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Accelerating the Transition to a Sustainable Society

Novel Business Models of Decentralized Energy, Water, and Holistic Utility Service Companies

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Contents

List of Acronyms

4GDH 4th Generation District Heating
5GDHC 5th Generation District Heating and Cooling
AC Alternating Current
AI Artificial Intelligence
ATES Aquifer Thermal Energy Storage
AWG Atmospheric Water Generation
BESS Battery Energy Storage Systems
BIPV Building Integrated Photo Voltaics
BMC Business Model Canvas
BTES Borehole Thermal Energy Storage
CAPEX Capital Expenditure
CDI Capacitive Deionization
CHP Combined Heat and Power
CFADS Cash Flow Available for Debt Service
CPOs Charge Point Operators
CSP Concentrated Solar Power
DCF Discounted Cash Flow
DC Direct Current
DHC District Heating and Cooling
DSCR Debt Service Coverage Ratio
DSO Distribution System Operator
DSOs Distribution System Operators
EPB Energy Performance of Buildings
ESCO Energy Service Company
ESCOs Energy Service Companies
ESG Environmental, Social and Governance
EU European Union
ETS2 Emissions Trading System 2
EV Electric Vehicle
EVs Electric Vehicles
GWP Global Warming Potential
HT High Temperature
ICE Internal Combustion Engine
IEA International Energy Agency
IoT Internet-of-Things
IRR Internal Rate of Return
IRENA International Renewable Energy Agency

KLB *Kabels en Leidingbeheerder*
Cables and Pipes Manager

KLIP *Kabels, Leidingen en Informatieportaal*
Cables, Pipes and Information Portal

KPIs Key Performance Indicators

MBA Master of Business Administration

MBR Membrane Bio Reactor

MBRs Membrane Bio Reactors

MASCO Material Service Company

MASCOs Material Service Companies

MOSCO Mobility Service Company

MOSCOs Mobility Service Companies

MPC Model Predictive Controller

MSPs Mobility Service Providers

NPV Net Present Value

ORC Organic Rankine Cyclus

OPEX Operational Expenditure

OTEC Ocean Thermal Energy Conversion

PC Photo Catalytic or Photo Chemical

PCM Phase Change Material

PCMs Phase Change Materials

PFAS Per- and polyfluoroalkyl Substances

PPP Public Private Partnership

PPAs Power Purchase Agreements

PT Photo Thermal

PTES Pit Thermal Energy Storage

PV Photo Voltaic

PVT Photo Voltaic and Thermal

RED Reverse Electrodialysis

RGV *Regels van Goed Vakmanschap*
Rules of Good Workmanship

SCBA Social Cost Benefit Analysis

SDG Sustainable Development Goal

SDGs Sustainable Development Goals

SLA Service Level Agreement

SLAs Service Level Agreements

SMR Small Modular Reactor

SMRs Small Modular Reactors

SMWT Small and Medium Wind Turbine

SMWTs Small and Medium Wind Turbines

SPV Special Purpose Vehicle
STES Seasonal Thermal Energy Storage
TES Thermal Energy Storage
TRL Technology Readiness Level
TRLs Technology Readiness Levels
TTES Tank Thermal Energy Storage
UN United Nations
USCO Utility Service Company
USCOs Utility Service Companies
UV Ultraviolet
VAT Value Added Tax
V2G Vehicle-to-Grid
VLARIO *Vlaams kenniscentrum en overlegplatform voor water*
Flemish knowledge centre and discussion platform for water
VMM *Vlaamse Mileumaatschappij*
Flemish Environmental Agency
VNR *Vlaamse Nutsregulator*
Flemish Utility Regulator
VREG *Vlaamse Regulator van de Elektriciteits- en Gasmarkt*
Flemish Regulator for the Electricity and Gas market
WACC Weighted Average Cost of Capital
WASCO Water Service Company
WASCOs Water Service Companies
WCW *Wet Collectieve Warmtevoorziening*
Law Collective Heating
WPP *Warmtepomp Platform*
Heat Pump Platform
WWTPs Waste Water Treatment Plants

1 Introduction

A sustainable world, as envisioned by the United Nations (UN) Sustainable Development Goals (SDGs), represents a future where development is balanced with environmental preservation, social equity, and economic growth, ensuring that the needs of the present are met without compromising the ability of future generations to meet their own needs. This vision includes eradicating poverty and hunger by ensuring that everyone has access to basic necessities such as food, clean water, and shelter. It also involves promoting health and well-being by providing access to quality healthcare and fostering healthy lifestyles. Quality education and gender equality are central, empowering individuals and communities to thrive. A sustainable world also emphasizes the need for clean water and sanitation, affordable and clean energy, and decent work and economic growth. Moreover, it seeks to reduce inequalities, build sustainable cities and communities, and ensure responsible consumption and production. Environmental sustainability is critical, focusing on urgent action to combat climate change, conserve oceans and marine resources, and protect terrestrial ecosystems. Lastly, it promotes peace, justice, and strong institutions, along with global partnerships to achieve these goals, reflecting a comprehensive and integrated approach to achieving a more just, inclusive, and sustainable world for all.

1.1 Utilities

Utilities, such as water, electricity, and sanitation services, are fundamental to achieving a sustainable world as envisioned by the UN SDGs. These essential services form the backbone of modern society, enabling health, well-being, economic development, and environmental sustainability.

Access to clean water and sanitation, for example, is crucial for public health, reducing the spread of diseases, and ensuring that people can live with dignity. This directly aligns with Sustainable Development Goal (SDG) 6, which aims to ensure availability and sustainable management of water and sanitation for all. Without reliable water utilities, communities face significant challenges in maintaining hygiene, preventing waterborne diseases, and supporting agriculture and industry, which are vital for food security and economic stability.

Electricity, as another key utility, is equally critical. It powers homes, schools, hospitals, and businesses, driving economic growth and improving the quality of life. Access to affordable and clean energy (SDG 7) is essential for reducing poverty, promoting education, and supporting sustainable industrialization. Clean energy utilities also play a pivotal role in combating climate change (SDG 13) by reducing reliance on fossil fuels and lowering greenhouse gas emissions.

In a sustainable world, utilities are not only about providing basic services but also about doing so in a way that is equitable, efficient, and environmentally friendly. They ensure that all communities, regardless of their location or economic status, have the resources they need to thrive. Moreover, sustainable utilities support the broader goals of reducing inequalities (SDG 10) and building resilient infrastructure and cities (SDG 9 and 11). Thus, utilities are integral to the foundation of a sustainable world, enabling the realization of multiple SDGs and ensuring that development is inclusive, resilient, and sustainable for future generations.

Next to the traditional utilities of water, energy, materials (what we now still perceive as "waste"), mobility, and telecom, we can see a novel utility penetrating our society, i.e. "compute" power. Just like mobility and telecom have become essential utilities for our society, compute power will become the next indispensible utility for society as it forms what is called the "third pillar" of science.

1.2 Communities

The utility market is undergoing significant disruption as it becomes increasingly decentralized, particularly evident in the energy sector with the rise of renewable sources like solar and wind. Traditionally, utilities such as electricity were generated at large, centralized power plants and distributed to consumers through an extensive grid. However, the growing adoption of decentralized energy systems, where power is generated closer to where it is consumed, is challenging this model [29].

Solar panels on rooftops and small-scale wind turbines allow individual buildings to produce their own electricity, reducing their reliance on the grid. While this shift towards decentralized energy generation is a crucial step towards sustainability, achieving true energy neutrality–where a building generates as much energy as it consumes–is not always technically feasible or economically viable at the level of an individual building. The limitations of space, varying energy needs, and the costs of installing and maintaining renewable energy systems can make it difficult for single buildings to fully meet their energy demands independently.

The more practical and sustainable solution lies in the development of smart communities, where utilities like energy are efficiently shared among a group of buildings or even across entire neighborhoods. In these smart communities, renewable energy generated from various sources–such as solar panels on rooftops, wind turbines, and possibly even energy storage systems–can be pooled and distributed according to demand. This collective approach allows for greater efficiency, as excess energy produced by one building can be used by another, balancing supply and demand across the community [109].

Moreover, smart communities leverage advanced technologies, such as smart grids and Internet-of-Things (IoT) devices, to monitor and manage energy use in real-time, optimizing consumption and reducing waste. By sharing utilities, these communities can achieve higher levels of sustainability and energy neutrality more cost-effectively than individual buildings could on their own.

In this context, the decentralization of utilities doesn't just mean shifting power generation from large plants to individual buildings; it also involves rethinking how energy and other utilities are managed and shared across communities. By embracing this model, we can create more resilient, efficient, and sustainable systems that benefit everyone.

1.3 Utility Service Companies

Creating smart communities that efficiently share utilities and achieve high levels of sustainability requires substantial investments in new and sustainable utility systems and infrastructure. These systems include advanced energy grids, renewable energy sources, water recycling facilities [28, 81], and innovative solutions like extracting heat from wastewater. The scale and complexity of these projects demand significant financial resources, raising important questions about how and when these investments can become affordable, financeable, and ideally, profitable.

The challenge lies in the fact that these are collective systems that benefit entire communities rather than individual buildings or properties. This collective nature means that traditional models of ownership and investment may not apply. The question of who will take ownership of these investments becomes critical, as these systems operate on a level that is above the capacity of any single individual or household to manage or finance.

The answer to this challenge lies in the emergence of Utility Service Companies (USCOs), an extension of what now is already known as Energy Service Companies (ESCOs) [48, 47, 97, 37, 10, 16]. These specialized companies are designed to take on the responsibility of implementing sustainable utilities within communities, driving the development of the necessary infrastructure to support smart, interconnected systems. USCOs operate with the goal of ensuring that the community prospers, not only in terms of sustainability but also in financial terms.

USCOs would manage the large-scale investments needed for these systems, leveraging economies of scale and expertise to make the projects financially viable. By doing so, they can ensure that the investments are not only affordable and financeable but also profitable. **USCOs would seek to achieve returns comparable or better to global financial indices, making the investments attractive to public, private and institutional investors**.

Moreover, USCOs would take ownership of the collective systems, ensuring their efficient operation and maintenance over the long term. By focusing on synergies, such as recycling water for different purposes or extracting heat from wastewater, USCOs can maximize the utility of resources and further enhance the sustainability of the community.

In essence, USCOs are the key to making smart communities a reality. They bridge the gap between the need for large-scale, sustainable utility systems and the financial realities of making such systems viable and profitable. By taking on the responsibility of implementing and managing these utilities, USCOs ensure that communities can thrive both environmentally and economically, paving the way for a sustainable future.

In this Master of Business Administration (MBA) research thesis, we investigate and asses the different most interesting novel business models that USCOs can encompass. The goal is to pinpoint the pros and cons, to identify which business models are most appropriate, and to setup a Business Model Canvas (BMC).

1.4 Proposed Model

As the alignment between environmentally-aware technology, economics, and legislation is essential for the successful realization of Utility Service Company (USCO) projects, the complex question of finding appropriate business models needs to be broken down in to multiple research questions. And to formalize these questions, we propose the USCO "table" model depicted in Figure 1.

We have three important legs that supports and stabilizes a tabletop, that represents the social stance which carries the USCO. All legs are important, because if one of them is removed, the concept of the USCO will fall with it.

1. **Technological-environmental**: The foundation of USCOs lies in technological solutions and innovations that are inherently environmentally conscious. These companies are driven by the need to create and implement utility systems that are not only efficient and effective but also sustainable. At the core of USCOs' operations are cutting-edge technologies that prioritize environmental stewardship, such as renewable energy sources, smart grids, water recycling systems, and advanced waste management

Figure 1: The presented "table" model of a USCO. Image ©Sammy Rogmans, composed with Adobe Firefly.

techniques.

These innovations enable USCOs to design utility infrastructures that minimize environmental impact while maximizing resource efficiency. For instance, by integrating renewable energy technologies like solar and wind power, USCOs reduce dependence on fossil fuels and lower greenhouse gas emissions. Similarly, advanced water treatment and recycling systems allow for the reuse of water within communities, conserving a precious resource and reducing strain on natural water sources.

USCOs leverage these environmentally aware technologies to create systems that are not only sustainable but also adaptable to the specific needs of each community. This adaptability ensures that the utility solutions provided are optimized for local environmental conditions, further enhancing their sustainability.

