas & Castro, 2021).

c) Compression and Storage: To compress or liquefy hydrogen for storage and transit, more energy is needed. These extra energy inputs affect the energy efficiency of hydrogen as an e-fuel and add to the overall energy requirements.

Concerning **E-fuels** other than hydrogen, such as synthetic liquid fuels, they involve additional conversion processes, as Fischer-Tropsch (F-T) synthesis or methanol synthesis, whose efficiency can vary depending on the specific conversion technology, feedstock, and process conditions (Zang, et al., 2021).

The quality of the CO_2 feedstock and the carbon capture technique employed both affect how well collected carbon dioxide (CO2) is converted into liquid e-fuels. The total energy efficiency of e-fuels can also be impacted by carbon capture systems, which might have different energy needs and efficiency levels.

However, e-fuels other than hydrogen, such as synthetic liquid fuels, typically do not require compression to be in liquid form at ambient temperature since they are not gas at standard pressure and temperature so, unlike hydrogen, they can be produced directly as liquids.

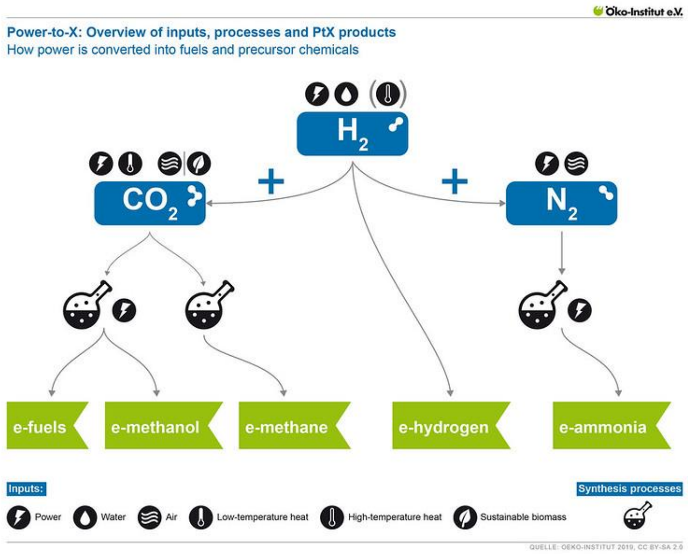

Figure 64- How power is converted into fuels and precursor chemicals (credit: Oeko-Institut e.V., CC BY-SA 2.0 via Flickr)

- *Availability of Renewable Energy*

The production of both e-fuels and hydrogen heavily relies on a consistent supply of renewable energy. However, there are some distinctions to consider since the processes involved are different but they both require access to a sufficient and reliable supply of renewable energy and limitations in the availability and scalability of renewable energy can pose challenges to the widespread production and adoption of both hydrogen and other e-fuels:

Hydrogen production through electrolysis requires a substantial supply of renewable electricity. If renewable energy sources are insufficient or unpredictable in a particular location, the widespread usage of hydrogen as an electric fuel may be constrained. The capability and effectiveness of renewable energy production systems also have an impact on the total availability of renewable energy for hydrogen synthesis.

The production of **e-fuels**, excluding hydrogen, similarly depends, although in a different way, on a steady and adequate supply of renewable energy due to the fact that for the particular energy-intensive conversion procedures used to make e-fuels, like (F-T) synthesis or methanol synthesis, the availability of renewable energy is crucial. To ensure that e-fuels have a positive environmental impact, the electricity required for these operations should ideally come from renewable sources.

- *Carbon Capture and Utilization:*

Many e-fuels require carbon dioxide (CO2) as a feedstock. Capturing and sourcing sufficient amounts of CO2 from industrial processes or directly from the atmosphere can be challenging. Developing efficient and scalable carbon capture technologies and establishing CO2 supply chains are necessary for sustainable e-fuel production.

Hydrogen production through electrolysis generally does not involve direct carbon capture and utilization. However, if the hydrogen manufacturing process contains carbon capture technology to lessen the carbon footprint connected with the electricity generation phase, carbon capture and utilisation may become relevant.

Other **e-fuels**, like synthetic liquid fuels, frequently need carbon dioxide (CO_2) to be captured and used as a feedstock. Through procedures like (F-T) synthesis or methanol synthesis, which combine hydrogen (typically sourced from renewable sources) with collected or recycled CO_2, these e-fuels can be created.

Technologies for carbon capture and utilisation are used to remove CO_2 emissions from the atmosphere or from industrial processes. The cleaned, stored CO_2 is then used as a feedstock to create synthetic fuels. Therefore, the CO_2 is recycled by being first captured during the production of the fuel and then released into the environment during its use (combustion), eliminating the net carbon emission. Production of e-fuels is dependent on the development of efficient conversion techniques, the availability of effective and scalable carbon capture systems, and the accessibility of CO2 sources.

The success of e-fuels and the switch to a more sustainable energy system are both made possible by the effective implementation of CO2 capture and exploitation.

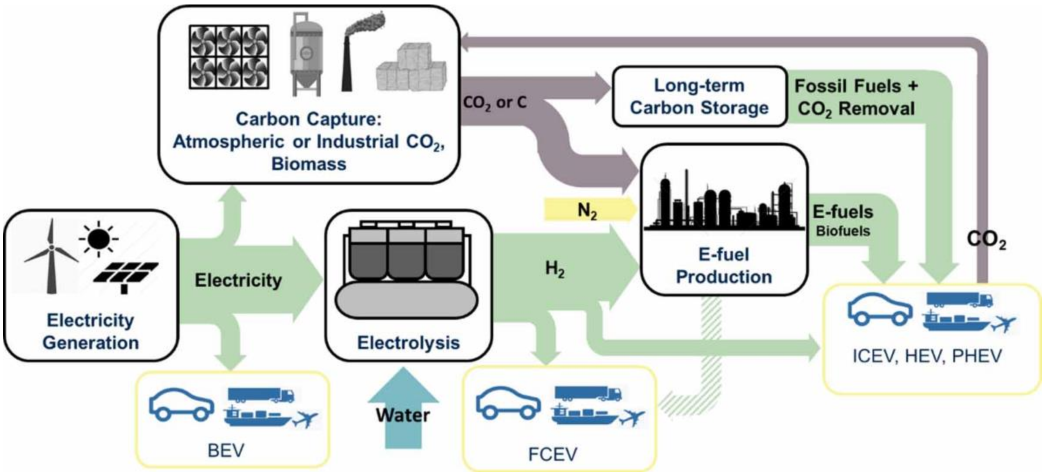

Figure 65 - Four decarbonization options for transport (BEV, battery electric vehicle; FCEV, fuel cell electric vehicle; HEV, hybrid electric vehicle; ICEV, internal combustion engine vehicle; PHEV, plug-in hybrid electric vehicle) (Credit: (Brynolf, et al., 2022) *, CC BY 4.0 via IOPScience)*

3.6.3 Economic Aspects

It is strategically important to build industrial synergies in addition to technology advancements in order to lower market entry costs since technologies for making sustainable fuels have been tried and tested in numerous installations around the world, but production costs are currently high, because the processes have not yet been scaled up, especially for e-fuels. Future development projects may comprise activities on various scale, up to pilot plant scale, encompassing multiple technology readiness levels. To meet this challenge, multifaceted technological know-how is required with skills that cover the entire e-fuels value chain and it is also necessary to conduct process and predictive assessments, technical, economic, and environmental feasibility studies. As usual, the key is developing lines of activity that bring together industrial partners with varied core businesses but which can find interest in shared technological advancement.

It is crucial to combine multiple lines of business that contribute to the total value chain of the technology in order to promote the development of sustainable fuels. This entails identifying and bringing together many parties, including producers of renewable energy, technologists, equipment and fuel manufacturers, and end users (such as industrial or transportation businesses). A comprehensive and all-encompassing strategy can be used to meet the opportunities and problems related to the development of sustainable fuels by merging different lines of activity.

Industrial partners from various core businesses and sectors can contribute distinctive perspectives, skills, and resources. These partners can be joined to create a collaborative framework that enables the sharing of expertise, resources, and investments. Industries like renewable energy, chemical manufacture, transportation, engineering, and others may participate in this collaboration. Each partner provides their own subject expertise, infrastructure, market insights, and customer base, resulting in a collaborative atmosphere that fosters the development of sustainable fuel technologies.

The co-development of technology can result in a number of advantages by utilising the combined talents and resources of industrial partners:

a. The inclusion of partners from other industries enables the exchange of thoughts, first-hand knowledge, and best practises. This sharing of knowledge encourages creativity and advances a deeper comprehension of the difficulties and possibilities posed by the development of sustainable fuels.

b. Business partners can pool resources including manufacturing plants, distribution systems, and research centres. This collaboration streamlines the usage of resources and eliminates redundancy, resulting in cost savings and a quicker adoption of new technology.

c. By collaborating with business entities from various industries, you can gain access to a variety of marketplaces and end users. Better commercialization possibilities are made possible by the facilitation of the discovery of market demands, customer needs, and prospective deployment options for sustainable fuels.

d. Spreading out the expenses and risks among commercial partners helps lessen the financial burden of technological development. Collaboration also enables a more thorough risk assessment and management approach, employing the partners' combined experience to successfully address possible issues.

e. By cooperating, industry partners may create a louder voice to promote laws and rules that encourage the creation and uptake of sustainable fuel technology. Through this partnership, they may have a greater impact on policymakers and help create an atmosphere that will support the development of sustainable fuels.

Elements of economic analysis

Economic analysis is crucial for evaluating the financial feasibility, market dynamics, and socio-economic impact of sustainable fuels technology. Understanding the economic viability, market dynamics, and socioeconomic effects of switching to sustainable fuel sources depends heavily on the economic analysis of this technology. The main facets of economic analysis are cost analysis, economic viability, market dynamics, socioeconomic impact, risk analysis, and financing concerns.

Cost Analysis

> Cost analysis for sustainable fuels technologies (Singh, et al., 2022) must consider both up-front and ongoing expenses. Investments in equipment, infrastructure, and R&D are included in capital expenses, while feedstock collection, processing, energy use, upkeep, and staff costs are all included in operational costs.

Economic Viability

> By examining how competitively priced sustainable fuels are compared to conventional fuels, we can determine if they are economically viable (Meng, et al., 2021). Examined are elements including pricing discrepancies, prospective cost savings from economies of scale, and technology developments. To assess the profitability and return on investment of sustainable fuel initiatives the payback duration, internal rate of return, and net present value, are considered.

Market Dynamics and Demand

> A comprehensive market analysis is essential. Supply and demand dynamics, market size, growth potential, and future projections must be explored (Fragkos, 2022). It is also necessary to look into the impact of government incentives, subsidies, carbon pricing mechanisms, and emissions reduction targets on market competitiveness and demand for sustainable fuels.

Socio-Economic Impact

Technology for sustainable fuels has the ability to provide jobs and promote economic growth. Analysis of the potential for direct and indirect employment generation along the whole value chain is needed (Brinkman, et al., 2019). Also, the local advantages, such as boosted earnings, business prospects, and regional expansion must be considered. The potential for trade and exports is assessed while considering the advantages and difficulties of doing business on foreign markets. The potential effects of sustainable fuels on various economic sectors are investigated too.

Risk Analysis and Uncertainty

The risks associated with sustainable fuel technology must be recognized (Pasman, 2011), including technological challenges, market volatility and political uncertainties (Wanitschke & Hoffmann, 2020) since understanding these risks helps identifying potential barriers and develop strategies to mitigate them.