In essence, the success of USCOs is built on their ability to harness technological innovations that are aligned with environmental principles. By focusing on environmentally aware solutions, USCOs play a crucial role in advancing the transition to sustainable communities, where resources are managed efficiently and the environmental impact is minimized.

2. **Economical**: The economics and financial viability of a project are often the critical factors that determine whether it will be brought to life. No matter how innovative or environmentally beneficial a project might be, it will only move forward if it can demonstrate financial sustainability. Like we already mentioned, this principle is particularly true for USCOs, which operate at the intersection of large-scale infrastructure development and community-wide utility management.

   For a USCO to be realized and remain sustainable, it must be financially viable. This means that the company must be able to generate sufficient returns on investment to cover the costs of development, operation, and maintenance of the utility systems, while also providing a profit that meets or exceeds the expectations of investors. Without this financial viability, even the most promising and environmentally friendly projects are unlikely to secure the necessary funding or stakeholder support.

   The financial model of a USCO needs to account for not only the initial capital investment but also the ongoing operational costs and potential risks. This requires careful planning, project management, realistic projections, and often, innovative financing strategies to ensure that the project can deliver consistent, reliable returns over the long term.

   In essence, the success of a USCO–and its ability to contribute to the development of sustainable communities–hinges on its financial soundness. Without a solid economic foundation, the most advanced technological solutions and environmentally conscious designs will remain on the drawing board, unrealized. Therefore, ensuring that a USCO is financially viable is not just a matter of business prudence; it is the key to turning visionary projects into reality.

3. **Political and Legal**: A USCO that uses environmentally-aware technology and is financially sound, is only viable when it is supported in the prevailing legislative and political context. Even the most innovative and financially viable technologies can only be successfully implemented if they align with existing laws, regulations, and political priorities.

   Legislation and political frameworks play a crucial role in determining the feasibility of USCO projects. These frameworks establish the rules for everything from environmental standards and energy tariffs to zoning laws and water usage rights. If the technology and business model of a USCO are not compatible with the current legal and regulatory environment, the project may face significant delays, increased costs, or even the risk of being blocked altogether.

   Furthermore, political support is often essential for the approval and smooth implementation of such large-scale utility projects. Governments and local authorities may need to provide incentives, subsidies, or favorable policies to make the deployment of environmentally-aware technologies more attractive to investors. They may also need to ensure that regulations are in place to facilitate the integration of new technologies into existing infrastructure.

In this context, a USCO must carefully navigate the legislative landscape and work closely with policymakers to ensure that their projects are not only financially and environmentally sound but also legally compliant and politically supported.

1.5 Research Questions

Our ultimate research question "*Which business models are most appropriate for USCOs?*" can be broken down, based on our introduced table model, in a number of key sub questions related to each "table leg," i.e. (Leg 1) the environmentally-aware technology, (Leg 2) the economics, and (Leg 3) the political-legal context:

- **Q1**: Which utility technologies are appropriate for decentral systems? (Leg 1)
- **Q2**: In what physical and time scale are these technologies financially viable? (Leg 2)
- **Q3**: What are the financing possibilities? (Leg 2)
- **Q4**: What are the judicial and political implications (Flanders)? (Leg 3)
- **Q5**: Which infrastructure is best public and which private? (Leg 3)

Answering the above research questions will be the breeding ground and prepare us to answer the ultimate question on which business models will be most appropriate for implementing USCOs. While not being fully exhaustive, you will find a big spectrum of answers in this MBA's Master thesis.

2 Technological and Environmental Opportunities

The transition to a sustainable, resilient society requires reimagining our infrastructure and utilities to support decentralized, environmentally sustainable technologies [74]. This chapter examines a range of innovative technologies across the essential utilities of the future: energy, water, materials/waste, compute, mobility, and telecom. Each of these domains will play a critical role in shaping sustainable cities and communities [9], with new technologies advancing the potential for self-sufficiency and reducing environmental impact.

Central to this exploration is the use of Technology Readiness Levels (TRLs), which help assess each technology's maturity and its readiness for commercial deployment. By understanding the TRL of these emerging solutions, we can better gauge their role in the near and long-term evolution of critical infrastructures.

In the realm of energy, we explore decentralized sources like solar power, wind energy, and aquathermal systems, as well as advanced storage and management solutions, including Vehicle-to-Grid (V2G) systems and hydrogen. For water, innovative desalination and atmospheric water generation technologies offer solutions to water scarcity, while compute focuses on the growing need for decentralized data centers and efficient, high-density computing to support Artificial Intelligence (AI) and data-intensive applications. Mobility looks at the future of transport systems, from electric vehicles to hydrogen-powered fleets, and telecom covers the infrastructure supporting seamless communication and smart grid technologies.

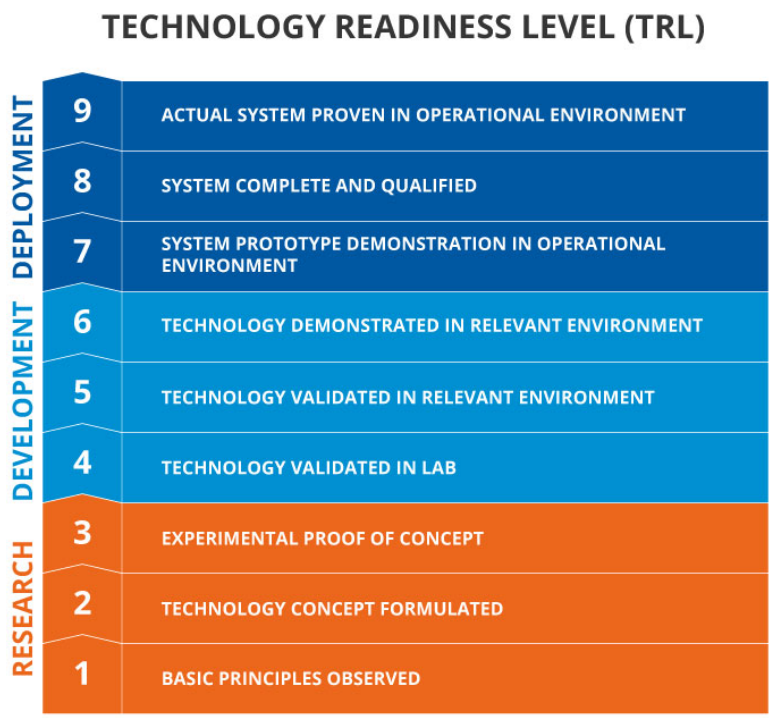

Figure 2: Description of the different Technology Readiness Level (TRL) levels. Image ©NASA, Federico Grasso Toro [43]

Each technology is assessed for its potential impact on cost, scalability, environmental sustainability, and compatibility with community needs. This document also includes a multicriteria assessment matrix that provides a structured comparison, allowing for a clear overview of each technology's strengths, limitations, and alignment with sustainability objectives.

By examining these technologies within the framework of the future utilities, this chapter offers insights into how they can integrate to create interconnected, efficient, and low-carbon communities. The insights presented here aim to support strategic planning, helping stakeholders navigate the challenges and opportunities in building resilient infrastructure for the future. The most relevant technologies are summarized, while their more detailed workings can be found in Appendix A.

2.1 Technology Readiness Level

The TRL [72] is a scale used to measure the maturity of a technology throughout its development process (see Figure 2). It ranges from TRL 1, where basic principles are first observed, to TRL 9, which indicates that the technology has been proven in an operational environment. This framework was originally developed by NASA but is now widely adopted across various industries and research institutions to evaluate and manage technological progress. By providing a standardized way to assess how close a technology is to being fully deployed, the TRL scale helps guide decision-making in research, funding, and innovation strategies.

2.2 Renewable Fuel Production (Green Molecules)

2.2.1 Biofuels

Biofuels are renewable energy sources derived from organic waste, offering flexible and sustainable fuel options for heating, electricity, and transport [26]. They can be produced locally through anaerobic digestion, which breaks down waste in low-oxygen environments to create methane-rich biogas, or through pyrolysis, which thermally decomposes biomass without oxygen to produce bio-oil, biochar, and syngas (see Figure 3). These processes are especially effective in areas with abundant organic waste and are already commercially viable, with technologies reaching TRL 8–9. In regions lacking sufficient local feedstock, biofuels can also be supplied via the energy grid to ensure consistent availability.

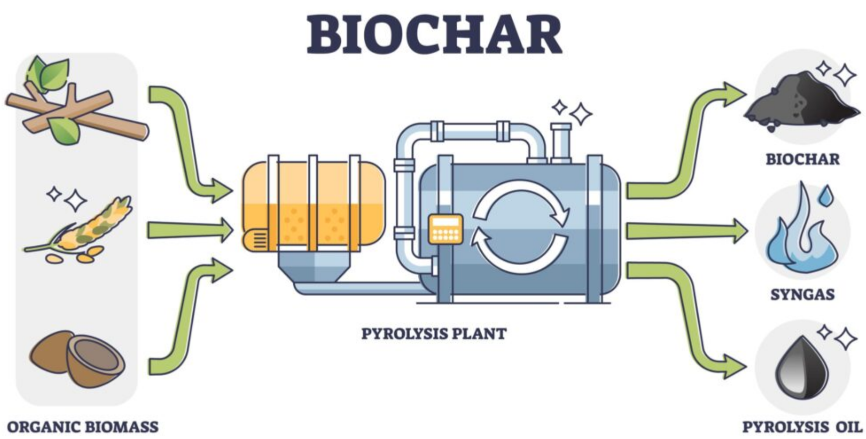

Figure 3: Process from organic biomass to biofuels. Image ©Energy Encyclopedia [30]

2.2.2 Green Hydrogen

Green hydrogen is a clean and versatile fuel produced using renewable resources [3]. The most mature method, electrolysis (TRL 8–9), uses renewable electricity to split water into hydrogen and oxygen with zero emissions. Emerging approaches include algae-based production, which leverages photosynthesis (TRL 7), and photo-chemical solar panels, which generate hydrogen directly from sunlight and water vapour (TRL 6–7). Green hydrogen can be produced locally or supplied through the grid (see Figure 4), making it a scalable solution for decarbonizing energy systems, industry, and transportation.

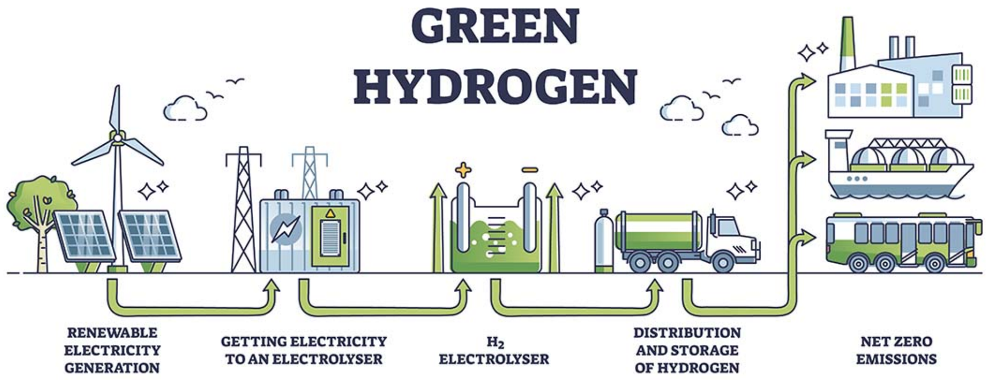

Figure 4: Supply chain for green hydrogen. Image ©Parishkar College [84]

2.3 Sustainable Thermal Energy Sources

2.3.1 Aquathermal Energy

Aquathermal energy harnesses the heat from surface water bodies like rivers, canals, and lakes for building heating and cooling [13]. Water is drawn, passed through a heat exchanger, and returned without being consumed. A heat pump then raises the temperature for indoor use, and the system can also provide cooling in summer by reversing the flow. This mature technology, generally at TRL 8–9, is already in commercial use and well-suited for urban areas near water sources, offering a low-emission, year-round renewable energy option.

2.3.2 Sewage Thermal Energy

Sewage thermal systems extract heat from wastewater, either at the influent stage (incoming sewage) or effluent stage (treated water leaving the plant). Both stages offer usable thermal energy, with influent typically warmer but less consistent. Heat exchangers and heat pumps elevate the captured heat to usable levels. These systems are highly mature (TRL 8–9) and effective in urban environments, reducing greenhouse gas emissions by turning wastewater into a renewable heating source.