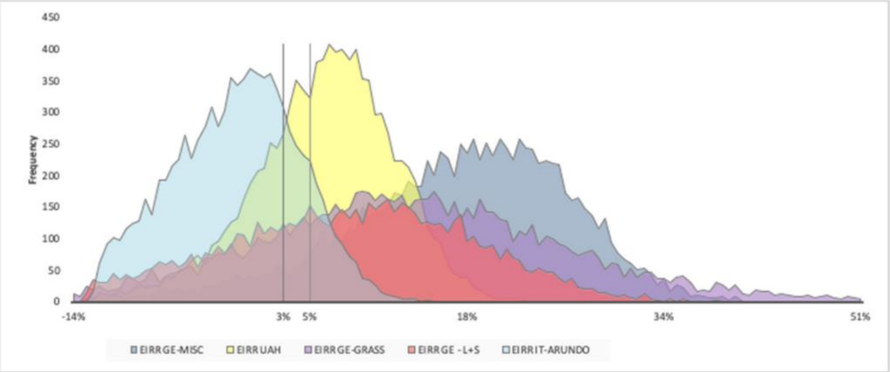

Figure 66- Overlay chart of Economic Internal Rate of Return (EIRR) of various competing investments (Credit: (Traverso, et al., 2021), CC BY 4.0 via MDPI)

Financing and Investment

Different funding sources need to be explored, including government grants, venture capital, and private investment and the overall legal framework (Skov & Schneider, 2022). Additionally, financial instruments and mechanisms are to be considered such as project financing, public-private partnerships, and carbon offsetting.

Economic analysis is crucial. By considering all the above elements, informed decisions are made and strategies that promote the adoption and successful implementation of sustainable fuels are developed.

Economic & Financial analysis tools

The economic and financial tools commonly used for economic analysis in assessing the feasibility of sustainable fuels technology provide valuable insights for decision-making, project planning, and securing the necessary funding for successful implementation. They include:

Cost-Benefit Analysis (CBA)

CBA is a widely used tool to evaluate the economic viability of sustainable fuel projects (Lee, 2016). It weighs both monetary and non-monetary elements when contrasting the expenses of putting the technology in place and running it with the advantages anticipated. CBA aids in calculating and contrasting costs and advantages to assess if the project is financially feasible.

Net Present Value (NPV)

NPV is a financial tool that calculates the present value of future cash flows generated by a project. The time value of money is accounted for by discounting future cash flows to their present value (Haghi, et al., 2017). A project's financial viability and ability to provide returns above the needed rate of return are both indicated by a positive NPV.

Internal Rate of Return (IRR)

IRR is another financial indicator used to evaluate a project's profitability. It stands for the discount rate at which NPV of the project is equal to zero. The project is financially feasible if the computed IRR is higher than the needed rate of return.

Sensitivity Analysis, Risk Analysis and Monte Carlo Simulation

These tools are frequently used in in assessing the feasibility of sustainable fuel project. Sensitivity analysis is used to assess the impact of changes in key parameters on the financial. Risk analysis evaluates the potential risks and uncertainties. Monte Carlo simulation is often employed to model the project's financial performance under various scenarios by randomly sampling different parameter values within specified ranges (Jang, et al., 2022).

Finally, Analysis of available financing options, such as government grants, subsidies, tax incentives, and private investment, is crucial to assess the financial feasibility of sustainable fuel projects.

3.6.4 Environmental Impact, Circularity and Acceptance

The potential for circularity in their production and consumption cycles, as well as their environmental effect, are critical factors to consider when thinking about sustainable fuel technologies. It is important to assess these fuels' overall sustainability and contribution to a circular economy even if they attempt to reduce the harmful environmental consequences of conventional fossil fuels.

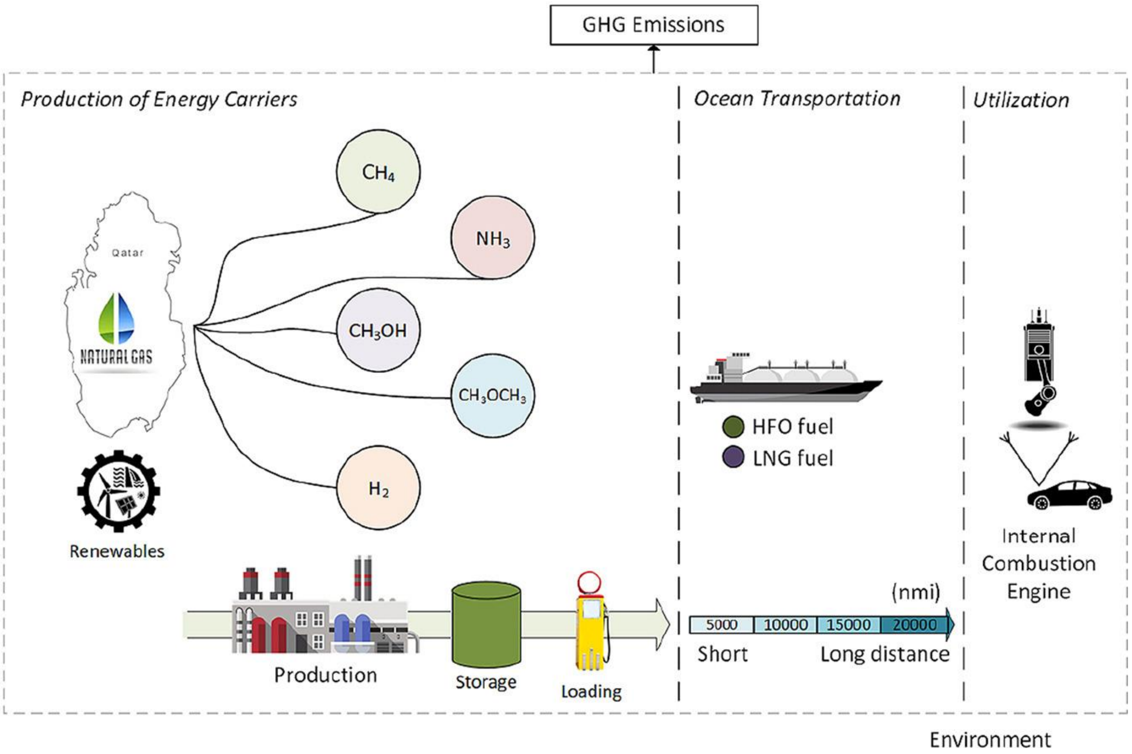

Figure 67- Life cycle assessment framework of sustainable energy carriers (Credit: (Al-Breiki & Bicer, 2021), CC BY 4.0 via ScienzeDirect)

Sustainable fuels are created primarily with the aim of lowering greenhouse gas emissions and their environmental impact. By utilizing renewable or low-carbon feedstocks and employing innovative conversion methodologies, these fuels exhibit significant reductions in their carbon dioxide, nitrogen oxide, and particulate emissions in comparison to fossil fuels. The circular economy theory places a strong emphasis on reducing waste production and increasing resource efficiency and this might entail using waste or leftovers from various sectors or processes as feedstocks in the case of sustainable fuels. Examples of circularity concepts in action include collecting and utilising carbon dioxide emissions from industrial facilities or using agricultural residues as biomass feedstocks for biofuels. The lifecycle assessment of sustainable fuels, which considers feedstock issues as well, is essential and the full lifespan, including the generation of feedstocks, fuels, distribution, and final use, is included by this evaluation (Al-Breiki & Bicer, 2021). By assessing the environmental effect at each stage, it is feasible to find potential areas for improvement and maximise the overall sustainability of future fuels. Important factors to evaluate are energy efficiency, land usage, water use, and waste creation. The circularity issue goes beyond the production stage. Consideration should be given to the management of sustainable fuels' by-products and end-of-life situations. It is crucial to have the option of recycling used biofuels, for instance, reusing them, or properly disposing of waste materials from production operations to prevent unwanted environmental effects.

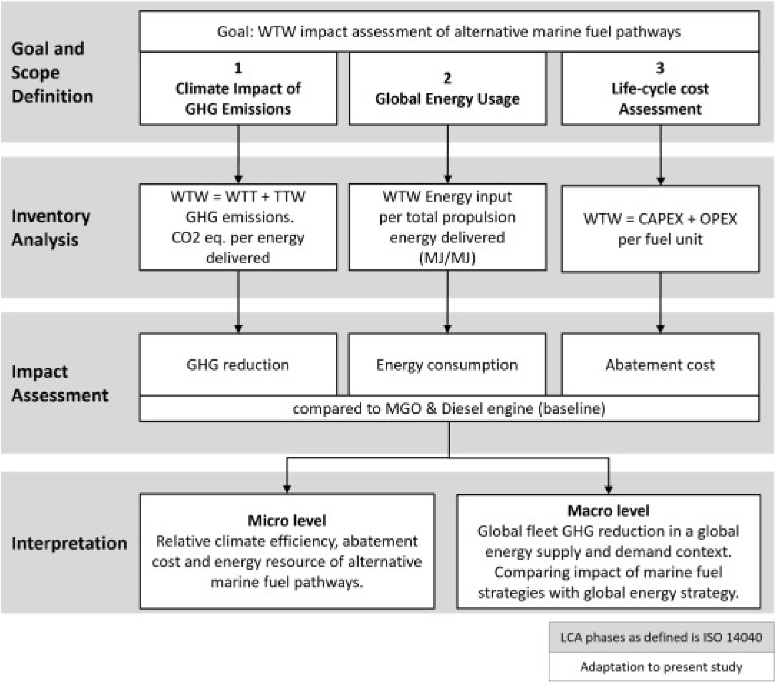

Figure 68- Life-cycle assessment (LCA) methodologies for marine fuel pathways (Credit: (Lindstad, et al., 2021) , CC BY 4.0, via ScienceDirect)

Collaboration amongst different stakeholders is critical to achieving optimum environmental benefits and circularity. The development and implementation of strong laws and regulations that support sustainable fuel technologies, stimulate the use of renewable or low-carbon feedstocks, and encourage circularity principles need collaboration between governments, businesses, and research organisations. Innovation and ongoing technological and industrial process improvement are also essential. To further reduce the environmental effect of sustainable fuels, research and development activities should concentrate on maximising energy efficiency, lowering waste creation, and improving resource utilisation.

Acceptance and social impact

The idea of sustainability has been widely discussed at many societal levels and covered in literature since the early 1990s. The three sustainability elements of ecological, economic, and social systems are mentioned in the definition of sustainability that is most frequently employed. From an emphasis on economic growth, which is frequently characterised as the increase of consumption and GNP, to a new viewpoint on development known as sustainable development, the notion of sustainability emerged (Assefa & Frostell, 2007).

The following requirements must be satisfied concurrently to accomplish full sustainability:

- Ecological sustainability refers to the preservation of nature's natural capital as well as environmental and territorial sustainability, the former of which is concerned with the ability of natural ecosystems to function as sinks and the latter of which assesses the spatial distribution of human activity and rural-urban arrangements.

- Economic sustainability, roughly defined, is the capacity of economic systems (institutions, laws, and norms of operation) to assure ongoing social equity, quantitative advancement, and qualitative improvement.
- Social sustainability, which also includes cultural sustainability as a consequence.
- Political sustainability: supplying a comprehensive framework for national and global governance that is satisfactory.

E-fuels, biofuels, and hydrogen must have a positive impact on people to be successfully adopted and integrated into our energy systems. Although these fuels provide potential answers to environmental problems, they frequently encounter social, cultural, and behavioural constraints that must be overcome in order for them to be widely accepted.

The general public's view of sustainable fuels is a crucial factor in acceptability and societal influence. People's desire to use these technologies, that is their acceptance, is significantly shaped by their attitudes, beliefs, and level of knowledge about them. The advantages of sustainable fuels, such as their favourable effects on lowering greenhouse gas emissions, boosting energy security, and improving the environment, must be adequately communicated. Building trust and encouraging acceptance across communities requires honest information sharing, public awareness campaigns, and educational initiatives. Furthermore, it is impossible to overlook how sustainable fuel technologies affect society. The switch to these fuels might have both beneficial and negative effects on the economy and the labour market. Heavy reliance on conventional fossil fuels may cause disruptions in industries and regions, necessitating careful planning and policies for a just transition. It is crucial to consider the potential social and economic repercussions and make sure that the advantages of sustainable fuels are fairly divided among all relevant parties. Community involvement and engagement are crucial for addressing issues and obtaining local viewpoints. Projects using sustainable fuels must account for the unique demands, goals, and cultural settings of local people. Better informed and more inclusive decisions may be made by including communities in the decision-making process, listening to their issues, and comprehending them.