2.3.3 Residual Heat

Residual heat is recovered from industrial processes, Combined Heat and Power (CHP) systems, exhaust gases, and data centers. Instead of letting this thermal energy dissipate, it is captured and repurposed for heating or electricity generation. Common in industrial and urban settings, this approach improves energy efficiency and reduces emissions [76]. Technologies like CHP and industrial waste heat recovery are at TRL 8–9, while newer applications like data center and transport exhaust heat capture are around TRL 7–8.

2.3.4 Geothermal Energy

Geothermal energy uses underground thermal storage to provide sustainable heating and cooling. Aquifer Thermal Energy Storage (ATES) and Borehole Thermal Energy Storage (BTES) are the main methods, storing heat in summer and extracting it in winter. ATES, widely used in Europe, is at TRL 8–9, while BTES, suitable for varied geological conditions, is generally at TRL 7–9. These systems offer stable, renewable energy for residential and commercial use across different climates.

2.3.5 Air-to-Water Heat Pump

Air-to-water heat pumps transfer heat from outdoor air to water for heating and hot water [45]. Available as split units, monobloc systems, and High Temperature (HT) models, they suit various building types and climates (see Figure 5). Split and monobloc units are fully commercial and widely used (TRL 9), while HT models, ideal for retrofitting older buildings, are approaching full maturity (TRL 8–9) [105]. These systems support the shift to low-carbon heating with flexible installation options.

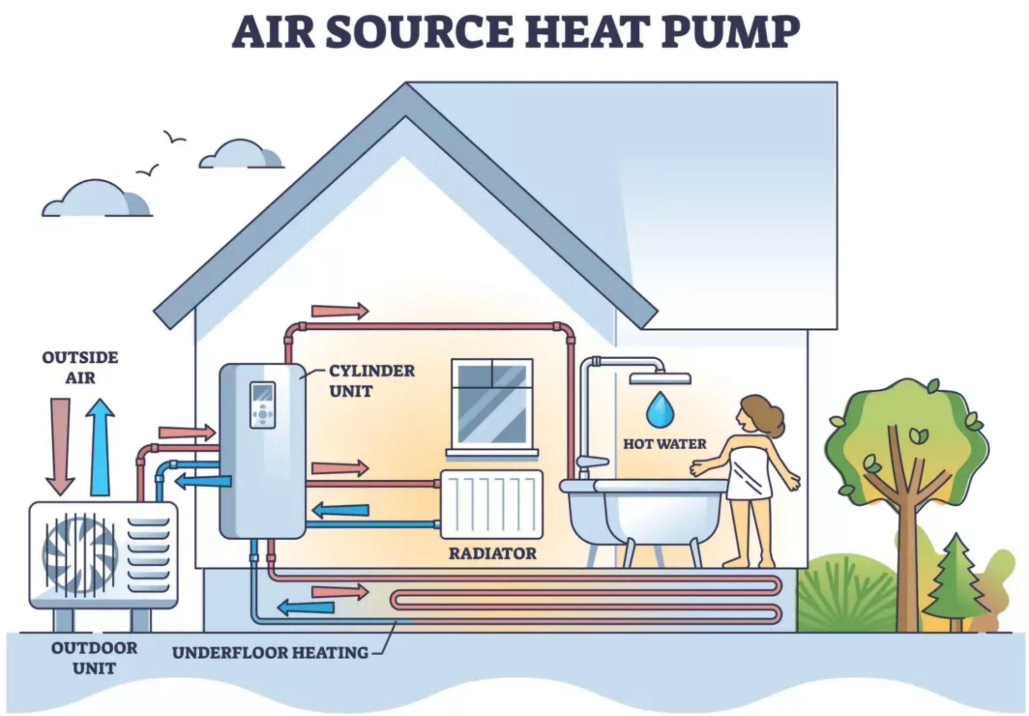

Figure 5: Concept of the air source heat pump. Image ©Warmtepomp Gids [113]

2.3.6 Absorption Cooling

Absorption cooling provides air conditioning using heat rather than electricity, ideal in settings with available waste or renewable heat [27]. Single-effect and double-effect systems are widely used in industrial and commercial applications and are fully mature (TRL 9). Triple-effect systems, offering higher efficiency with high-temperature heat sources, are still developing at TRL 7–8. Absorption cooling reduces electricity use and is a sustainable alternative for large-scale cooling needs.

2.4 Renewable Powers

2.4.1 Solar Power

Solar energy is harnessed using various panel technologies, each serving different functions. Photo Voltaic (PV) panels convert sunlight into electricity and are fully mature at TRL 9, widely used across residential and utility scales [54, 87]. Photo Thermal (PT) panels capture solar heat for hot water and space heating, also at TRL 9 [59]. Photo Voltaic and Thermal (PVT) panels, which generate both electricity and heat, are gaining traction and are rated TRL 8–9. Photo Catalytic or Photo Chemical (PC) panels, which produce hydrogen from sunlight and water, are still in development at TRL 6–7. Together, these solar technologies support electricity, heating, and hydrogen production in a sustainable way.

2.4.2 Concentrated Solar Power

Concentrated Solar Power (CSP) systems use mirrors to focus sunlight onto a small area, generating high temperatures to drive turbines for electricity production [53]. Parabolic troughs and solar towers are the most mature (TRL 8–9), with large-scale deployments and thermal storage capabilities. Linear Fresnel reflectors offer a cost-effective alternative at TRL 8–9, while parabolic dishes remain at TRL 7–8 for smaller applications. CSP is especially effective in sunny regions and stands out for its ability to store heat, enabling energy production even after sunset.

2.4.3 Wind Power

Wind energy is a fully mature technology (TRL 9), deployed in both large-scale and small- to medium-scale wind turbines [23]. Large turbines are used in utility-scale onshore and offshore wind farms, while novel Small and Medium Wind Turbine (SMWT) provide local power for homes, farms, and off-grid areas (see Figure 6). Both are reliable, cost-effective, and central to many national renewable energy strategies. SMWTs, in particular, offer flexibility and energy independence in rural or decentralized settings [66].

2.4.4 Hydropower

Hydropower converts flowing water into electricity and includes both large-scale and small-scale systems [58]. Micro hydropower, such as Turbulent's vortex technology, is designed for small rivers and streams without needing large infrastructure. These systems, gener-

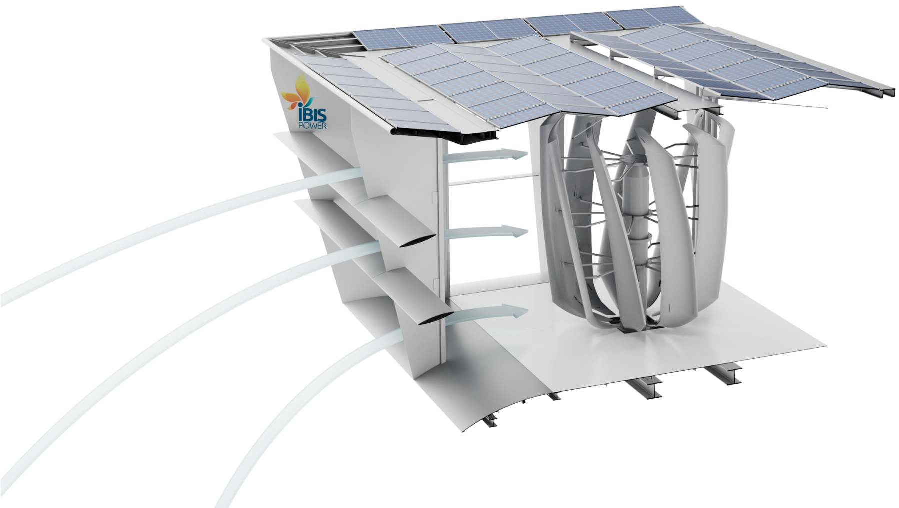

Figure 6: Integrated small and medium wind turbines. Image ©IBIS Power [50]

ally at TRL 8–9, are minimally invasive and ideal for rural or off-grid communities. Micro hydropower offers a scalable, eco-friendly solution for consistent local energy generation using modest water flows.

2.4.5 Ocean Power

Ocean power includes technologies that harness waves, tides, thermal gradients, and ocean currents [91]. Wave energy converters are at TRL 5–7, still in demonstration. Tidal energy turbines, more advanced at TRL 7–8, are operational in several locations. Ocean Thermal Energy Conversion (OTEC) is at TRL 6–7, requiring specific warm-to-cold water gradients. Currents-based systems are in early development at TRL 5–6. While ocean energy is still emerging, it holds strong potential for coastal regions seeking diverse renewable sources.

2.4.6 Heat-to-Power

Organic Rankine Cyclus (ORC) systems convert low- to medium-temperature heat into electricity using organic fluids with low boiling points [107, 49]. Operating effectively between 80°C and 350°C, ORC systems are widely used in industrial waste heat recovery, geothermal plants, and biomass facilities. With a TRL of 8–9, this mature technology enhances energy efficiency by repurposing unused heat, contributing to emissions reduction and sustainable industrial processes[49].

2.4.7 Nuclear Power

Small Modular Reactors (SMRs) and micro reactors offer compact, safe nuclear energy options for decentralized power [2]. SMRs (TRL 7–8) produce 10–300 MW and are nearing commercial deployment with enhanced safety features and modular design. Micro reactors, producing 1–10 MW, are in early demonstration (TRL 6–7) and suited for remote or mobile applications. These advanced nuclear systems promise clean, stable power where traditional renewables may be less viable, supporting energy security and carbon reduction.

2.5 Sustainable Energy Distribution and Storage

2.5.1 District Heating and Cooling Networks

4th and 5th generation District Heating and Cooling (DHC) networks are advanced systems providing efficient, low-carbon heating and cooling for urban areas [18]. 4th Generation District Heating (4GDH) operates at 50–70°C, allowing integration with renewable and low-grade heat sources like geothermal, solar thermal, and industrial waste heat. 5th Generation District Heating and Cooling (5GDHC) operates at ambient temperatures (10–30°C) and enables bidirectional energy exchange among buildings, enhancing efficiency and minimizing waste. Both technologies are commercially mature at TRL 8–9, offering scalable, future-ready solutions for sustainable urban energy systems (see Figure 7).