Infrastructure accessibility and availability are also key factors in social acceptability. For instance, the availability of hydrogen and biofuel delivery networks as well as electric car charging stations might affect how convenient and simple it is to switch to sustainable fuels. To increase acceptability and adoption, infrastructure must be improved, its dependability must be guaranteed, and equal access must be considered. Finally, the importance of enabling laws and policies cannot be emphasised enough. Governments must provide a stable and transparent regulatory environment that promotes the creation and application of sustainable fuel technology. Business and consumer adoption of these fuels can be facilitated by incentives, subsidies, and long-term planning (Skov & Schneider, 2022).

Social acceptance is a dynamic process rather than static. It calls for interaction between many stakeholders during the individual valuation process. Changes in modern technology will also elicit reactions from many socioeconomic groups, particularly locals. This suggests that if future biofuel and e-fuels technological directions are considered, future social acceptability may be forecasted. This is crucial since sustainable fuel is a rapidly evolving technology (Chin, et al., 2014).

By addressing the above aspects, we can create an enabling environment that fosters acceptance and paves the way for the successful integration of sustainable fuels into our energy systems, ultimately contributing to a more sustainable and cleaner future.

3.7 Green and Energy Efficiency Financing

3.7.1 Introduction

Green financing refers to financial activities and investment aimed at supporting environmentally friendly projects, such as renewable energy, energy efficiency, and sustainable transportation. It is a growing sector within the financial industry that seeks to provide capital for projects that promote environmental sustainability and help mitigate the effects of climate change.

Green financing is a fundamental instrument since it complements public resources which are not enough to support a large-scale energy transition. For example, the scale of investment required to achieve the goals of the European Green Deal and the energy transition is significant, and private financing can help fill the gap left by limited public funding.

Green financing can take many forms, including green bonds, green loans, and impact investing. These financial products and services are designed to channel capital towards projects and businesses that have a positive impact on the environment and promote sustainability.

When Green Financing is focused on energy efficiency projects, it is referred to as *Energy Efficiency Financing*.

Energy efficiency financing is a way to fund energy efficiency measures, such as upgrading building insulation, replacing inefficient lighting, or purchasing energy-efficient equipment, by using innovative financial schemes.

Cities and urban areas are particularly important targets for energy efficiency financing, as they account for a significant portion of energy use and emissions. By improving the energy efficiency of buildings, transportation systems, and industrial processes in cities, energy efficiency financing can help reduce energy consumption and greenhouse gas emissions, while also creating economic and social benefits for city residents (i.e., non-energy benefits).

Financial Institutions face several barriers when approaching green financing, including a lack of standardization and clarity in definitions, uncertainty about future energy prices, high transaction costs, limited access to data, uncertainty about policy and regulatory frameworks, perceived higher risk, and lack of knowledge and expertise. More specifically:

- **Lack of standardization and clarity in definitions**: There is a lack of standardization and clarity in definitions of green finance, making it difficult for financial institutions to accurately assess the environmental impact of investments.
- **Uncertainty about future energy prices**: Financial institutions may be concerned about the uncertainty surrounding future energy prices, as fluctuations in energy prices can impact the financial returns from green finance investments.
- **High transaction costs**: The high transaction costs associated with green finance, such as the costs of designing, implementing, and monitoring projects, can be a barrier for financial institutions.
- **Limited access to data**: Financial institutions may struggle to access the data they need to accurately assess the financial returns and risks associated with green finance, particularly in the case of smaller projects or those in emerging markets.
- **Uncertainty about policy and regulatory frameworks**: Financial institutions may be uncertain about the future of policy and regulatory frameworks that support green finance, and the

impact that changes in these frameworks may have on the financial returns from green finance investments.

- **Perceived higher risk**: Some financial institutions may perceive green finance as higher risk compared to traditional investments, due to the relatively new and untested nature of many green finance projects.
- **Lack of knowledge and expertise**: Financial institutions may lack the in-depth knowledge and technical expertise needed to evaluate the potential financial returns and risks associated with green financing.

It is then mandatory to work on the financial institutions side in order to overcome these barriers and untap the potential of providing capital for supporting green financing. For example, the implementation of de-risking instruments and technical partnerships (e.g., with energy utilities) are pivotal.

On the other hand, also on the final users' side there are barriers to overcome which are usually linked to **preferences** and **irrational behaviour** as deeply discussed by (Cattaneo, 2019).

Preferences can be grouped in three categories, namely time, risk, and environment. Time preferences represent the fact that, in general, people are willing to invest in measures which give feedback shortly in time. Risk attains the personal inclination towards higher or lower risky investments/decisions. Whereas environmental preference is the positive attitude towards the implementation of measures which have a positive environmental impact.

The irrational behaviour is typical for consumers. As highlighted by (Cattaneo, 2019), consumers rarely adopt rational choices, differently from what was thought according to neoclassical economic theories. Having a rational behaviour implies to be able to evaluate all the variables and parameters leading to a choice in a correct way, but this is rather uncommon and even more difficult in the energy sector. To behave rationally in taking investment decisions related to the implementation of energy measures mean to have the necessary know-how for understanding the related implications.

Usually, consumer choices are affected by different effects, namely (Cattaneo, 2019):

- **Reference-dependence and non-linear probability weighting.** Decisions are taken according to a reference point that can be incorrect. Furthermore, common people may tend to overestimate small probabilities and underestimate moderate or large probabilities.
- **Rational Inattention.** Consumers often have inattention to some product attribute. Usually, there is less attention to operating cost and higher attention to purchase price. This provokes a lower willingness to invest in green technologies and energy efficiency.
- **Bounded Rationality.** Consumers are usually unable to process much information. This pushes them to rely on *rules of thumb* or to oversimplify the decision-making process. Thus, the irrational behaviour is determined by too much information which is difficult to analyse.
- **Present bias and myopia.** These aspects emphasize how the consumers are unable to evaluate future contexts. The present bias leads to the applications of higher discount rates to future benefits, whereas myopia indicates the inability to develop foresight. Thus, this determines a scarce attitude towards investments which have a long duration.
- **Status quo bias.** This is linked with the inertia in taking decision which would change the current condition. This hampers the uptake of investments in energy efficiency and green technologies.

To address time preferences and irrationality, information instruments are relevant. As discussed by (Cattaneo, 2019), it is not only important the content of the information but also the way it is presented. It is necessary to guide and assist the final users in their decision-making process. Municipalities, utilities, etc. should support the consumers in this process.

The barriers hampering the implementation of green investment discussed so far can be overcome by capacity building approaches, partnership (e.g., for financial institutions) and better targeted information campaigns (e.g., for final users).

Another relevant barrier is represented by the financing of green investments, since from one side financial institutions are reluctant in investing in green technologies and, from the other side, final users, when they are willing to invest, are limited by the upfront investment costs. To prevent this stalling situation, innovative business models and supportive mechanisms have been devised, and many of them are highly effective in promoting investments in urban areas.

(Bertoldi, et al., 2021) developed a comprehensive overview of financing mechanisms with a specific focus on energy efficiency in buildings. Whereas (Taghizadeh-Hesary & Yoshino, 2022), (Hafnera, et al., 2020), and (Akomea-Frimpong, et al., 2022) propose a broader analysis of green financing mechanisms.

In the following a detailed analysis of on-bill mechanisms, on-tax systems and green mortgages is proposed since they seem the most suitable approaches for supporting the green transition in cities.

3.7.2 On-bill Mechanisms

On-Bill programs are schemes for supporting the execution of energy investments by providing the upfront capital through the utilities. The capital is then repaid “on the bill”, namely the usual energy bill will include an additional line which refers to the repayment of the capital cost due to the application of the on-bill scheme.

The approach results quite attractive for supporting energy transition since it is completely based on private capital. Energy utilities can use own funds, in such case programs are defined as “on-bill financing”. Alternatively, they can provide the service in cooperation with a financial institution which provides the capital and in this case the programs are defined as “on-bill repayment”.

On-Bill schemes, both “on-bill financing” or “on-bill repayment”, are based on the detailed knowledge that energy utilities have of their customers, especially as regards the payment history of the bill which can be used as a risk hedging strategy since utilities can propose to step-in possible on bill programs only to the customers who have a regular payment history.

These programs are very attractive due to their flexibility and scalability. They can be designed to promote energy efficiency measures, installation of renewables, e-mobility, etc. and can target small investments usually not attractive for banks or financial institutions due to the difficulty in managing many small clients and to the high transaction costs. On the contrary, this is the daily business of energy utilities, used to manage thousands of small customers (e.g., residential users) paying relatively small individual amounts.

These schemes have been active in USA for more than 30 years with excellent results (Zimring, et al., 2014). The default rate in paying the on-bill fee was detected to be very low, i.e. low than 2%. It is to be said that in USA it is possible the disconnection from the grid for non-payment. This is less applicable to the EU context due to a different social approach. Usually, the disconnection for non-payment is strictly regulated by energy authorities in different EU countries and on-bill programs can hardly enter in this category as energy is considered a primary good.

USA presents different success cases (Zimring, et al., 2014) related to the application of on-bill schemes, as well as some success stories can be found also in developing countries. On the contrary, in Europe there is the experience of the "UK Green Deal" which is a failure story (Mundaca & Kloke, 2018), while new programs offered by energy utilities are emerging.

On-bill schemes are very relevant for urban contexts where there is a high fragmentation of the customer basis (e.g., residential users) which is not attractive for large investors.

Through on bill programs, energy utilities may work as aggregators of the demand of many small interventions and making them viable, e.g., by reaching the necessary critical mass, for financing from financial institutions. This represents an interesting solution for financial institutions which manage a B2B relationship, namely financial institutions vs. energy utilities, so they do not need to manage the relation with all the different final users but just with the utility managing the program. In other words, they can provide capital to the utilities for developing on-bill programs.

In turn the utility will manage the relation with final users, but this relation is already in place for the traditional energy supply, so the extra effort is minimal.

However, this requires a substantial change in the business models of energy utilities which are not anymore energy suppliers, but energy service suppliers. An analysis of different business models can be found in (Bianco, et al., 2022).

In some EU countries, e.g., Germany, it is very common to have municipal utilities, namely utilities owned by the local municipality, thus on-bill schemes can be promoted by the single municipality as an instrument to reduce the consumption of fossil fuels by developing individual RES systems, energy efficiency measures, and sustainable mobility actions.

In turn, citizens can obtain a double benefit:

- reduction of their energy bill (e.g., power, heat, natural gas);
- exploitation of non-energy benefits (e.g., better indoor comfort).

Non-energy benefits are not secondary (Popescu, et al., 2012), and they are gaining relevance especially in the post-pandemic world where people realized how important is the indoor well-being, so that it is reflected in the value of dwellings market for both rents and sales.

3.7.3 On-tax Systems

On-Tax schemes for supporting energy efficiency are models which support the implementation of energy efficiency measures or green technologies by awarding a tax discount in various forms (e.g., tax deduction, decrease of tax rate, repayment of upfront capital cost in form of taxes, etc.).

On-Tax approaches can be very effective in urban context since the scheme can be created and implemented directly by municipalities for reaching specific targets. For example, they could be a strategic instrument for fulfilling some of the objectives of the SEAP/SECAP plans for the municipalities' members of the Covenant of Mayors.

A successful example is represented by the PACE (Property Assessed Clean Energy Programs) scheme. PACE allows property owners, both residential or commercial, to finance the upfront cost of the energy renovation and then to pay-back within a specified period. The program is directly administrated by a municipality which provides the capital after an energy assessment which prescribes the implementation of specific measures. The innovative aspect of the PACE is that it is tied to the property so if the property is sold the next owner will be responsible for PACE repayments or, usually, the last owner has the option to pay in one solution the missing part.

The transferability of the PACE to the next owner is an effective way to overcome the barrier due to the split incentives. Often the owner will not invest in the retrofitting of the dwelling since the investment lasts many years and it is not known if the benefits will be exploited and the investment recovered when the dwelling is sold. On the contrary, if the payment of the PACE can be transferred to the next owner the issue is less sensitive, since all the owners pay the share of investment they will actually benefit.

The relevant innovation in PACE is that the loan repayment responsibilities are integrated into the property tax statement, and the property owner agrees to pay the loan repayments simultaneously with the customary property taxes (Bardhan, et al., 2014). This substantially limits the non-payment as to pay taxes is perceived as an important duty by citizens and, in any case, the non-payment of taxes will determine the application of strict sanctions or fines to pay.

Up to 2019 over 200,000 homeowners invested $5 billion in energy efficiency and other improvements to their dwellings through PACE financing[2].

As highlighted by (Bardhan, et al., 2014), PACE is an effective way for municipalities and local governments (usually at level of Contee) to invest public money. The PACE investments plans are developed to ensure that the present value of the expected savings exceeds the present capital cost of the energy saving measures. Furthermore, the scheme can be designed so that the extra tax to pay is aligned or lower than the achieved energy bill savings. Namely, the bill neutrality is reached and citizens can immediately experience the benefit of the energy retrofitting. This is a powerful incentive for other citizens to apply for the program.

By attaching PACE to property taxes, the program appears as a low-risk investment option, which often allows municipalities to sell PACE credits to investors. This provides the cities with immediate access to new capital for day-to-day operations and the implementation of various projects.

Furthermore, as discussed by (Rose & Wei, 2020), PACE provides both direct and indirect benefits to the urban environment as summarized in Table *1*. Indirect benefits are those not directly linked to the main aim of the program, but they have an impact in evaluating its effectiveness.

As noted by (Rose & Wei, 2020), indirect impacts may have a relevant role. For USA they estimated that that indirect benefits allows to increase by the 30% the value generated by direct benefits.

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[2] https://www.energy.gov/scep/slsc/property-assessed-clean-energy-programs

Direct Benefits	Indirect Benefits
Decrease Fossil Fuel Consumption	Increase in local GDP due to the increased volumes of activities
Increased Share of Renewables	Increased value of the dwellings
Decrease in carbon & pollutant emissions	Increased quality of the local urban environment
Improving indoor living conditions	Improvement of public health and decrease of corresponding externality costs

Table 1. PACE Direct and Indirect benefits *(Rose & Wei, 2020)*

3.7.4 Green Mortgages

Green mortgages are a financial instrument which allow to buy an energy efficient dwelling or provide loans for reaching specific energy efficiency standard of an existing dwelling. The advantage is to benefit from lower interest rate or in getting more capital with respect to standard mortgages.

Usually, an Energy Performance Certificate (EPC) of a specific class must be demonstrated for buying a dwelling in an existing building or a target EPC score must be shown for retrofitting of an existing one.

Green Mortgages are relevant since they are an instrument leveraging on private financing, i.e., financial institutions, without any intervention of the state. It is possible that supra-national organizations, e.g. World Bank, European Investment Bank, etc., provide some capital on the secondary market to financial institutions at advantageous rate provided that this money is used for issuing green mortgage. Thus, there could be a little incentive, but still without affecting public expenses since just a discount on the interest rate is usually applied. Other incentives mechanisms consist in the possibility to establish some risk-hedging mechanisms.

This instrument gained a lot of attention since it targets small properties which are the most complex to consider, since there are many counterparties to approach. If an urban context is considered, the large majority of the buildings is destined to residential users. Therefore, if the small residential properties are not targeted, it is difficult to implement the energy transition in cities.

However, despite their potential benefits, the diffusion of green mortgages has hampered in many countries due to various barriers as shown in the following:

- **Lack of awareness and information**: One of the main barriers to the diffusion of green mortgages is the lack of awareness and information among homeowners. Many homeowners are not aware of the benefits of energy-efficient and sustainable practices or the availability of green mortgages. As a result, they may not be motivated to invest in energy-efficient and sustainable improvements, and they may not seek out green mortgage products. The interest regarding energy efficiency in EU raised during the last months as a consequence of the Russian-Ukrainian war and the spike prices reached by natural gas.
- **Lack of market standards:** Another barrier to the diffusion of green mortgages is the lack of market standards and guidelines. This can create confusion for consumers who may not know what criteria to look for when assessing green mortgage products. It can also make it difficult

for lenders to develop and market green mortgage products, as there may be no standard definition or certification for what constitutes a "green" home.

- **Higher upfront costs:** One of the main reasons why homeowners may be hesitant to adopt energy-efficient and sustainable practices is the higher upfront costs associated with these improvements. While green mortgages can help offset these costs, they may not be enough to fully incentivize homeowners to invest in green improvements.
- **Appraisal and valuation challenges:** Another barrier to the diffusion of green mortgages is the lack of standardization in appraisal and valuation methods for green homes. Appraisers may not be familiar with the unique features and benefits of energy-efficient and sustainable homes, which can make it difficult to accurately assess their value. Furthermore, also the risk profile assessment of the counterparty is often complicated and limit the financing of the initiatives.
- **Regulatory and policy barriers:** Finally, regulatory and policy barriers can also hinder the diffusion of green mortgages. Some regulatory frameworks may not fully recognize or incentivize green mortgage products, which can make it difficult for lenders to develop and market these products. Similarly, some policies may not provide sufficient incentives for homeowners to invest in energy-efficient and sustainable improvements, which can limit the demand for green mortgages.

Green mortgages are a financial instrument which is gaining world-level importance. As illustrated by (Lee, et al., 2018), savings in electricity consumption and diffusion of green mortgages show a certain degree of correlation in Taiwan.

A very successful scheme of green mortgage is the so-called German KfW (Henger & Voigtländer, 2013). The scheme foresees the combination of traditional mortgages with the KfW support. Part of the investment is financed through the KfW if it guarantees specific energy efficiency and carbon emissions reduction levels appraised by a certified energy consultant. The scheme allows to overcome the barrier represented by the high upfront investment costs for energy retrofitting and renewable integration and allows to small owners to renovate their home. The issue is very sensitive in Germany since winter heating may represent a substantial cost for citizens.

Green Mortgages have been in place in USA since The Energy Policy Act of 1992. Two types of green mortgage were introduced, one for new construction and one for existing buildings. The Energy Efficient Mortgage (EEM) is designed for home buyers and uses energy savings from a new, energy-efficient home to increase their buying power, capitalizing the energy savings in the appraisal (Henger & Voigtländer, 2013). Oppositely, the Energy Improvement Mortgage (EIM) is designed for homeowners and finances the energy upgrading of an existing home using monthly energy savings. To qualify for either type of mortgage, an evaluation of the home's energy efficiency and expected energy costs with the Home Energy Rating System (HERS) is necessary (Henger & Voigtländer, 2013). This national scheme is supported by various state- and lender-specific loan programs. In addition, homebuyers can benefit from tax breaks since the interest on mortgage payments is tax deductible (Henger & Voigtländer, 2013). Although this financing scheme has been available in the United States for 20 years, the success has remained limited probably for the low interest rate reduction.

Green mortgages can be useful for supporting energy transition in urban contexts because they can encourage homeowners to make energy-efficient upgrades to their homes, reducing the amount of energy consumed and ultimately contributing to a more sustainable urban environment.

Urban areas tend to have higher energy consumption due to the concentration of buildings and people in a relatively small space. Thus, the implementation of energy efficiency measures and integration of renewables is pivotal since it allows to reduce pollutant and greenhouse gas emissions connected with energy consumption in buildings. This has not only an impact on the energy bill of the final users, but also on the health conditions of the citizens who can live in a cleaner environment.

Furthermore, energy retrofitting and modernization of the urban building stock led to a re-qualification of districts which become more attractive and appealing so that also the value of the building stock tends to increase. Finally, the implementation of energy efficiency measures and renewables integration also affects the local job market since it provides new job opportunities. Moreover, the measures can be oriented towards circularity and utilization of local and recycled materials in order to activate a virtuous circle for all the urban ecosystems.

4. Roadmap for Decarbonisation of Cities

4.1 Introduction

Cities have emerged as pivotal in the fight against climate change. As the world's population continues to concentrate in cities, the environmental impact of urban areas has become increasingly evident. The urgent need to decarbonize urban spaces and transition towards sustainable, low-carbon alternatives has taken centre stage in the global agenda. The issue is very relevant in EU, where a high degree of urbanisation is present.

The present roadmap aims to outline a comprehensive strategy for the decarbonization of urban contexts, providing a clear path forward for governments, city planners, policymakers, and stakeholders. By strategically addressing key aspects of urban development and infrastructure, this roadmap seeks to achieve ambitious emission reduction targets while simultaneously fostering resilient, livable, and environmentally conscious cities.

The achievement of the decarbonization targets requires a multifaceted approach that combines innovative technology, effective governance, robust policy frameworks, innovative financing and active community engagement. It recognizes that each urban context is unique, and solutions must be tailored to local circumstances, challenges, and opportunities. The roadmap presented here offers a flexible framework that can be adapted and customized to suit different cities' specific needs and capacities.

The proposed roadmap is conceived following three main implementation paths:

Sustainable Energy Transformation of the Building Stock. The first path focuses on transitioning urban building stock from reliance on fossil fuels to sustainable and renewable energy sources. This includes encouraging the adoption of solar, wind, and geothermal energy, as well as promoting energy efficiency measures in buildings. All this can be achieved only by enforcing and developing the energy infrastructure by integrating smart grids, energy storage solutions, and decentralized energy generation, urban areas can become more resilient, self-sufficient, and emissions-free.

Development of a Sustainable Transportation System. The second path considers the second sectors in terms of energy consumption in cities, namely transportation. The success of cities' decarbonization is closely connected with the decarbonization of its transportation system. Decarbonization in transportation should be achieved by using a mix of solutions (e.g., electrification, utilization of renewable fuels, etc.) and it is difficult to use just one solution since this would create a rigid system or would determine a relevant stress of the infrastructure (e.g., distribution network in case of electrical transports) which is difficult to sustain even in presence of substantial investments.

Circular Economy and Sustainable Consumption. The third path addresses the importance of transitioning urban contexts towards a circular economy model, where resources are efficiently used, recycled, and repurposed. It promotes waste reduction, recycling initiatives, and the adoption of circular business models to minimize the consumption of raw materials and reduce greenhouse gas emissions associated with production and waste disposal.

To be truly successful, the implementation paths should be connected and developed by implementing appropriate business models which can guarantee a profitable development, not only based on public incentives but also on private financing.

The successful implementation of this roadmap requires collaboration between governments, businesses, civil society, and citizens. It demands a paradigm shift in urban governance, innovative financing mechanisms, and the active participation of communities in decision-making processes. By aligning efforts and working towards a common goal, urban contexts can lead the way in achieving global decarbonization objectives.

4.2 Building Sector Roadmap

The development of renewable energy sources and energy efficiency measures, particularly in the building sector, plays a crucial role in supporting the development of the proposed roadmap for decarbonization of cities. The buildings roadmap to the decarbonization can be articulated in 6 points as follows.

1- Mitigating Greenhouse Gas Emissions. The use of fossil fuels in energy generation is a significant contributor to greenhouse gas and pollutant emissions, which are the primary cause of climate change. By transitioning to renewable energy sources such as solar, wind, and geothermal, urban contexts can drastically reduce their carbon footprint. Renewable energy generation produces little to no emissions during operation, providing a cleaner alternative to traditional fossil fuel-based energy systems. This leads to a drastic reduction of the externality cost with a positive impact for urban population.

2- Reduced Dependency on Fossil Fuels. The roadmap emphasizes the need to reduce reliance on fossil fuels at EU level. This has recently turned into a relevant geopolitical issue after the unjustified invasion of Ukraine by Russian Federation. By developing renewable energy sources, cities can massively contribute to reduce EU dependency on fossil fuel imports, enhancing energy security and reducing exposure to volatile energy prices. This shift towards local and decentralized renewable energy generation requires relevant investment in enforcing the energy infrastructure (e.g., distribution grid) and also requires the development of innovative business models which need to be supported by regulatory changes.

3- Energy Efficiency and Demand Reduction. The building sector is a significant consumer of energy, accounting for a significant portion of urban energy consumption. Energy efficiency measures, such as improved insulation, high-efficiency appliances, and smart building technologies, can significantly reduce energy demand in buildings both in summer and winter. By implementing energy-efficient practices and technologies, urban contexts can minimize energy waste, decrease overall energy consumption, and subsequently lower their carbon emissions. For example, the massive implementation of green roofs and walls can also limit the phenomenon of urban heat island which is becoming more and more pressing in many cities. Nature based solutions are usually easily to implement and are not capital intensive. The development of easy to implement nature-based solutions will be key in the next year.