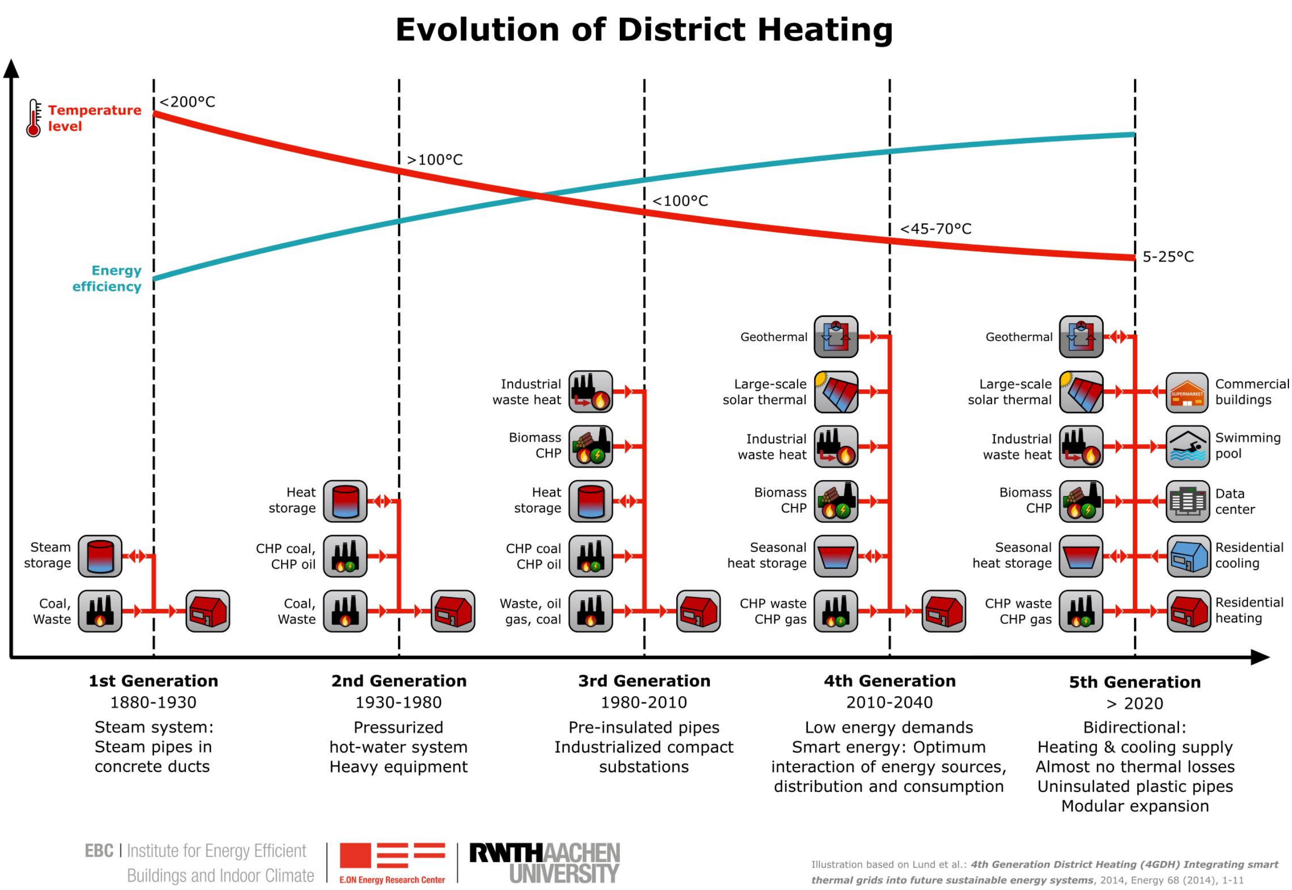

Figure 7: The evolution of district heating. Image ©Marco Wirtz [117]

2.5.2 Innovative Seasonal Thermal Energy Storage

Seasonal Thermal Energy Storage (STES) systems store excess heat in summer for use in winter, optimizing renewable integration and balancing energy demand year-round [95]. Pit Thermal Energy Storage (PTES) and Tank Thermal Energy Storage (TTES) use water-filled, insulated structures and are fully commercial at TRL 8–9. Rock Cavern Storage, suitable for large-scale applications, leverages underground rock formations and is at TRL 7–8. These systems, along with ATES and BTES, provide reliable, adaptable options for district heating and large energy networks seeking to reduce reliance on fossil fuels.

2.5.3 Innovative Thermal Buffers

Thermal buffers store heat or cold for short- to medium-term use, helping balance demand and improve energy efficiency. Ice Storage (TRL 8–9) is widely used for cooling, storing energy during low-demand periods. Sand Thermal Storage (TRL 6–7) is an emerging technology using sand to store heat at very high temperatures. Molten Salt Storage (TRL 8–9) is common in CSP plants for electricity generation after sunset [86]. Phase Change Materials (PCMs) (TRL 8–9) absorb and release heat as they change phase, offering stable temperature control in building and industrial applications. Together, they enhance grid stability and renewable energy utilization [44, 86].

2.5.4 Battery Energy Storage Systems

Battery Energy Storage Systems (BESS) store and release electricity as needed, supporting grid balance, renewable integration, and backup power [70, 100]. Lithium-ion BESS are dominant in the market due to their high energy density and reliability, with TRL 9. Flow batteries, ideal for long-duration storage and scalable designs, are emerging at TRL 7–8 [119]. Lead-acid batteries, a mature and cost-effective option (TRL 9), are often used for backup in critical applications like hospitals [119]. BESS are essential for short-to-medium duration energy storage and play a key role in decarbonizing power systems.

2.6 Energy CAPEX and OPEX Prices

The Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) costs provided here are drawn from a range of reputable sources, including industry reports, energy technology assessments, and recent project data. Key sources include the International Energy Agency (IEA) and International Renewable Energy Agency (IRENA), which offer global averages and benchmarks, as well as European Union (EU) research and policy documents that provide insights. Mature market data, like that for solar, wind, geothermal, and BESS, relies on industry analyses, such as Lazard's Levelized Cost of Energy Analysis, while costs for newer technologies, like sand thermal storage and small modular reactors, are based on pilot projects and emerging data. These values were also verified with experts from Sweco, ensuring accuracy and relevancy within the industry.

These prices apply to the 2022–2024 period and reflect current estimates at a time of rapid advancement in renewable and low-carbon technologies. Cost fluctuations, especially for

TECHNOLOGY	TRL	CAPEX (€/kW)	OPEX (% of CAPEX per year)
Biogas Production (Anaerobic Digestion)	8-9	2,000–5,000	3–5%
Bio-Oil Production (Pyrolysis)	6-9	3,000–6,000	4–6%
Green Hydrogen Production (Electrolysis)	7-9	1,500–2,500	2–4%
Aquathermal Energy Systems	8-9	500–3,000	2–3%
Sewage Thermal Energy Systems	8-9	1,000–2,000	2–3%
Residual Heat Recovery Systems	8-9	500–1,500	1–2%
Geothermal Energy Systems (ATES/BTES)	8-9	1,000–3,000	1–3%
Absorption Cooling	8-9	Variable	Variable
Air-to-Water Heat Pumps	9	800–1,200	2–3%
Solar Panels (PV)	9	600–1,000	1–1.5%
Solar Panels (PT)	9	800–1,200	1.5–2%
Solar Panels (PVT)	8-9	1,000–1,500	1.5–2.5%
Solar Panels (PC)	6-7	Variable	Variable
Concentrated Solar Power (CSP)	8-9	3,000–5,000	2–3%
Wind Energy Systems (Onshore)	9	1,200–1,800	1.5–2.5%
Small and Medium Wind Turbines (SMWT)	8-9	2,000–3,000	2–3%
Micro Hydropower	8-9	3,000–7,000	2–4%
Ocean Power	5-7	Variable	Variable
Organic Rankine Cycle (ORC) Systems	8-9	2,000–4,000	2–4%
Small Modular Reactors (SMRs) and Micro Reactors	7-8	4,000–8,000	5–7%
District Heating (4th Generation)	8-9	800–1,200	1.5–2.5%
District Heating and Cooling (5th Generation)	8-9	500–1,000	1–2%
Seasonal Thermal Energy Storage (PTES)	8-9	2–6 €/kWh	0.5–1%
Seasonal Thermal Energy Storage (Tank)	8-9	4–12 €/kWh	1–1.5%
Seasonal Thermal Energy Storage (Rock Cavern)	7-9	2-4 €/kWh	0.5–1%
Thermal Buffer (Ice Storage)	9	200–300 €/kWh	1–2%
Thermal Buffer (Sand Storage)	6-9	10–20 €/kWh	0.5–1%
Thermal Buffer (Molten Salt)	8-9	30–50 €/kWh	1–1.5%
Thermal Buffer (PCMs)	8-9	100–150 €/kWh	1–2%
Battery Energy Storage Systems (BESS)	9	400–900 €/kWh	1–2%

Table 1: Levelized CAPEX ranges of different energy technologies.

newer technologies like green hydrogen, thermal storage, and BESS, are expected as market demand rises, production scales up, and technology matures.

Additional context is important for understanding these costs. For instance, geothermal systems (ATES/BTES), aquathermal systems, and BESS can vary significantly by location and application, as factors such as geology, local water temperatures, and grid characteristics can affect installation and operational costs. Emerging technologies, such as sand thermal storage, photo-chemical solar panels, and advanced BESS, currently have higher CAPEX due to limited production and specialized equipment, but costs are expected to decrease as these technologies scale up.

Seasonal thermal energy storage costs are provided in terms of energy storage capacity (€/kWh), given their design for long-term storage rather than immediate power output. BESS, however, offer shorter-duration storage and are suited for applications that require rapid response and flexibility, such as grid balancing, which is reflected in their pricing. For highly mature systems, such as 5GDHC, advanced geothermal applications, and lithium-ion-based BESS, CAPEX may be higher but OPEX tends to be lower, reflecting their efficiency and stability.

Finally, market conditions, policy support, and grid factors have a strong influence on costs. For example, hydrogen production via electrolysis is sensitive to electricity prices, which can vary based on local policies and renewable incentives. Similarly, BESS costs are impacted by battery material prices and policy incentives, especially as governments aim to support grid resilience and renewable energy integration.

In sum, these CAPEX and OPEX estimates offer a clear view of the investment landscape for sustainable technologies, with expert input from Sweco ensuring accuracy. However, actual project costs may vary depending on site conditions, policy frameworks, and ongoing shifts in market dynamics, particularly for newer and evolving technologies like BESS, ocean power and green hydrogen.

2.7 Energy Multicriteria Matrix

The multicriteria matrix allows a more detailed assessment of each technology's strengths and limitations across key criteria [21]. Technologies that perform well, like solar panels (PV, PT, PVT, PC), residual heat recovery, and 5GDHC, generally show strong scores in environmental impact, scalability, and reliability, making them well-suited for sustainable development goals.

By contrast, technologies with high upfront costs or complex permitting requirements, like SMRs and ocean power, face more challenges in feasibility and deployment [92]. This matrix serves as an indicative tool for decision-makers to evaluate and prioritize technologies based on cost, impact, scalability, and overall performance.

Criteria Explained:

- CAPEX: Capital expenditure, reflecting the upfront investment required for each technology. Technologies with lower CAPEX are rated higher because they are more affordable to implement.
- OPEX: Operational expenditure, which represents the ongoing costs of running and maintaining each technology. Lower OPEX scores indicate cost-effective, low maintenance solutions.
- Scale: Evaluates the scalability of each technology, or how easily it can be adapted for different project sizes, from small applications to large-scale infrastructure.
- Lifetime: The expected operational lifespan of the technology. Technologies with longer life expectancies receive higher ratings, as they offer more durability and longevity.
- Impact: The environmental impact of each technology, with lower impacts rated higher. Technologies that minimize emissions, resource use, and ecological disruption score better.
- Reliable: Reflects the reliability and consistency of each technology in delivering stable performance over time.
- Permit: Assesses the ease of obtaining necessary permits for installation and operation. Lower permit difficulty scores indicate simpler, faster approval processes.
- Noise: Rates the noise pollution generated by each technology. Technologies with low noise output score higher, making them more suitable for residential and noise-sensitive areas.
- Score: A combined total score calculated from all criteria. The total score is expressed as a percentage to provide an overall rating of each technology's suitability.

The score formula translates qualitative ratings (such as `+++`, `+`, `0`, etc.) into numerical scores to create an overall rating for each technology.

1. **Assigning Scores to Ratings:** Each rating from +++ to --- is assigned a value:

   `+++ = +3, ++ = +2, + = +1, 0 = 0, - = -1, -- = -2, --- = -3`

   This allows qualitative assessments to be consistently represented in numerical form.
2. **Summing Scores:** Each technology is evaluated across multiple criteria (e.g., CAPEX, OPEX, Scalability). The scores for each criterion are summed to create a total score, which can range from -24 (all ---) to $+24$ (all +++).
3. **Adjusting to a 0–48 Range:** To simplify comparison, the total score is adjusted to a range of 0 to 48 by adding 24 to the raw total:

$$\text{Adjusted Score} = \text{Raw Score} + 24$$

4. **Convert to a Percentage:** The adjusted score is then converted to a percentage:

$$\text{Percentage Score} = \left(\frac{\text{Adjusted Score}}{48}\right) \times 100$$

Final Score Interpretation: The percentage score (ranging from 0% to 100%) reflects each technology's overall "transition" performance. Higher percentages indicate stronger performance across cost, scalability, environmental impact, and reliability, facilitating easier comparison between technologies.

However, this score is only indicative for the year 2024. As technologies mature, costs and other factors will evolve. Additionally, unique circumstances may affect outcomes. Therefore, this ranking should be used as a guideline–informative, but not definitive.