4- Cost Savings and Economic Benefits. Transitioning to renewable energy sources and implementing energy efficiency measures can lead to substantial cost savings in the long run. Renewable energy costs have been declining over the years, making them increasingly competitive with fossil fuels. By adopting renewables and improving energy efficiency, urban areas can reduce energy bills, stimulate local economies through job creation in renewable energy sectors, and attract investment in sustainable technologies. Furthermore, other non-energy benefits can be achieved such as the increased value of buildings due to its energy retrofitting or the extra value due to the improved living conditions (e.g., warmer in winter and colder in summer).

5- Improved Indoor and Outdoor Air Quality. Fossil fuel combustion in buildings contributes to air pollution, which has adverse effects on public health. By promoting renewable energy sources and energy-efficient buildings, urban areas can reduce emissions of pollutants such as particulate matter, nitrogen oxides, and volatile organic compounds. This transition results in improved indoor air quality for occupants and cleaner outdoor air for the entire community, leading to better health outcomes and a higher quality of life.

6- Demonstrating Leadership and Inspiring Replication. By actively pursuing the development of renewable energy sources and energy efficiency measures, urban contexts can serve as role models and inspire others to follow suit. Successful implementation showcases the feasibility and benefits of sustainable practices, encouraging neighboring cities and regions to replicate similar initiatives. This domino effect can accelerate the overall transition to a low-carbon economy and contribute to global decarbonization efforts.

In summary, the development of renewable energy sources and energy efficiency measures, particularly in the building sector, provides a foundation for the proposed roadmap for decarbonization of urban contexts. These measures mitigate greenhouse gas emissions, reduce dependency on fossil fuels, promote energy security, generate cost savings, improve air quality, and inspire replication. By integrating these strategies, urban areas can lead the way towards a more sustainable and resilient future.

4.3 Transportation Sector Roadmap

The development of renewable energy sources and energy efficiency measures in the transportation sector, plays has a crucial role in supporting the development of the proposed roadmap for decarbonization of cities. The transportation roadmap for the decarbonisation is articulated in six points as follows.

1- Reduction of Transportation Emissions. The transportation sector is a significant contributor to greenhouse gas emissions, mainly through the combustion of fossil fuels in vehicles. By transitioning to renewable energy sources such as electric power, biofuels, or hydrogen, cities can substantially reduce emissions from transportation. Renewable energy-powered vehicles produce little to no direct emissions, leading to a significant reduction in carbon dioxide and air pollutants, thus supporting the decarbonization efforts.

2- Decreased Dependency on Fossil Fuels. Shifting away from fossil fuel-powered transportation reduces dependency on petroleum imports and enhances energy security. By developing renewable energy sources to power electric vehicles (EVs) or adopting other sustainable transportation solutions like hydrogen fuel cells or biofuels, urban contexts can diversify their energy sources and reduce vulnerability to volatile oil prices and supply disruptions.

3- Improved Air Quality and Public Health. Fossil fuel-powered vehicles contribute to air pollution, leading to adverse health effects for urban residents. By promoting renewable energy sources in transportation, cities can significantly reduce emissions of harmful pollutants such as particulate matter, nitrogen oxides, and volatile organic compounds. This transition leads to improved air quality, reduces the risk of respiratory illnesses, and enhances public health and overall quality of life for the community.

4- Enhanced Energy Efficiency. Energy efficiency measures in transportation, such as promoting public transit systems, optimizing traffic management, and encouraging active modes of transportation like walking and cycling, can contribute to energy savings and reduce greenhouse gas emissions. By integrating renewable energy-powered public transit systems, cities can further enhance energy efficiency and decrease reliance on private vehicles, resulting in reduced congestion, shorter travel times, and improved mobility options.

5- Demonstrating Leadership and Influencing Behavior Change. Cities that actively pursue renewable energy-powered transportation initiatives can serve as models of sustainability and inspire behavior change. By demonstrating the feasibility, convenience, and benefits of low-carbon transportation options, cities can encourage residents and businesses to adopt sustainable practices. This can lead to a broader societal shift towards clean transportation choices, further supporting the decarbonization of urban contexts.

In summary, the development of renewable energy sources and energy efficiency measures in the transportation sector supports the proposed roadmap for decarbonization of cities. These measures reduce transportation emissions, decrease dependency on fossil fuels, improve air quality and public health, enhance energy efficiency, foster technological advancements, generate cost savings, and influence behavior change. By integrating these strategies, cities can make significant progress towards sustainable and low-carbon transportation systems, contributing to a greener and more livable future.

4.4 Energy System Integration Roadmap

A more effective energy system integration, both in terms of sectors and energy sources, has a fundamental role in supporting the development of the proposed roadmap for decarbonization of cities. A roadmap based on seven points is proposed.

Optimal Resource Allocation. Effective energy system integration allows for optimal allocation of energy resources across different sectors. It enables the coordination and sharing of energy generation, storage, and distribution infrastructure, ensuring efficient use of renewable energy sources. By integrating various sectors, such as electricity, transportation, and buildings, cities can optimize resource allocation and minimize wastage, leading to a more sustainable and cost-effective energy system. However, to implement such a strategy, it is fundamental to have highly qualified professionals working on these aspects which require a high level of specialization and multidisciplinary knowledge.

Flexibility and Resilience. Energy system integration provides flexibility and resilience to cities. By diversifying energy sources and integrating renewable energy generation, cities can reduce their vulnerability to supply disruptions or fluctuations in any single energy source. For example, integrating solar power with energy storage systems allows excess energy generated during the day to be stored and used during peak demand periods or when solar generation is limited. This flexibility enhances the reliability and stability of the energy system.

Demand-Side Management. Effective energy system integration enables demand-side management strategies, which involve optimizing energy consumption based on availability, cost, and environmental factors. By integrating smart grids, smart meters, and energy management systems, urban contexts can actively manage energy demand in response to supply variations and grid constraints. This demand-side flexibility allows for load shifting, peak shaving, and demand response programs, ultimately leading to more efficient and sustainable energy use.

Synergies and System Efficiency. Energy system integration allows for synergies between different sectors, enabling system-level optimization and efficiency gains. For instance, excess heat generated from industrial processes can be captured and utilized for district heating or combined heat and power systems, reducing the need for additional energy inputs. Integrated approaches can also facilitate the use of renewable energy sources, such as wind or solar, to power electric vehicle charging infrastructure, thereby maximizing the utilization of clean energy.

Decentralization and Local Energy Systems. Energy system integration supports the development of decentralized and localized energy systems, which can enhance energy security and resilience. By integrating distributed energy resources, such as rooftop solar panels, microgrids, and community energy projects, urban contexts can reduce transmission losses and enhance local energy self-sufficiency. This decentralized approach also promotes community engagement, empowers local stakeholders, and fosters a sense of ownership in the energy transition.

Technological Innovation and Collaboration. Effective energy system integration fosters technological innovation and collaboration across sectors. The integration of different energy sources and technologies encourages the development of complementary solutions, such as coupling renewable energy with energy storage, electric vehicle charging infrastructure, and demand-side management systems. Collaboration between stakeholders, including utilities, technology providers, policymakers, and researchers, becomes crucial in exploring innovative solutions and driving progress towards decarbonization goals.

Policy and Regulatory Frameworks. Energy system integration requires supportive policy and regulatory frameworks to overcome barriers and promote cooperation between different sectors. It involves coordinating standards, regulations, and market mechanisms to enable the seamless integration of diverse energy sources and sectors. Clear policies that incentivize renewable energy deployment, encourage energy efficiency, and promote cross-sector collaboration are essential to create an enabling environment for effective energy system integration.

In summary, a more effective energy system integration, in terms of sectors and energy sources, supports the proposed roadmap for decarbonization of cities. It optimizes resource allocation, enhances flexibility and resilience, enables demand-side management, fosters synergies and system efficiency, promotes decentralization, drives technological innovation and collaboration, and requires supportive policy and regulatory frameworks. By embracing energy system integration, urban areas can transition towards sustainable, low-carbon energy systems, contributing to a greener and more resilient future.

5. Conclusions

The present report proposed an in-depth analysis of eleven renewable technologies, fuels, and strategies. This basket of items is identified after engaging with stakeholders through direct interviews, surveys, and analysis of relevant documents.

Technologies and fuels were analysed along with four dimensions, namely, technical feasibility, economic analysis, circularity, and environmental impact. The analysis shows that some relevant technologies are already available on the market (i.e., solar PV or solar thermal collectors) and they offer the best performances when coupled with *technology enablers* such as heat pumps or thermal storage systems, which are not renewable systems, but they allow RES development and massive utilization.

Large improvements can be achieved in the circularity dimension by promoting actions, even in regulatory terms, to oblige the re-utilization and re-use of components, which often contain critical materials. Thus, dismissed plants can also become a source of critical raw materials (e.g., PV panels and batteries).

An interesting approach is also represented by the implementation of nature-based solutions such as green roofs and walls, which support the insulation of building walls in both summer and winter by guaranteeing more comfortable living conditions. Besides, green roofs and walls also help to limit the heat island effects, which are becoming more and more prominent in cities.

Renewable fuels are an essential component for the decarbonization and sustainability of urban contexts since, after the building sector, transport sector is the most carbon intensive and it is also difficult to decarbonize. As for cars, relevant progresses have been made for their electrification, but for heavy duty vehicles, planes, ships, etc., the situation is much more complex and they result hard to abate; namely the decarbonization is difficult. For these categories, innovative fuels such as biofuels, e-fuels, and hydrogen could represent a turning point. Biofuels produced from organic waste or exhausted vegetable oils are also characterized by a substantial level of circularity and process symbiosis.

Financing systems also have a pivotal role since final users need resources to implement renewable and sustainable solutions, thus it is important to develop self-sustainable systems which are accessible for the community. Three mechanisms are considered in this report, namely on-bill mechanisms, on-tax systems, and green mortgages.

All the renewable technologies, fuels and strategies analysed in the present report represent a brick of the future energy context of cities. A balanced mix of all of them is necessary to achieve the energy transition and decarbonisation. In general, the urban energy system cannot be unbalanced on a specific technology, fuel, or strategy but an optimal mix of them is necessary to tackle the volatility and uncertainty which affect renewable sources.

Finally, it is also fundamental to create a positive regulatory context which supports the implementation and testing, e.g., through *regulatory sandboxes*, of innovative technologies to have on-field feedback.

All the analysed aspects are then summarized to propose a roadmap for the decarbonization of cities. In particular, three factors are emphasized, namely buildings, transportation and energy system integration. They are considered the key-drivers to achieve energy transition in cities, since buildings and the transportation sector are two main energy consumers, whereas energy system integration is pivotal to implement innovative approaches and business models which support the energy transition in cities.

References

Abd Alla, S., Bianco, V., Tagliafico, L. A. & Scarpa, F., 2020. An innovative approach to local solar energy planning in Riva Trigoso, Italy. *Journal of Building Engineering,* 1, Volume 27, p. 100968.

Abdeen, M. O., 2008. Ground-source heat pumps systems and applications. *Renewable and Sustainable Energy Reviews,* 12(2), pp. 344-371. DOI: 10.1016/j.rser.2006.10.003.

Abokersh, M. H. et al., 2021. A framework for sustainable evaluation of thermal energy storage in circular economy. *Renewable Energy,* 175(September), pp. 686-701. DOI: 10.1016/j.renene.2021.04.136.

Adams, B., 2008. *Green Development- Environment and Sustainability in a Developing World.* 3rd Edition a cura di London: Routledge.

Akomea-Frimpong, I., Adeabah, D., Ofosu, D. & Tenakwah, E. J., 2022. A review of studies on green finance of banks, research gaps and future directions. *Journal of Sustainable Finance & Investment,* 12(4), pp. 1241-1264.

Alashqar, M., Xue, ,. Y., Yang, C. & Zhang, X.-P., 2022. Comprehensive economic analysis of PV farm - A case study of Alkarsaah PV farm in qatar. *Frontiers in Energy Research,* 10(art. no. 987773), p. DOI: 10.3389/fenrg.2022.987773.

Al-Breiki, M. & Bicer, Y., 2021. Comparative life cycle assessment of sustainable energy carriers including production, storage, overseas transport and utilization. *Journal of Cleaner Production,* 279(123481), pp. 1-16. DOI: 10.1016/j.jclepro.2020.123481.

Alshehri, F. et al., 2021. Sensitivity analysis of a vertical geothermal heat pump system in a hot dry climate. *Renewable Energy,* 178(November 2021), pp. 785-801, DOI: 10.1016/j.renene.2021.06.058.

Alva, G., Lin, Y. & Fang, G., 2018. An overview of thermal energy storage systems. *Energy,* Volume 144, pp. 341-378. DOI: 10.1016/j.energy.2017.12.037.

Amelia, A. R. et al., 2016. Investigation of the effect temperature on photovoltaic (PV) panel output performance. *Int. J. Adv. Sci. Eng. Inf. Technol,* 6(5), pp. 682-688. DOI:10.18517/ijaseit.6.5.938.

Andenæs, E., Kvande, T., Muthanna, T. & Lohne, J., 2018. Performance of Blue-Green Roofs in Cold Climates: A Scoping Review. *Buildings,* 8(4)(55), pp. 1-24. DOI: 10.3390/buildings8040055.

Anderson, L. G., 2015. Effects of using renewable fuels on vehicle emissions. *Renewable and Sustainable Energy Reviews,* 47(July), pp. 162-172. DOI: 10.1016/j.rser.2015.03.011.

Angerer, M. et al., 2018. Design of a MW-scale thermo-chemical energy storage reactor. 4(november), pp. 507-519. DOI: 10.1016/j.egyr.2018.07.005.

Ardente, F., Beccali, G., Cellura, M. & Lo Brano, V., 2005. Life cycle assessment of a solar thermal collector. *Renewable Energy,* 30(7), pp. 1031-1054. DOI: 10.1016/j.renene.2004.09.009.

Arslan, O. & Arslan, A. E., 2022. Performance evaluation and multi-criteria decision analysis of thermal energy storage integrated geothermal district heating system. *Process Safety and Environmental Protection,* 167(November), pp. 21-33. DOI: 10.1016/j.psep.2022.08.073.

Ascione, F. et al., 2013. Green roofs in European climates. Are effective solutions for the energy savings in air-conditioning?. *Applied Energy,* 104(Aprile), pp. 845-859. DOI: 10.1016/j.apenergy.2012.11.068.

Assefa, G. & Frostell, B., 2007. Social sustainability and social acceptance in technology assessment: A case study of energy technologies. *Technology in Society,* 29(1), pp. 63-78. DOI: 10.1016/j.techsoc.2006.10.007.

Azzuni, A. & Breyer, C., 2018. Energy security and energy storage technologies. *Energy Procedia,* 155(november), pp. 237-258. DOI: 10.1016/j.egypro.2018.11.053.

Baeten, B., Rogiers, F. & Helsen, L., 2017. Reduction of heat pump induced peak electricity use and required generation capacity through thermal energy storage and demand response. *Applied Energy,* 195(june), pp. 184-195. DOI: 10.1016/j.apenergy.2017.03.055.

Bardhan, A., Jaffee, D., Kroll, C. & Wallac, N., 2014. Energy efficiency retrofits for U.S. housing: Removing the bottlenecks. *Regional Science and Urban Economics,* Volume 47, pp. 45-60.

Bernal, D.C., et al., 2021. Environmental assessment of latent heat thermal energy storage technology system with phase change material for domestic heating applications. *Sustainability (Switzerland),* 13(20), p. art. no. 11265. DOI: 10.3390/su132011265.

Bertoldi, P. et al., 2021. How to finance energy renovation of residential buildings:Review of current and emerging financing instruments inthe EU. *WIREs Energy and Environment,* Volume 10, p. e384.

Betancur-Arboleda, L. et al., 2021. Experimental study of the thermal performance of a PCM in heat sinks. *Periodicals of Engineering and Natural Sciences,* 9(4), pp. 744-754. DOI: 10.21533/pen.v9i4.1991.

Bianchini, F. & Hewage, K., 2012. Probabilistic social cost-benefit analysis for green roofs: A lifecycle approach. *Building and Environment,* 12, Volume 58, pp. 152-162. DOI: 10.1016/j.buildenv.2012.07.005.

Bianco, V. & Sonvilla, P. M., 2021. Supporting energy efficiency measures in the residential sector. The case of on-bill schemes. *Energy Reports,* Volume 7, pp. 4298-4307. DOI: 10.1016/j.egyr.2021.07.011.

Bianco, V., Sonvilla, P. M., Gonzalez Reed, P. & Prado, A. V., 2022. Business models for supporting energy renovation in residential buildings. The case of the on-bill programs. *Energy Reports,* Volume 8, pp. 2496-2507.

Borri, E. et al., 2022. Compressed Air Energy Storage—An Overview of Research Trends and Gaps through a Bibliometric Analysis. *Energies,* 15(20), p. 7692. DOI: 10.3390/en15207692.

Brinkman, M. L., Wicke, B., Faaij, A. P. & van der Hilst, F., 2019. Projecting socio-economic impacts of bioenergy: Current status and limitations of ex-ante quantification methods. *Renewable and Sustainable Energy Reviews,* 115(109352), pp. 1-16. DOI: 10.1016/j.rser.2019.109352.

Bruck, M., Sandborn, P. & Goudarzi, N., 2018. A Levelized Cost of Energy (LCOE) model for wind farms that include Power Purchase Agreements (PPAs). *Renewable Energy,* 7, Volume 122, pp. 131-139.

Brynolf, S. et al., 2022. Review of electrofuel feasibility—prospects for road, ocean, and air transport. *Progress in Energy,* 4(4), pp. 1-29. DOI: 10.1088/2516-1083/ac8097.

Cabeza, L. F., de Gracia, A., Zsembinszki, G. & Borri, E., 2021. Perspectives on thermal energy storage research. *Energy,* 231(120943), pp. 1-10. DOI: 10.1016/j.energy.2021.120943.

Calheiros, C. S. C. & Stefanakis, A. I., 2021. Green Roofs Towards Circular and Resilient Cities. *Circular Economy and Sustainability 2021 1:1,* 3, 1(1), pp. 395-411. DOI: 10.1007/s43615-021-00033-0.

Calise, F. et al., 2022. A solar-driven 5th generation district heating and cooling network with ground-source heat pumps: a thermo-economic analysis. *Sustainable Cities and Society,* Issue 76, p. 103438. DOI: 10.1016/j.scs.2021.103438..

Carrol, P., Chesser, M. & Lyons, P., 2020. Air Source Heat Pumps field studies: A systematic literature review. *Renewable and Sustainable Energy Reviews,* 134(December), pp. 1-12, 110275. DOI: 10.1016/j.rser.2020.110275.

Carter, T. & Jackson, C. R., 2007. Vegetated roofs for stormwater management at multiple spatial scales. *Landscape and Urban Planning,* 3, 80(1-2), pp. 84-94. DOI: 10.1016/j.landurbplan.2006.06.005.

Cattaneo, C., 2019. Internal and external barriers to energy efficiency: which role. *Energy Efficiency,* Volume 12, pp. 1293-1311.

Charalambous, P. G., Maidment, G. G., Kalogirou, S. A. & Yiakoumetti, K., 2007. Photovoltaic thermal (PV/T) collectors: A review. *Applied Thermal Engineering,* 2, 27(2-3), pp. 275-286.

Chaurasia, R., Gairola, S. & Pal, Y., 2022. Technical, economic feasibility and sensitivity analysis of solar photovoltaic/battery energy storage off-grid integrated renewable energy system. *Energy Storage,* 4(1), pp. -:e283. DOI: 10.1002/est2.283.

Chin, H.-C., Choong, W.-W., Wan Alwi, S. R. & Mohammed, A. H., 2014. Issues of social acceptance on biofuel development. *Journal of Cleaner Production,* 71(May), pp. 30-39. DOI: 10.1016/j.jclepro.2013.12.060.

Choe, W., Ooka, R. & Nam, Y., 2018. Impact of long-term operation of ground-source heat pump on subsurface thermal state in urban areas. *Sustainable Cities and Society,* Volume 38, pp. 429, 439, DOI: 10.1016/j.scs.2017.12.036..

Commission, E., 2020. *A new Circular Economy Action Plan For a cleaner and more competitive Europe.* [Online]
Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

David, B. R., Spencer, S., Miller, J. & Almahmoud, S., 2021. Comparative environmental life cycle assessment of conventional energy storage system and innovative thermal energy storage system. *International Journal of Thermofluids,* 12(November, 100116), pp. 1-11. DOI: https://doi.org/10.1016/j.ijft.2021.100116.

de Gracia, A. & Cabeza, L. F., 2015. Phase change materials and thermal energy storage for buildings. *Energy and Buildings,* 103(september), pp. 414-419. DOI: 10.1016/j.enbuild.2015.06.007.

Dincer, I., 2002. On thermal energy storage systems and applications in buildings. *Energy and Buildings,* 34(4), pp. 377-388. DOI: 10.1016/S0378-7788(01)00126-8.

Dunn, R. I., Hearps, P. J. & Wright, M. N., 2012. Molten-Salt Power Towers: Newly Commercial Concentrating Solar Storage. *in Proceedings of the IEEE,* 100(2), pp. 504-515. DOI: 10.1109/JPROC.2011.2163739.

Dusseault, B. & Pasquier, P., 2021. Usage of the net present value-at-risk to design ground-coupled heat pump systems under uncertain scenarios. *Renewable Energy,* 173(August 2021), pp. 953-971, DOI: 10.1016/j.renene.2021.03.065.

El-Khawad, L., Bartkowiak, D. & Kümmerer, K., 2022. Improving the end-of-life management of solar panels in Germany. *Renewable and Sustainable Energy Reviews,* 10, Volume 168, p. 112678.

Fayaz, H. et al., 2012. An overview of hydrogen as a vehicle fuel. *Renewable and Sustainable Energy Reviews,* 16(8), pp. 5511-5528. DOI: 10.1016/j.rser.2012.06.012.

Fragkos, P., 2022. Decarbonizing the International Shipping and Aviation Sectors. *Energies ,* 15(25), pp. 1-25. DOI: 10.3390/en15249650.

Gao, Y. et al., 2011. Assessing deforestation from biofuels: Methodological challenges. *Applied Geography,* 31(2), pp. 508-518. DOI: 10.1016/j.apgeog.2010.10.007.

Garber, D., Choudhary, R. & Soga, K., 2013. Risk based lifetime costs assessment of a ground source heat pump (GSHP) system design: Methodology and case study. *Building and Environment,* 60(February 2013), pp. 66-80, DOI: 10.1016/j.buildenv.2012.11.011.

Gaurav, N. et al., 2017. Utilization of bioresources for sustainable biofuels: A Review. *Renewable and Sustainable Energy Reviews,* 73(June), pp. 205-2014. DOI: 10.1016/j.rser.2017.01.070.

Gaur, M. K. & Tiwari, G. N., 2010. Optimization of number of collectors for integrated PV/T hybrid active solar still. *Applied Energy,* 87(5), pp. 1763-1772. DOI: 10.1016/j.apenergy.2009.10.019.

Gil, A. et al., 2010. State of the art on high temperature thermal energy storage for power generation. Part 1—Concepts, materials and modellization. *Renewable and Sustainable Energy Reviews,* 14(1), pp. 31-55. DOI: 10.1016/j.rser.2009.07.035.

Gökgöz, F. & Güvercin, M. T., 2018. Energy security and renewable energy efficiency in EU. *Renewable and Sustainable Energy Reviews,* 96(November), pp. 226-239. DOI: 10.1016/j.rser.2018.07.046.

Graves, C., Ebbesen, S. D., Mogensen, M. & Lackner, K. S., 2011. Sustainable hydrocarbon fuels by recycling CO2 and H2O with renewable or nuclear energy. *Renewable and Sustainable Energy Reviews,* 15(1), pp. 1-23. DOI: 10.1016/j.rser.2010.07.014.