Technology	CAPEX	OPEX	Scale	Lifetime	Impact	Reliable	Permit	Noise	Score
Solar Panels (PV, PT, PVT, PC)	+++	+++	+++	+++	+++	+++	+	+++	96%
Thermal Buffer (Sand Storage)	+++	+++	++	+++	+++	++	+	+++	92%
District Heating and Cooling (5th Gen)	++	+++	+++	++	+++	+++	0	+++	90%
Residual Heat Recovery Systems	+++	+++	+	++	+++	+++	0	+	83%
Air-to-Water Heat Pumps	++	+++	++	++	++	+++	+	-	79%
Thermal Buffer (Ice Storage)	++	++	+	+	++	+++	0	+++	79%
Thermal Buffer (PCMs)	++	++	+	+	++	++	+	+++	79%
Seasonal Thermal Energy Storage (PTES)	+++	+++	0	++	+	+++	0	++	79%
Seasonal Thermal Energy Storage (Tank)	++	++	0	++	++	+++	0	++	77%
Seasonal Thermal Energy Storage (Rock Cavern)	++	+++	0	++	++	+++	--	+++	77%
Wind Energy Systems (Onshore/SMWT)	0	++	++	+++	+++	+++	+	--	75%
Thermal Buffer (Molten Salt)	++	++	+	+	++	+++	-	++	75%
Aquathermal Energy Systems	+	+	0	++	++	+++	0	+++	75%
Geothermal Energy Systems (ATES/BTES)	0	++	0	+++	+++	+++	--	++	73%
Sewage Thermal Energy Systems	0	0	0	++	+++	+++	0	+++	73%
District Heating (4th Gen)	0	++	++	++	++	+++	--	++	73%
Battery Energy Storage Systems (BESS)	0	++	+++	+	0	+++	+	+	73%
Absorption Cooling	0	0	+	++	++	++	-	+++	69%
Green Hydrogen Production (Electrolysis)	0	--	++	+	+++	+	--	+	58%
Biogas Production (Anaerobic Digestion)	--	0	0	+	+	++	0	+	56%
Small Modular Reactors (SMRs)	---	--	++	+++	0	+++	---	+++	56%
Organic Rankine Cycle (ORC) Systems	--	0	0	++	+	++	--	++	56%
Micro Hydropower	--	++	0	++	++	+++	---	-	56%
Concentrated Solar Power (CSP)	---	--	-	+++	++	++	--	+	50%
Bio-Oil Production (Pyrolysis)	---	--	0	+	0	+	-	-	40%
Ocean Power	---	0	---	+	0	0	---	++	38%

Table 2: Multicriteria matrix of different energy technologies.

2.8 Sustainable Water Production

2.8.1 Water Harvesting

Rainwater harvesting captures and stores rainwater from surfaces like rooftops for later use in drinking (with further processing), irrigation, cleaning, or industrial applications [15]. The system typically includes gutters, filters, storage tanks, and a first-flush diverter to ensure water quality (see Figure 8). It is a low-cost, sustainable solution for water conservation, especially in regions facing scarcity. This mature technology is widely adopted and offers a reliable alternative to groundwater or municipal supply systems.

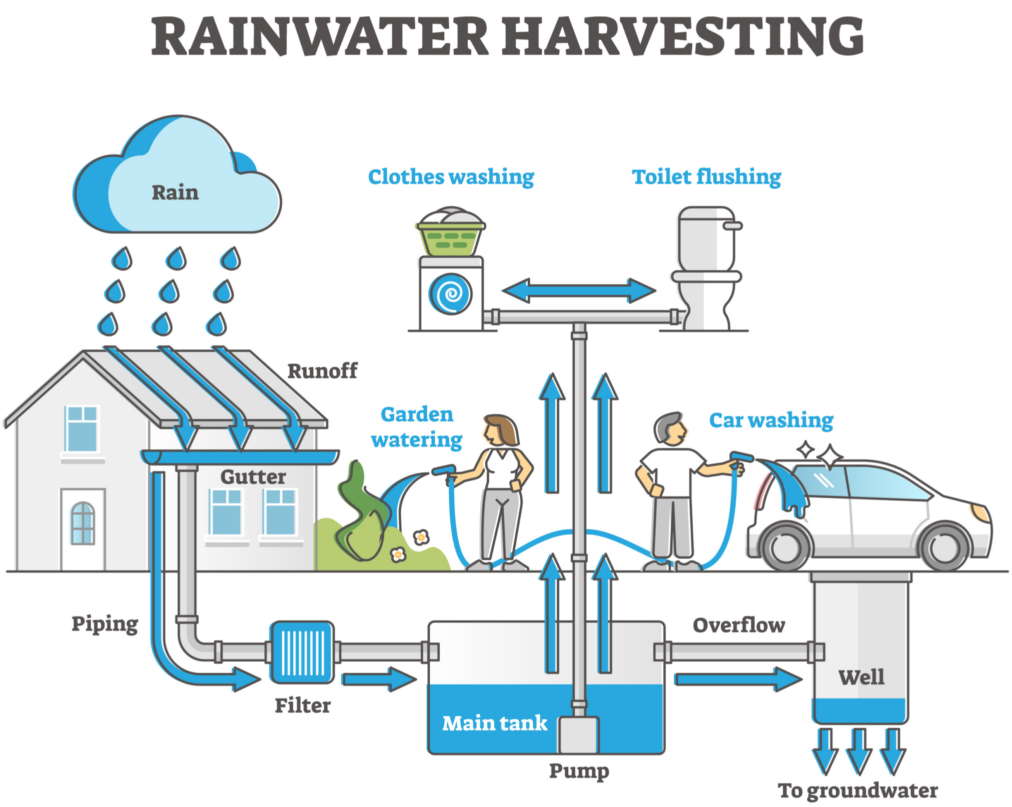

Figure 8: Rainwater harvesting. Image ©Duke Antwi [7]

2.8.2 Membrane Bioreactor

Membrane Bio Reactor (MBR) technology combines biological treatment and membrane filtration to regenerate wastewater from sinks, showers, and appliances [57]. The resulting high-quality water is reused for non-potable purposes like toilet flushing, irrigation, or cooling. With a relative compact, modular design, MBR systems are ideal for decentralized water recycling in residential, commercial, and industrial settings. The technology is commercially mature and operates at TRL 8–9, making it a proven solution for sustainable water reuse.

2.8.3 Innovative Desalination and Filtration

New desalination and filtration technologies offer sustainable water treatment with varied readiness levels:

- **CSP desalination** uses solar heat to desalinate seawater (*TRL 7–8*).
- **Graphene-based filtration** employs nano-membranes (*TRL 5–6*).
- **Forward osmosis** uses osmotic pressure for low-waste treatment [20] (*TRL 6–7*).
- **Biomimetic membranes** mimic low-energy cellular processes [116] (*TRL 4–5*).
- **Capacitive Deionization (CDI)** removes salts using electrodes [90] (*TRL 7*).

These methods address water scarcity with a range of applications, from industrial use to remote, off-grid systems [99, 35].

2.8.4 Atmospheric Water Generation

Atmospheric Water Generation (AWG) technologies extract moisture from the air, offering a renewable water source, especially in arid regions [62]. Key methods include:

- **Fog and dew harvesting**, using meshes to collect airborne droplets [85] (*TRL 8–9*).
- **Hydrogel-based systems**, which absorb moisture and release it with heat (*TRL 5–6*).
- **Hydropanels**, solar-powered systems that condense water from air (*TRL 7–8*).
- **Biomimetic membranes**, mimicking natural water capture processes (*TRL 4–5*).

These technologies vary in maturity but all aim to provide decentralized, sustainable water in challenging climates.

2.9 Sustainable Compute Power

2.9.1 Third Pillar of Science

The third pillar of science (see Figure 9), known as computational science, is transforming how we understand, simulate, and innovate in complex systems across nearly every domain. Traditionally, science relied on experimentation and theory; now, computation enables us to model intricate phenomena, test hypotheses at massive scales, and reveal insights that were previously inaccessible.

The democratization of compute power – making powerful computing resources widely available – has been a groundbreaking, albeit underappreciated, advancement in human history. This shift is propelling scientific fields like aerospace engineering, biotechnology, materials science, and climate modeling into new territories of discovery. Most significantly, it has been the catalyst that has made modern AI possible.

2.9.2 Compute as the Next Utility

AI, built on vast data processing and pattern recognition, has evolved from basic rule-based systems into complex, deep-learning architectures due to unprecedented computational

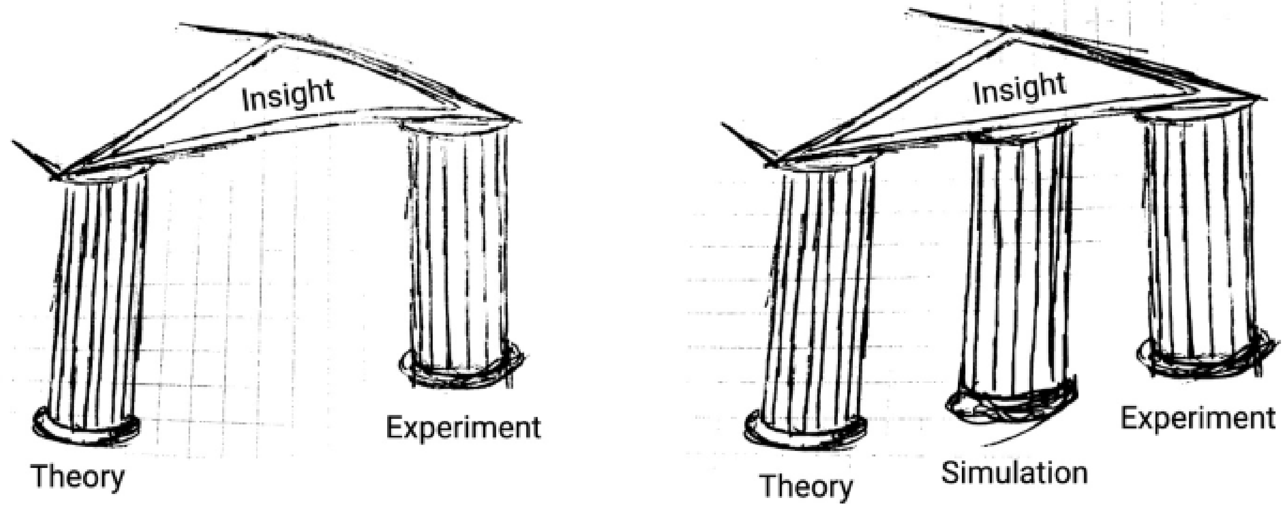

Figure 9: Illustration of the third pillar of science. Image ©Tobias Weinzierl [115]

power (see Figure 10) [73, 65]. Just as the smartphone revolutionized personal productivity and connectivity, AI is poised to be even more transformative.

AI elevates human productivity across domains–personalized medicine, optimized energy, advanced manufacturing, and creative tools–redefining how we live and work. However, behind each AI-driven solution lies significant computational demand. Even a single task, such as generating an image or interpreting a dataset, involves millions of calculations [56].

As interactions with AI grow in complexity and frequency, compute power will become as essential as energy, water, mobility, and telecommunications. In this future, compute is not merely a digital tool–it becomes the backbone of our daily existence, powering intelligent systems, infrastructures, and economies.

2.9.3 Future Data Centers

The surging demand for compute, especially from AI, is fueling the global expansion of data centers–akin to how factories powered the industrial revolution [106]. But this growth brings massive energy needs, requiring both a sustainable energy transition and radical efficiency improvements [101].

To meet sustainability goals, data centers must integrate:

- Advanced energy-efficient architectures
- Next-generation cooling systems
- Heat reuse strategies (e.g., for district heating)

Liquid-cooled systems are replacing traditional air-cooled, adiabatic methods [93]. Supporting up to 100–200 kW per rack and significantly reducing water consumption, they enable higher energy density, better heat recovery, and improved exergy efficiency [22]. These systems are now at TRL 7–8, with adoption expanding among hyperscalers and major tech companies. They are expected to reach TRL 9 as costs fall and industry standards mature.