Gray, N. et al., 2021. Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. *Advances in Applied Energy,* 1(100008), pp. 1-24. DOI: 10.1016/j.adapen.2021.100008.

Hachem-Vermette, C. & Singh, K., 2021. Analysis of Urban Energy Resources to Achieve Net-Zero Energy Neighborhoods. *frontiers in Sustainable Cities,* 3(663256), pp. 1-10, DOI: 10.3389/frsc.2021.663256.

Hafnera, S., Jonesa, A., Anger-Kraavib, A. & Pohla, J., 2020. Closing the green finance gap – A systems perspective. *Environmental Innovation and Societal Transitions,* Volume 34, pp. 26-60.

Haghi, E., Fwoler, M. & Raahemifar, K., 2017. *Economic analysis of hydrogen production in context of a microgrid.* Oshawa, ON, IEEE , pp. 79-84. DOI: 10.1109/SEGE.2017.8052780.

Hameer, S. & Van Niekerk, . J. L., 2016. Thermodynamic modelling of thermal energy storage systems. *Energy Procedia,* Volume 93, pp. 25-30. DOI: 10.1016/j.egypro.2016.07.145.

Henger, R. & Voigtländer, M., 2013. Green investments and green mortgages in Germany. *EMF HYPOSTAT,* pp. 18-21.

Hepbasli, A. et al., 2014. A key review of wastewater source heat pump (WWSHP) systems. *Energy Conversion and Management,* 88(December), pp. 700-722. DOI: 10.1016/j.enconman.2014.08.065.

Hoivik, N., et al., 2019. Long-term performance results of concrete-based modular thermal energy storage system. *Journal of Energy Storage,* 24(art. no. 100735), pp. 1-12. DOI: 10.1016/j.est.2019.04.009.

Ibrahim, H., Ilinca, A. & Perron, J., 2008. Energy storage systems—Characteristics and comparisons. *Renewable and Sustainable Energy Reviews,* 12(5), pp. 1221-1250. DOI: 10.1016/j.rser.2007.01.023.

IEA, I. E. A., 2022. *A 10-Point Plan.* [Online]
Available at: https://www.iea.org/reports/a-10-point-plan-to-reduce-the-european-unions-reliance-on-russian-natural-gas

IEA, I. E. A., 2022. *Heat Pumps - Analysis - IEA.* [Online]
Available at: https://www.iea.org/reports/heat-pumps

IRENA & IEA-PVPS, 2016. End-of-Life Management: Solar Photovoltaic Panels. *International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems.*

Jang, D. et al., 2022. Techno-economic analysis and Monte Carlo simulation of green hydrogen production technology through various water electrolysis technologies. *Energy Conversion and Management,* 258(115499), pp. 1-13. DOI: 10.1016/j.enconman.2022.115499.

Kalogirou, S. A., 2004. Solar thermal collectors and applications. *Progress in Energy and Combustion Science,* 1, 30(3), pp. 231-295.

Kathirgamanathan, A., De Rosa, M., Mangina, E. & P.Finn, D., 2021. Data-driven predictive control for unlocking building energy flexibility: A review. *Renewable and Sustainable Energy Reviews,* 135(110120), pp. 1-17, DOI: 10.1016/j.rser.2020.110120.

Khan, M. et al., 2021. Investigation of Biofuel as a Potential Renewable Energy Source. *Atmosphere ,* 12(10), pp. 1-24. DOI: 10.3390/atmos12101289.

Koroneos, C. J. & Nanaki, E. A., 2012. Life cycle environmental impact assessment of a solar water heater. *Journal of Cleaner Production,* 12, Volume 37, pp. 154-161.

Langergraber, G. et al., 2021. Framework for Addressing Circularity Challenges in Cities with Nature-Based Solutions.. *Water,* 13(17), pp. 1-31. DOI: 10.3390/w13172355.

Laube, T. et al., 2020. Thermodynamic Analysis of High-Temperature Energy Storage Concepts Based on Liquid Metal Technology. *Energy Technology,* 8(3), pp. 1-10. DOI: 10.1002/ente.201900908.

Lee, D.-H., 2016. Cost-benefit analysis, LCOE and evaluation of financial feasibility of full commercialization of biohydrogen. *International Journal of Hydrogen Energy,* 41(7), pp. 4347-4357. DOI: 10.1016/j.ijhydene.2015.09.071.

Lee, N., Su, H.-J. & Lin, M.-C., 2018. Electricity Consumption and Green Mortgage: New Insights into the Threshold Cointegration Relationship. *International Journal of Energy Economics and Policy,* 8(2), pp. 39-46.

Lindstad, E. et al., 2021. Reduction of maritime GHG emissions and the potential role of E-fuels. *Transportation Research Part D: Transport and Environment,* 101(103075), pp. 1-15. DOI: 10.1016/j.trd.2021.103075.

Longo, S., Beccali, M., Cellura, M. & Guarino, F., 2020. Energy and environmental life-cycle impacts of solar-assisted systems: The application of the tool “ELISA”. *Renewable Energy,* Volume 145, pp. 29-40. DOI: 10.1016/j.renene.2019.06.021.

Ma'bdeh, S. N., Ali, H. H. & Rabab'ah, I. O., 2022. Sustainable assessment of using green roofs in hot-arid areas – Residential buildings in Jordan. *Journal of Building Engineering,* 1, Volume 45, p. 103559. DOI: 10.1016/j.jobe.2021.103559.

Mahdiyar, A., Tabatabaee, S., Yahya, K. & Mohandes, S., 2021. A probabilistic financial feasibility study on green roof installation from the private and social perspectives. *Urban Forestry & Urban Greening,* 58(126893), pp. 1-11. DOI: 10.1016/j.ufug.2020.126893.

Mahmoudi, S., Huda, N. & Behnia, M., 2020. Environmental impacts and economic feasibility of end of life photovoltaic panels in Australia: A comprehensive assessment. *Journal of Cleaner Production,* 260(art. no. 120996), p. DOI: 10.1016/j.jclepro.2020.120996.

Martinopoulos, G. & Tsalikis, G., 2014. Active solar heating systems for energy efficient buildings in Greece: A technical economic and environmental evaluation. *Energy and Buildings,* 1, 68(PARTA), pp. 130-137.

McKenna, R., Fehrenbach , D. & Merkel, E., 2018. The role of seasonal thermal energy storage in increasing renewable heating shares: A techno-economic analysis for a typical residential district. *Energy and Buildings,* 187(March), pp. 38-49. DOI: 10.1016/j.enbuild.2019.01.044.

Meng, F. et al., 2021. Bioethanol from autoclaved municipal solid waste: Assessment of environmental and financial viability under policy contexts. *Applied Energy,* 298(117118), pp. 1-13. DOI: 10.1016/j.apenergy.2021.117118.

Mohr, A. & Raman, S., 2013. Lessons from first generation biofuels and implications for the sustainability appraisal of second generation biofuels. *Energy Policy,* 63(Dicember), pp. 114-122. DOI: 10.1016/j.enpol.2013.08.033.

Mundaca, L. & Kloke, S., 2018. On-Bill Financing Programs to Support Low-Carbon Energy Technologies: An Agent-Oriented Assessment. *Review of Policy Research,* 35(4), pp. 502-534.

Naves, A. X. et al., 2019. Life cycle costing as a bottom line for the life cycle sustainability assessment in the solar energy sector: A review. *Solar Energy,* 11, Volume 192, pp. 238-262.

Nemmour, A., Inayat, A., Janajreh, I. & Ghenai, C., 2023. Green hydrogen-based E-fuels (E-methane, E-methanol, E-ammonia) to support clean energy transition: A literature review. *International*

Journal of Hydrogen Energy, Volume In Press, Corrected Proof, pp. 1-23. DOI: 10.1016/j.ijhydene.2023.03.240.

Ode Sang, Å., Thorpert, P. & Fransson, A. M., 2022. Planning, Designing, and Managing Green Roofs and Green Walls for Public Health – An Ecosystem Services Approach. *Frontiers in Ecology and Evolution,* 4, Volume 10, p. 336. DOI: 10.3389/fevo.2022.804500.

Oduro, R. A. & Taylor, P. G., 2023. Future pathways for energy networks: A review of international experience in high income countries. *Renewable and Sustainable Energy Reviews,* 171(113002), pp. 1-17, DOI: 10.1016/j.rser.2022.113002.

O'Hegarty, R., Kinnane, O., Lennon, D. & Colclough, S., 2022. Air-to-water heat pumps: Review and analysis of the performance gap between in-use and product rated performance. *Renewable and Sustainable Energy Reviews,* 155(March), pp. 1-21, 111887. DOI: 10.1016/j.rser.2021.111887.

Ovaitt, S., Mirletz, H., Seetharaman, S. & Barnes, T., 2022. PV in the circular economy, a dynamic framework analyzing technology evolution and reliability impacts. *iScience,* 25(1, art. no. 103488), pp. , DOI: 10.1016/j.isci.2021.103488.

Pasini, G., Lutzemberger, G. & Ferrari, L., 2023. Renewable Electricity for Decarbonisation of Road Transport: Batteries or E-Fuels?. *Batteries,* 9(2)(135), pp. 1-25. DOI: 10.3390/batteries9020135.

Pasman, H. J., 2011. Challenges to improve confidence level of risk assessment of hydrogen technologies. *International Journal of Hydrogen Energy,* 36(3), pp. 2407-2413. DOI: 10.1016/j.ijhydene.2010.05.019.

Pearson, R. J. & Turner, W., 2012. Renewable fuels: An automotive perspective. *Comprehensive Renewable Energy,* Volume 5, pp. 305-342. DOI: 10.1016/B978-0-08-087872-0.00522-9.

Peñaloza, D. et al., 2022. Social and market acceptance of photovoltaic panels and heat pumps in Europe: A literature review and survey. *Renewable and Sustainable Energy Reviews,* 155(111867), pp. , DOI: 10.1016/j.rser.2021.111867.

Perea-Moreno, M. A., Hernandez-Escobedo, Q. & Moreno, A. J. P., 2018. Renewable Energy in Urban Areas: Worldwide Research Trends. *energies,* 11(577), pp. 1-19, DOI: 10.3390/en11030577.

Popescu, D., Bienert, S., Schützenhofer, C. & Boazu, R., 2012. Impact of energy efficiency measures on the economic value of buildings. *Applied Energy,* Volume 89, pp. 454-463.

Pratiwi, A. S. & Trutnevyte, E., 2021. Life cycle assessment of shallow to medium-depth geothermal heating and cooling networks in the State of Geneva. *Geothermics,* 90(February 2021), pp. 1-14, 101988, DOI: 10.1016/j.geothermics.2020.101988.

Prieto, C. & Cabeza, L. F., 2021. Thermal energy storage with phase change materials in solar power plants. Economic analysis. *Journal of Energy Storage,* 43(103184), pp. 1-15. DOI: 10.1016/j.est.2021.103184.

Pulighe, G. et al., 2019. Ongoing and emerging issues for sustainable bioenergy production on marginal lands in the Mediterranean regions. *Renewable and Sustainable Energy Reviews,* 103(April), pp. 58-70. DOI: 10.1016/j.rser.2018.12.043.

Ramirez, A., Sarathy, M. S. & Gascon, J., 2020. CO2 Derived E-Fuels: Research Trends, Misconceptions, and Future Directions. *Trends in Chemistry,* 2(9), pp. 785-795. DOI: 10.1016/j.trechm.2020.07.005.

Ram, M., Aghahosseini, A. & Breyer, C., 2020. Job creation during the global energy transition towards 100% renewable power system by 2050. *Technological Forecasting and Social Change,* 151(119682), pp. 1-19. DOI: Breyer.

Ramusino, L., Cortese, M. & Lennard, Z., 2017. Re-Naturing the City: Nature4Cities Project to Elevate the Concept of Nature-Based Solutions. *Proceedings (MDPI Proceedings series journal),* 1(7), pp. 1-3. DOI: 10.3390/proceedings1070696.