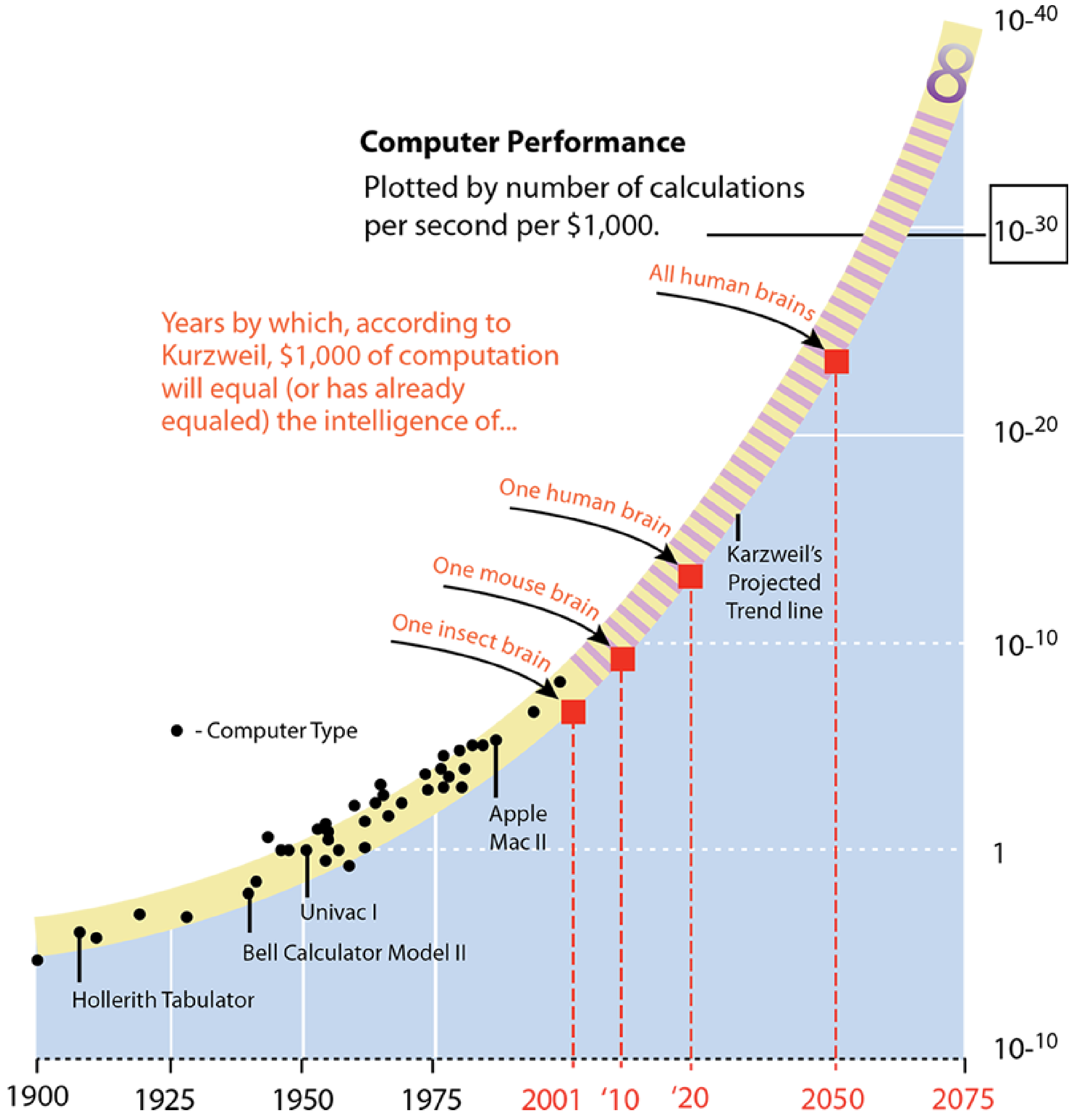

Figure 10: Exponential growing power of computers. Image ©Ray Kurzweil, Jeff Graham [73]

Future data centers will be decentralized and integrated into urban infrastructure (see Figure 11), becoming active participants in city-wide energy and water systems–transforming into critical community assets [80, 102].

2.9.4 Scale of the Challenge

Consider a complex generative AI query involving speech recognition and image generation. Such a query typically consumes up to 30 Wh per instance. Assuming just 10% of a person's daily thoughts (~500 out of 5.000–6.000) are digitally augmented:

- Daily energy use per person: **15 kWh**
- Continuous compute demand per person: **625 W**

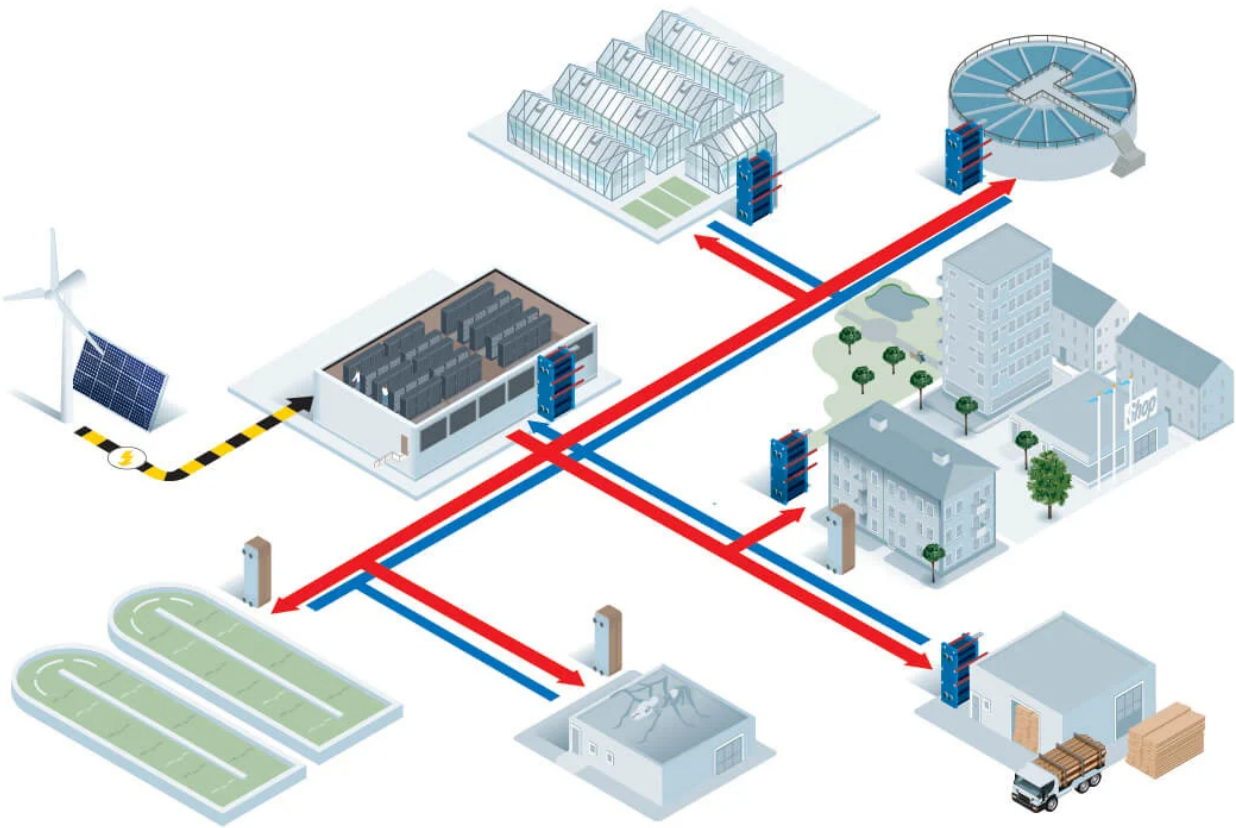

Figure 11: An energy community linked to a liquid cooled data center. Image ©Alfa Laval [5]

For an average Belgian town like Diepenbeek (about 20.000 residents), this translates to a 12,5 MW data center. For larger cities:

- Brussels: 750 MW
- Antwerp: 350 MW
- Ghent: 170 MW
- New York City: 5.160 MW
- Belgium total: 7.350 MW

This implies **7 GW** of additional AI-driven data center capacity in Belgium alone, costing approximately 70 billion EUR (based on 10 million EUR/MW construction cost). With a design fee of 10%, this means 7 billion EUR in potential design contracts for engineering firms, such as Sweco. Spread over 20 years, this equates to:

- Annual construction: **3,5 billion EUR**
- Annual design fees: **350 million EUR**

Globally, this scales to:

- **4,4 TW** total capacity
- **44 trillion EUR** construction cost

- **2,2 trillion EUR/year** over 20 years
- **220 billion EUR/year** for Europe (10%)

These data centers would dissipate enormous heat. For Belgium's 7 GW, around 65 TWh of heat is released annually–compared to 92 TWh in total residential heating demand. This opens massive opportunities for waste heat reuse. In any case, this large amount of dissipated heat cannot just be evacuated to the atmosphere because of obvious reasons.

2.10 Future Mobility and Telecom

2.10.1 Vehicle-to-Grid

V2G technology enables Electric Vehicles (EVs) to not only draw power from the grid but also to return excess power back to it when needed (see Figure 12) [60]. This bidirectional energy flow allows Electric Vehicle (EV) batteries to act as flexible energy storage units, making them invaluable for stabilizing the grid during peak demand times and supporting the integration of renewable energy sources like wind and solar. By temporarily discharging stored energy, V2G can help balance supply and demand, reducing the need for additional infrastructure and fossil-fuel backup.

As the number of EVs on the road grows, V2G will play a vital role in the energy transition, transforming parked EVs into a decentralized network of mobile energy reserves. This capability will not only increase grid resilience but also allow EV owners to contribute to and benefit from grid stability, potentially earning credits or payments for the energy they supply back to the grid.

V2G technology is currently at TRL 7—8, with several pilot projects and commercial deployments underway in regions with advanced EV infrastructure. As it advances toward TRL 9, V2G is expected to become a standard feature, integrating EVs seamlessly into the renewable energy landscape and helping to accelerate the shift to a sustainable, resilient energy future.

As EVs take on an essential role in energy management, they will be valued not only for transportation but also as mobile energy assets. This dual function, however, creates a challenge: balancing the need for energy storage and grid support with the traditional requirement for mobility. Managing these dual demands will be complex, particularly as EVs become embedded in grid infrastructure.

This interplay is expected to promote mobility-as-a-service business models, where fleets of EVs are shared, rather than individually owned, to maximize their availability for both transport and energy storage [83]. When self-driving technology becomes mainstream, these EV fleets could be autonomously coordinated to fulfill energy and transportation demands seamlessly, optimizing schedules to support the grid during peak times and providing flexible mobility for users. This integration of mobility and energy services has the potential to reshape urban systems, creating more sustainable and efficient city infrastructure.

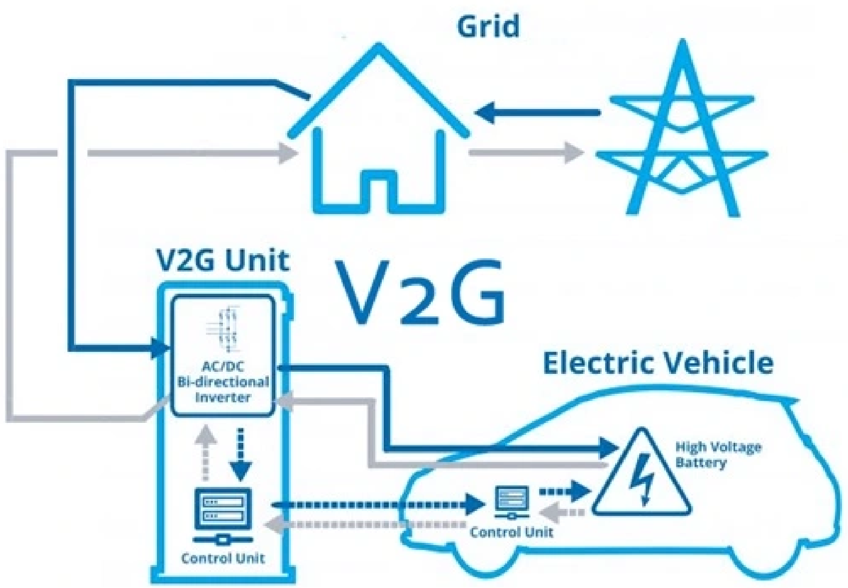

Figure 12: Concept of Vehicle-to-Grid (V2G) technology. Image ©Grasen Power [42]

2.10.2 Hydrogen mobility

Hydrogen mobility uses hydrogen fuel cells to power vehicles, offering a clean alternative to traditional combustion engines [8]. In a fuel cell vehicle, hydrogen reacts with oxygen in a fuel cell stack, generating electricity to drive the motor with water as the only emission. This makes hydrogen an attractive option for decarbonizing transportation, especially for heavy-duty and long-range applications like trucks, buses, and trains, where battery-electric solutions face limitations in weight and recharging times.

Hydrogen mobility is currently at a TRL of 7–8, with fuel cell vehicles available commercially in limited markets and an expanding network of hydrogen refueling stations. While still scaling, hydrogen-powered transport is seen as a vital component of a sustainable, zero-emission future, especially as hydrogen production and infrastructure continue to improve (see Figure 13), pushing the technology closer to widespread adoption.

2.10.3 Telecom

Telecommunications is an established sector that provides critical infrastructure for communication, connecting individuals, businesses, and governments worldwide. It includes traditional phone services, mobile networks, broadband internet, and increasingly, high-speed data and 5G networks [68]. While telecom is continuously evolving with innovations–like faster data speeds, improved connectivity, and integration of the IoT–it is not a sector directly driving the transition to a more sustainable society.

Telecom innovations primarily focus on improving connectivity, speed, and data capacity to meet growing digital demands, enhancing areas like smart devices, cloud computing, and virtual experiences. While there are sustainable developments within telecom–such as energy-efficient data centers and infrastructure sharing–its main purpose remains provid-

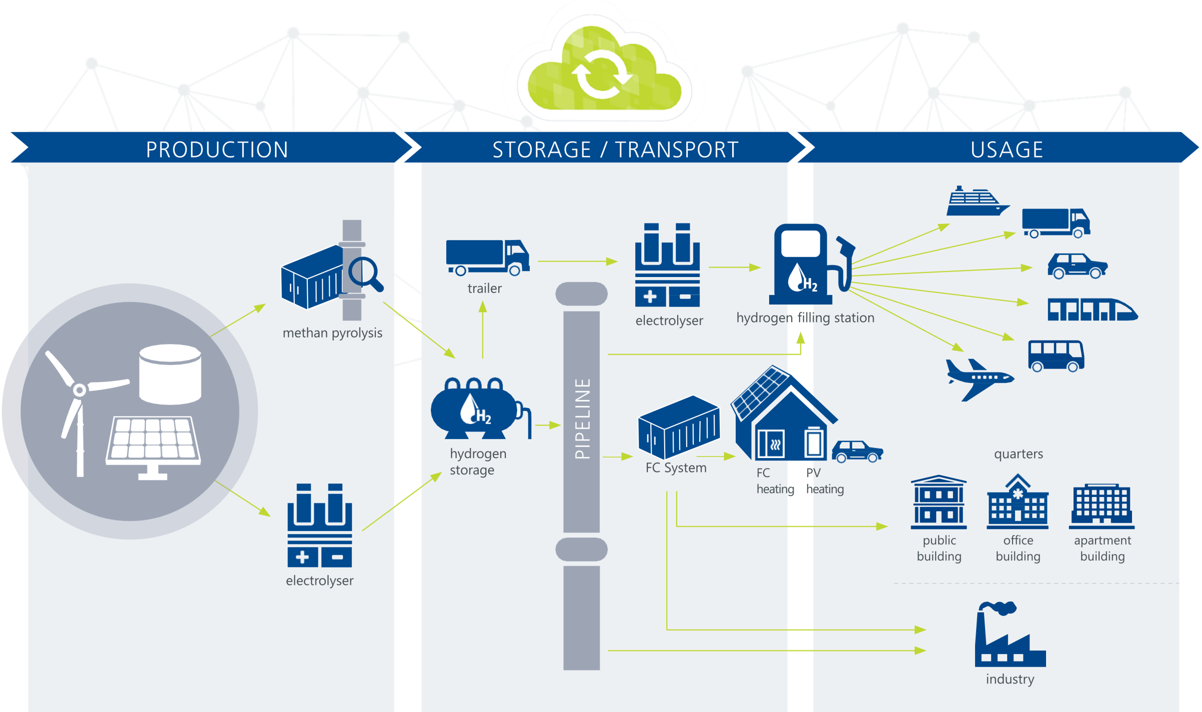

Figure 13: The ecosystem for hydrogen from production to usage. Image ©ITK Engineering [55]

ing digital connectivity rather than directly addressing larger environmental or sustainability challenges.

3 Economical Analysis

The transition to sustainable energy systems is not only a technological challenge but also a financial and operational one. Understanding the payback potential of renewable and energy-efficient technologies is crucial for ensuring their successful implementation and long-term viability. This chapter explores the scalability and economic feasibility of various energy technologies across different community sizes and time horizons, providing valuable insights for decision-makers and stakeholders.

To capture a broad spectrum of energy needs, the analysis focuses on three distinct community scales:

- A small-scale community with an annual energy demand of approximately 100 MWh, equivalent to 20–30 dwellings.
- A medium-scale community with an annual demand of around 1 GWh, representing 200–300 dwellings.
- A large-scale community with a yearly demand of roughly 10 GWh, accommodating

2,000–3,000 dwellings.

Each community size reflects unique energy requirements, financial dynamics, and technological implications, offering a diverse perspective on the performance of these solutions.

The study spans a 50-year time horizon, ensuring a comprehensive understanding of long-term costs, savings, and returns. By evaluating technologies such as solar power, wind energy, geothermal systems, hydrogen production, district heating, and advanced thermal storage, the deliverable provides a detailed assessment of their scalability and payback potential. It examines how technologies can adapt to varying community sizes while balancing initial investments, operational costs, and energy savings. Moreover, the analysis highlights the broader environmental and financial benefits that these solutions bring, ensuring they align with the long-term goals of energy self-sufficiency and sustainability.

By focusing on the interplay between scale, performance, and economic viability, this chapter serves as a practical guide for driving effective energy transitions in communities of all sizes, offering pathways to a more sustainable and economically resilient future [14, 78].

3.1 Context and Used Parameters

The analysis in this chapter evaluates the financial potential of energy technologies by assessing their CAPEX, OPEX, and turnover potential across three community sizes: small (100 MWh), medium (1 GWh), and large (10 GWh). To reflect realistic cost efficiencies, we have adapted the parameters based on the scale of the community [11].

For CAPEX, we used the high end of the price ranges for small-scale communities (100 MWh), recognizing that smaller installations lack the economies of scale found in larger systems. Conversely, for the large-scale communities (10 GWh), we applied the low end of the price ranges, reflecting the improved cost efficiency achievable in large installations. The same approach was applied to OPEX, with higher operational costs assumed for smaller systems and lower relative costs for larger setups.

The turnover potential was calculated based on the type of energy output produced by each technology:

1. Heating and Cooling: We considered the market price of heating and cooling to be equivalent, simplifying the valuation while recognizing their similar intrinsic value in community energy systems.
2. Electricity: For technologies producing electricity [94], we used current average market prices for electrical energy in Belgium as a baseline for turnover potential.
3. Hydrogen Output: Hydrogen was treated separately due to its dual potential to be converted into either heat or electricity, which gives it a unique intrinsic value. In particular, pressurized hydrogen was considered, as its storage and transport capabilities further enhance its utility and worth.

For energy carriers like biogas and bio-oil, we assumed their output would primarily serve heating purposes, aligning with their typical use in community energy systems. Technologies like PTES, TTES, ice storage, molten salt, sand thermal storage, and BESS were analyzed differently because they function as energy storage systems, not direct energy production systems. Their value lies in their ability to store energy for later use, enhancing the efficiency and reliability of broader energy systems rather than directly generating energy.

By using this structured approach, the analysis accommodates differences in scale, technology purpose, and energy output types, providing a comprehensive evaluation of each technology's financial and operational potential within the context of diverse community sizes. This ensures that the findings are practical, realistic, and tailored to varying energy needs and scenarios.

3.1.1 Exclusion of Specific Technologies from General Evaluation

While this chapter provides a comprehensive evaluation of various energy technologies, certain systems–absorption cooling, PC solar panels, and ocean power–are excluded from the general analysis. These technologies are characterized by their highly project-specific nature, making it challenging to assess them in a standardized or generalistic manner.

- Absorption Cooling: The feasibility and efficiency of absorption cooling systems are heavily influenced by factors such as the availability of waste heat, specific cooling demands, and the integration with other energy systems in a given project. As a result, these installations require customized assessments tailored to the unique circumstances of each application, particularly in terms of energy inputs and operational requirements.
- Photochemical Solar Panels: This emerging technology, while promising, is still in its early stages of development and deployment. Its performance and cost parameters are highly variable, depending on the specific application, location, and level of integration with other systems. Consequently, PC solar panels cannot yet be evaluated within the generalized framework applied to more mature technologies.
- Ocean Power: The deployment of ocean power systems, including tidal and wave energy, is dictated by site-specific conditions such as marine geography, tidal patterns, and wave dynamics. These unique requirements make it impractical to apply a generalized analysis, as each project necessitates a bespoke engineering and financial evaluation.

Given these challenges, absorption cooling, PC solar panels, and ocean power systems are best assessed on a case-by-case basis, where the specific project conditions and energy demands can be thoroughly accounted for. This ensures that their feasibility and potential are accurately determined, even if they fall outside the scope of this generalized evaluation.

3.1.2 Used CAPEX parameters (in EUR/kW)

Used CAPEX parameters can be found in table 3.

TECHNOLOGY	100MWh CAPEX (€/kW)	1GWh CAPEX (€/kW)	10GWh CAPEX (€/kW)
Biogas Production (Anaerobic Digestion)	5.000	3.500	2.000
Bio-Oil Production (Pyrolysis)	6.000	4.500	3.000
Green Hydrogen Production (Electrolysis)	2.500	2.000	1.500
Aquathermal Energy Systems	3.000	1.750	500
Sewage Thermal Energy Systems	2.000	1.500	1.000
Residual Heat Recovery Systems	1.500	1.000	500
Geothermal Energy Systems (ATES/BTES)	3.000	2.000	1.000
Absorption Cooling	Variable	Variable	Variable
Air-to-Water Heat Pumps / Drycooler	1.200	1.000	800
Solar Panels (PV)	1.000	800	600
Solar Panels (PT)	1.200	1.000	800
Solar Panels (PVT)	1.500	1.250	1.000
Solar Panels (PC)	Variable	Variable	Variable
Concentrated Solar Power (CSP)	5.000	4.000	3.000
Wind Energy Systems (Onshore)	1.800	1.500	1.200
Small and Medium Wind Turbines (SMWT)	3.000	2.500	2.000
Micro Hydropower	7.000	5.000	3.000
Ocean Power	Variable	Variable	Variable
Organic Rankine Cycle (ORC) Systems	4.000	3.000	2.000
Small Modular Reactors (SMRs) and Micro Reactors	8.000	6.000	4.000
District Heating (4th Generation)	1.200	1.000	800
District Heating and Cooling (5th Generation)	1.000	750	500

Table 3: Used levelized CAPEX parameters for different scales of implementation.

TECHNOLOGY	100MWh OPEX (%/y)	1GWh OPEX (%/y)	10 GWh OPEX (%/y)
Biogas Production (Anaerobic Digestion)	5,00%	4,00%	3,00%
Bio-Oil Production (Pyrolysis)	6,00%	5,00%	4,00%
Green Hydrogen Production (Electrolysis)	4,00%	3,00%	2,00%
Aquathermal Energy Systems	3,00%	2,50%	2,00%
Sewage Thermal Energy Systems	3,00%	2,50%	2,00%
Residual Heat Recovery Systems	2,00%	1,50%	1,00%
Geothermal Energy Systems (ATES/BTES)	3,00%	2,00%	1,00%
Absorption Cooling	Variable	Variable	Variable
Air-to-Water Heat Pumps / Drycooler	3,00%	2,50%	2,00%
Solar Panels (PV)	1,50%	1,25%	1,00%
Solar Panels (PT)	2,00%	1,75%	1,50%
Solar Panels (PVT)	2,50%	2,00%	1,50%
Solar Panels (PC)	Variable	Variable	Variable
Concentrated Solar Power (CSP)	3,00%	2,50%	2,00%
Wind Energy Systems (Onshore)	2,50%	2,00%	1,50%
Small and Medium Wind Turbines (SMWT)	3,00%	2,50%	2,00%
Micro Hydropower	4,00%	3,00%	2,00%
Ocean Power	Variable	Variable	Variable
Organic Rankine Cycle (ORC) Systems	4,00%	3,00%	2,00%
Small Modular Reactors (SMRs) and Micro Reactors	7,00%	6,00%	5,00%
District Heating (4th Generation)	2,50%	2,00%	1,50%
District Heating and Cooling (5th Generation)	2,00%	1,50%	1,00%

Table 4: Used OPEX parameters for different scales of implementation.