Refrigeration, I. I. o., 2016. *Guideline for life cycle climate performance v.12.* [Online]
Available at: https://iifiir.org/en/news/iir-working-group-publishes-guidelines-for-life-cycle-climate-performance

Rose, A. & Wei, D., 2020. Impacts of the Property Assessed Clean Energy (PACE) program on the economy of California. *Energy Policy,* Volume 137, p. 111087.

Salgado, V., Cerdá, I., Solar, D. & T.G., N., 2022. Can photovoltaic systems be profitable in urban areas? Analysis of regulation scenarios for four cases in Valencia city (Spain). *Solar Energy,* Volume 233, pp. 461-477. DOI: 10.1016/j.solener.2022.01.057.

Sarbu, I. & Dorca, A., 2019. Review on heat transfer analysis in thermal energy storage using latent heat storage systems and phase change materials. *International Journal of Energy Research,* 43(1), pp. 29-64. DOI: 10.1002/er.4196.

Sayegh, M. A. et al., 2018. Heat pump placement, connection and operational modes in European district heating. *Energy and Buildings,* pp. 122-144. DOI: 10.1016/j.enbuild.2018.02.006..

Scarpa, F., Tagliafico, L. A. & Tagliafico, G., 2011. Integrated solar-assisted heat pumps for water heating coupled to gas burners; control criteria for dynamic operation. *Applied Thermal Engineering,* 1, 31(1), pp. 59-68.

Scharrer, D., et al., 2020. Life cycle assessment of a reversible heat pump - Organic rankine cycle - Heat storage system with geothermal heat supply. *Energies,* 13(12, art. no. 3253), pp. 1-18. DOI: 10.3390/en13123253.

Sevindik, S., Spataru, C., Aparisi , T. D. & Bleischwitz, R., 2021. A Comparative Environmental Assessment of Heat Pumps and Gas Boilers towards a Circular Economy in the UK. *Energies,* 14(11, 3027), pp. 1,26. DOI: 10.3390/en14113027.

Sharma, A., Tyagi, V. V., Chen, C. R. & Buddhi, D., 2009. Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews,* 13(2), pp. 318-345. DOI: 10.1016/j.rser.2007.10.005.

Sharma, R. K., Ganesan, P. & Tyagi, V. V., 2016. Long-term thermal and chemical reliability study of different organic phase change materials for thermal energy storage applications. *Journal of Thermal Analysis and Calorimetry,* Volume 124, pp. 1357–1366.DOI: 10.1007/s10973-016-5281-5.

Simó-Solsona, M., Palumbo, M., Bosch, M. & Fernandez, A. I., 2021. Why it’s so hard? Exploring social barriers for the deployment of thermal energy storage in Spanish buildings. *Energy Research & Social Science,* 76(102057), pp. 1-11. DOI: 10.1016/j.erss.2021.102057.

Sims, R. E., Mabee, W., Saddler, J. N. & Taylor, M., 2010. An overview of second generation biofuel technologies. *Bioresource Technology,* 101(6), pp. 1570-1580. DOI: 10.1016/j.biortech.2009.11.046.

Singh, H. et al., 2022. A critical review of technologies, costs, and projects for production of carbon-neutral liquid e-fuels from hydrogen and captured CO2. *Energy Advances,* Volume 1, pp. 580-605. DOI: 10.1039/D2YA00173J.

Sipra, A. T., Gao, N. & Sarwar, H., 2018. Municipal solid waste (MSW) pyrolysis for bio-fuel production: A review of effects of MSW components and catalysts. *Fuel Processing Technology,* 175(June), pp. 131-147. DOI: 10.1016/j.fuproc.2018.02.012.

Skov, I. . R. & Schneider, N., 2022. Incentive structures for power-to-X and e-fuel pathways for transport in EU and member states. *Energy Policy,* 168(113121), pp. 1-10. DOI: 10.1016/j.enpol.2022.113121.

Sun, X., Brown, M. A., Cox, M. & Jackson, R., 2016. Mandating better buildings: a global review of building codes and prospects for improvement in the United States. *Wiley Interdisciplinary Reviews: Energy and Environment,* 5(2), pp. 188-215. DOI: 10.1002/wene.168.

Susca, T., Gaffin, S. R. & Dell'Osso, G. R., 2011. Positive effects of vegetation: Urban heat island and green roofs. *Environmental Pollution,* 8, 159(8-9), pp. 2119-2126. DOI: 10.1016/j.envpol.2011.03.007.

Swain, P. K., 2017. Utilisation of Agriculture Waste Products for Production of Bio-Fuels: A Novel Study. *Materials Today: Proceedings,* 4(11, part 3), pp. 11959-11967, DOI: 10.1016/j.matpr.2017.09.117.

Tabassum, M., Kashem, S. & Siddique, M., 2017. *Feasibility of using Photovoltaic (PV) technology to generate solar energy in Sarawak.* 1st International Conference on Computer and Drone Applications: Ethical Integration of Computer and Drone Technology for Humanity Sustainability. IConDA 2017, s.n., pp. 11-16. DOI: 10.1109/ICONDA.2017.8270391.

Taghizadeh-Hesary, F. & Yoshino, N., 2022. Sustainable Solutions for Green Financing and Investment in Renewable Energy Projects. *Energies,* 13(4), p. 788.

Thellufsen, J. Z. & Lund, H., 2016. Roles of local and national energy systems in the integration of renewable. *Applied Energy,* 183(1), pp. 419-429, DOI: 10.1016/j.apenergy.2016.09.005.

Tian, Z., Perers, B., Furbo, S. & Fan, J., 2018. Thermo-economic optimization of a hybrid solar district heating plant with flat plate collectors and parabolic trough collectors in series. *Energy Conversion and Management,* 6, Volume 165, pp. 92-101.

Tolderlund, L., 2010. *Design Guidelines and Maintenance Manual for Green Roofs in the Semi-Arid and Arid West | US EPA.* [Online]
Available at: https://www.epa.gov/green-infrastructure/design-guidelines-and-maintenance-manual-green-roofs-semi-arid-and-arid-west
[Consultato il giorno 26 1 2023].

Traverso, L. et al., 2021. Cost Benefit and Risk Analysis of Low iLUC Bioenergy Production in Europe Using Monte Carlo Simulation. *Energies,* 14(6), pp. 1-18. DOI: 10.3390/en14061650.

Tsiklios, C., Schneider, S., Hermesmann, M. & Müller, T. E., 2023. Efficiency and optimal load capacity of E-Fuel-Based energy storage systems. *Advances in Applied Energy,* 10(100140), pp. 1-27. DOI: 10.1016/j.adapen.2023.100140.

Ueckerdt , F. et al., 2021. Potential and risks of hydrogen-based e-fuels in climate change mitigation. *Nature Climate Change,* 11(May), p. 384–393.

Van de Bor, D. M., Ferreira, C. I. & Kiss, A. A., 2015. Low grade waste heat recovery using heat pumps and power cycles. *Energy,* 89(September), pp. 864-873. DOI: 10.1016/j.energy.2015.06.030.

Vega, M. et al., 2022. Life cycle assessment of the inclusion of phase change materials in lightweight buildings. *Journal of Energy Storage,* 56 B(105903), pp. 1-12. DOI: 10.1016/j.est.2022.105903.

Vidas, L. & Castro, R., 2021. Recent Developments on Hydrogen Production Technologies: State-of-the-Art Review with a Focus on Green-Electrolysis. *Applied Sciences ,* 11(23), pp. 1-27. DOI: 10.3390/app112311363.

Visa, I., Comsit, M. & Duta, A., 2014. Urban acceptance of facade integrated novel solar thermal collectors. *Energy Procedia,* Volume 48, pp. 1429-1435. DOI: 10.1016/j.egypro.2014.02.161.

Viteri, J. P., Viteri, S., Alvarez-Vasco, C. & Henao, F., 2023. A systematic review on green hydrogen for off-grid communities –technologies, advantages, and limitations. *International Journal of Hydrogen Energy,* Volume In Press, Corrected Proof, pp. 1-21. DOI: 10.1016/j.ijhydene.2023.02.078.

Volkova, A. et al., 2019. Small low-temperature district heating network development prospects. *Energy,* 7, Volume 178, pp. 714-722.

Wanitschke, A. & Hoffmann, S., 2020. Are battery electric vehicles the future? An uncertainty comparison with hydrogen and combustion engines. *Environmental Innovation and Societal Transitions,* 35(June), pp. 509-523. DOI: 10.1016/j.eist.2019.03.003.

Weiler, S. & Scholz-Barth, K., 2009. *Green roof systems: a guide to the planning, design, and construction of landscapes over structure.* 1th Edition, a cura di s.l.:John Wiley & Sons, ISBN: 978-0-471-67495-5.

Wiens, J., Fargione, J. & Hill, J., 2011. Biofuels and biodiversity. *Ecological Applications,* 21(4), pp. 1085-1095. DOI: 10.1890/09-0673.1.

Williams, K. J. et al., 2019. Appraising the psychological benefits of green roofs for city residents and workers. *Urban Forestry & Urban Greening,* 8, Volume 44, p. 126399. DOI: 10.1016/j.ufug.2019.126399.

Windarta, J. et al., 2021. Technical and economic feasibility analysis of solar power plant design with off grid system for remote area MSME in Semarang City. *IOP Conference Series: Earth and Environmental Science,* 896(1, art. no. 012007), pp. . DOI: 10.1088/1755-1315/896/1/012007.

Xu, Z. Y., Mao, H. C., Liu, D. S. & Wang, R. Z., 2018. Waste heat recovery of power plant with large scale serial absorption heat pumps. *Energy,* 165, part B(December), pp. 1097-1105. DOI: 10.1016/j.energy.2018.10.052.

Yang, T., Liu, W., Kramer, G.J. & Sun, Q., 2021. Seasonal thermal energy storage: A techno-economic literature review. *Renewable and Sustainable Energy Reviews,* 139(art. no. 110732), pp. 1-22. DOI: 10.1016/j.rser.2021.110732.

Yang, H., Zhou, Y. & Liu, J., 2009. Land and water requirements of biofuel and implications for food supply and the environment in China. *Energy Policy,* 37(5), pp. 1876-1885. DOI: 10.1016/j.enpol.2009.01.035.

Yang, J., Yu, Q. & Gong, P., 2008. Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment,* 10, 42(31), pp. 7266-7273. DOI: 10.1016/j.atmosenv.2008.07.003.

Zambrano-Prado, P. et al., 2021. Perceptions on barriers and opportunities for integrating urban agri-green roofs: A European Mediterranean compact city case,. *Cities,* 114(103196), pp. 1-15. DOI: 10.1016/j.cities.2021.103196.

Zang, G. et al., 2021. Performance and cost analysis of liquid fuel production from H2 and CO2 based on the Fischer-Tropsch process. *Journal of CO2 Utilization,* 46(101459), pp. 1-12. DOI: 10.1016/j.jcou.2021.101459.

Zhang, X., et al., 2022. Values of latent heat and thermochemical energy storage technologies in low-carbon energy systems: Whole system approach. *Journal of Energy Storage,* 50(104126), p. DOI: 10.1016/j.est.2022.104126.

Zhang, L., Jiang, i., Dong, J. & Yao, Y., 2018. Advances in vapor compression air source heat pump system in cold regions: A review. *Renewable and Sustainable Energy Reviews,* 81 part 1(January), pp. 353-365. DOI: 10.1016/j.rser.2017.08.009.

Zhang, S. & Yan, Y., 2023. Energy, exergy and economic analysis of ceramic foam-enhanced molten salt as phase change material for medium- and high-temperature thermal energy storage. *Energy,* 262 part A(125462), pp. 1-13. DOI: 10.1016/j.energy.2022.125462.

Zimring, M. et al., 2014. *Financing Energy Improvements on Utility Bills: Market Updates and Key Program Design Considerations for Policymakers and Administrators,* s.l.: State and Local Energy Efficiency Action Network..

Žuvela-Aloise, M., Koch, &. R., Buchholz, &. S. & Früh, &. B., 2016. Modelling the potential of green and blue infrastructure to reduce urban heat load in the city of Vienna. Volume 135, pp. 425-438. DOI: 10.1007/s10584-016-1596-2.