3.1.3 Market Parameters for the Analysis

In this analysis, we use the following market parameters to evaluate the financial potential of energy technologies. These parameters represent (near) future-proof price conditions in the Belgian market, informed by current trends and anticipated policy changes:

MARKET PARAMETERS		
Market price heat/cooling	120	EUR/MWh
Market price electricity	300	EUR/MWh
Market price hydrogen	175	EUR/MWh
Market price water	5	EUR/m^3

Table 5: Used market parameters.

These values are designed to reflect the evolving economic and regulatory environment in Belgium, taking into account:

- The Flemish Coalition Agreement of Late 2024: This agreement includes a planned tax shift from electricity to fossil fuels, aligning with broader decarbonization goals and incentivizing electrification in heating and transportation.
- The EU Emissions Trading System (ETS2): Set to expand to buildings and road transport sectors, ETS2 will likely drive up the cost of fossil fuel-based energy, further reinforcing the competitiveness of low-carbon alternatives.

Heat/Cooling (€120/MWh)
This price reflects a balanced and competitive cost for sustainable heating and cooling systems, considering future efficiency gains and regulatory measures encouraging electrification and district heating.

Electricity (€300/MWh)
The electricity price accounts for Belgium's reliance on renewable energy sources and its heavily taxed electricity market. The tax shift is expected to increase the price of fossil fuels while stabilizing or slightly reducing the burden on electricity.

Hydrogen (€175/MWh)
Hydrogen's price reflects its dual nature as a valuable energy carrier and storage medium, with costs impacted by production methods (e.g., green hydrogen through electrolysis) and its applications in industry, transportation, and grid balancing.

Water (€5/m^3)
This price is consistent with the cost of clean water supply in Belgium, representing the baseline value for technologies relying on water as an input (e.g., electrolysis for hydrogen production or advanced filtration systems). Nevertheless, a price increase in the medium term is to be expected, as potable water will become more scarce in the future due to climate change.

3.1.4 Power to Energy Conversion

In our analysis, the CAPEX of each technology is primarily determined by its installed power capacity (measured in kW). However, the turnover potential is based on the amount of energy the installation generates (measured in kWh or MWh). This creates a critical relationship between the power capacity of a system and its energy output, which depends on the hours of operation and the effectiveness of the technology in its specific context.

A power installation (e.g., 1 kW of capacity) will generate a certain amount of energy over time (e.g., in MWh), but this power-to-energy conversion is highly influenced by factors such as location, environmental conditions, and the specific performance characteristics of the technology. For instance:

- Solar PV panels in Belgium will convert power to energy less effectively than the same installation in southern Spain, due to lower solar irradiation levels. A 1 kW PV installation might produce 0.85 MWh annually in Belgium, compared to 1.5 MWh or more in

Spain. [17]

- Hydropower installations depend heavily on local conditions, such as rainfall, river flow, and landscape characteristics. For example, a hydropower plant in a rainy region with steep slopes and fast-moving rivers will generate far more energy than the same system in a drier, flatter area.

To provide a clear and actionable analysis, we summarize the power-to-energy conversion parameters specific to Belgium, while also considering general values that can apply more broadly. This ensures that the turnover potential reflects realistic operating conditions and highlights the geographic and environmental factors that significantly influence energy generation. By grounding our analysis in these conversion parameters, we provide a comparative assessment of each technology's financial and operational performance in both local and general contexts:

TECHNOLOGY	AVG CONVERSION MWh/kW (BELGIUM)	ENERGY FORM
Biogas Production (Anaerobic Digestion)	0,7	Heat
Bio-Oil Production (Pyrolysis)	0,6	Heat
Green Hydrogen Production (Electrolysis)	0,33	Hydrogen
Aquathermal Energy Systems	1,1	Heat
Sewage Thermal Energy Systems	0,9	Heat
Residual Heat Recovery Systems	0,5	Heat
Geothermal Energy Systems (ATES/BTES)	1,5	Heat/Cooling
Absorption Cooling	0,4	Cooling
Air-to-Water Heat Pumps / Drycooler	0,9	Heat/Cooling
Solar Panels (PV)	0,85	Electricity
Solar Panels (PT)	0,85	Heat
Solar Panels (PVT)	0,85	Heat/Electricity
Solar Panels (PC)	0,85	Hydrogen
Concentrated Solar Power (CSP)	1	Electricity
Wind Energy Systems (Onshore)	1,8	Electricity
Small and Medium Wind Turbines (SMWT)	1,5	Electricity
Micro Hydropower	3	Electricity
Ocean Power	1,5	Electricity
Organic Rankine Cycle (ORC) Systems	0,7	Electricity
Small Modular Reactors (SMRs) and Micro Reactors	2	Electricity
District Heating (4th Generation)	0,5	Heat
District Heating and Cooling (5th Generation)	0,7	Heat/Cooling

Table 6: Used power to energy conversion factors.

3.1.5 Rationale

By adopting these parameters, the analysis aligns with anticipated market realities under a decarbonized energy economy. These prices and conversion parameters ensure that our evaluation reflects realistic financial outcomes, accounting for the policy-driven shift toward sustainable energy and resource management in Belgium and the European Union.

3.2 Turnover Potential for the Energy Production Technologies

The yearly turnover potential of energy technologies is evaluated for three community sizes, representing different scales of energy demand: small (100 MWh), medium (1 GWh), and large (10 GWh). The turnover potential is based on the market prices of energy outputs, including heat/cooling, electricity, and hydrogen.

These figures demonstrate how turnover potential scales with community size, highlighting

ENERGY FORM	SMALL (100 MWh)	MEDIUM (1 GWh)	LARGE (10 GWh)	
Heat/Cooling	€12.000	€120.000	€1.200.000	yearly turnover potential
Electricity	€30.000	€300.000	€3.000.000	yearly turnover potential
Hydrogen	€17.500	€175.000	€1.750.000	yearly turnover potential

Table 7: Turnover potential for the different scales and energy forms.

the financial opportunities for heat, electricity, and hydrogen production across varying levels of energy demand. Large communities, with higher energy consumption, offer the most significant potential, underlining the importance of scaling technologies to match local energy needs and maximize economic returns [96].

3.3 Expenses

While the turnover potential of each technology is determined solely by its energy output–be it heat, cooling, electricity, hydrogen, or water–the expenses associated with each technology vary significantly [67]. These expenses are influenced by the specific characteristics of the technology, such as its CAPEX, OPEX, and maintenance requirements.

The turnover potential is uniform in its calculation, based on the type and quantity of energy produced and the market price for that energy (e.g., €120/MWh for heat, €300/MWh for electricity). However, the expenses differ across technologies due to factors such as:

- Initial Investment: Some technologies, like solar PV, have relatively high upfront costs, and others, like district heating systems, require significant infrastructure investments. The CAPEX is reverse calculated from the required energy for the community and the power to energy conversion for each specific technology.
- Operational Costs: Technologies also differ in their operational expenses. The OPEX range mentioned in Table 4 is used, to calculate an indivualized OPEX cost, based on their respective CAPEX.

To reflect these differences, we list the expenses technology by technology in the analysis. This approach ensures that the financial evaluation of each technology considers not only its revenue-generating potential but also the unique cost structure required to achieve that output. By differentiating between turnover potential and expenses, we provide a clearer picture of the financial viability of each technology, tailored to its specific attributes.

3.3.1 Variation in CAPEX Across Different Community Sizes

The CAPEX of energy technologies varies significantly across different community sizes–small (100 MWh), medium (1 GWh), and large (10 GWh)–due to the effects of economies of scale. Larger installations benefit from reduced per-unit costs, as fixed expenses like infrastructure, design, and permitting are spread over a greater capacity.

In smaller communities, CAPEX per kW is typically higher because the scale of the installation does not allow for cost efficiencies. Fixed costs are distributed over a smaller power capacity, making each unit of capacity more expensive. Additionally, smaller installations often lack the bulk purchasing or construction advantages available to larger systems.

For larger communities, CAPEX per kW decreases significantly. Bulk purchasing, streamlined construction processes, and greater capacity utilization result in lower material, labor, and administrative costs. This makes larger-scale projects more cost-efficient and better suited for delivering energy at a lower investment cost per unit of capacity.

By accounting for these variations in CAPEX across different community sizes, our analysis ensures a realistic assessment of the financial viability of each technology, tailored to the scale of the application [36].

TECHNOLOGY	100MWh CAPEX	1GWh CAPEX	10GWh CAPEX
Biogas Production (Anaerobic Digestion)	€714.286	€5.000.000	€28.571.429
Bio-Oil Production (Pyrolysis)	€1.000.000	€7.500.000	€50.000.000
Green Hydrogen Production (Electrolysis)	€757.576	€6.060.606	€45.454.545
Aquathermal Energy Systems	€272.727	€1.590.909	€4.545.455
Sewage Thermal Energy Systems	€222.222	€1.666.667	€11.111.111
Residual Heat Recovery Systems	€300.000	€2.000.000	€10.000.000
Geothermal Energy Systems (ATES/BTES)	€200.000	€1.333.333	€6.666.667
Absorption Cooling			
Air-to-Water Heat Pumps / Drycooler	€133.333	€1.111.111	€8.888.889
Solar Panels (PV)	€117.647	€941.176	€7.058.824
Solar Panels (PT)	€141.176	€1.176.471	€9.411.765
Solar Panels (PVT)	€176.471	€1.470.588	€11.764.706
Solar Panels (PC)			
Concentrated Solar Power (CSP)	€500.000	€4.000.000	€30.000.000
Wind Energy Systems (Onshore)	€100.000	€833.333	€6.666.667
Small and Medium Wind Turbines (SMWT)	€200.000	€1.666.667	€13.333.333
Micro Hydropower	€233.333	€1.666.667	€10.000.000
Ocean Power			
Organic Rankine Cycle (ORC) Systems	€571.429	€4.285.714	€28.571.429
Small Modular Reactors (SMRs) and Micro Reactors	€400.000	€3.000.000	€20.000.000
District Heating (4th Generation)	€240.000	€2.000.000	€16.000.000
District Heating and Cooling (5th Generation)	€142.857	€1.071.429	€7.142.857

Table 8: Total CAPEX for different scales of implementation.

3.3.2 Variation in OPEX Across Different Community Sizes

OPEX for each technology vary significantly depending on the size of the community–small (100 MWh), medium (1 GWh), and large (10 GWh)–primarily due to economies of scale. As the scale of an energy system increases, the operational costs per unit of energy produced tend to decrease, creating distinct financial dynamics for different community sizes.

For smaller communities, OPEX is generally higher on a per-unit basis. This is because fixed costs, such as routine maintenance, staffing, and administrative overhead, cannot be spread across a large energy output. Additionally, smaller systems often operate with lower efficiency, either due to underutilized capacity or less advanced infrastructure, further driving up costs.

In larger communities, OPEX per unit of energy produced is significantly reduced. Larger systems benefit from economies of scale, where fixed costs are distributed across a much greater output. These systems are also more likely to incorporate advanced technologies and optimized processes, resulting in lower operational costs and higher efficiency over time.

By reflecting these differences in OPEX across varying community sizes, our analysis provides a realistic and scalable assessment of the financial performance of each technology. This approach ensures that the evaluation accounts for the critical role that scale plays in determining operational efficiency and overall cost-effectiveness, enabling a more accurate comparison of technologies for communities of different sizes.

3.4 Static Payback Analysis

In this analysis, we start by calculating the static payback periods for each technology. This approach provides a straightforward measure of the initial viability of the technologies, offering a clear understanding of how quickly the initial investment can be recovered based on current costs and revenues.

Additionally, the static payback periods allow us to perform a sensitivity analysis on the economies of scale, helping us identify which technologies perform best at different community sizes. By evaluating the static payback across varying scales, we gain valuable insights into the relationship between scale and financial performance, which is critical for guiding investment decisions and optimizing technology deployment for different community sizes.

3.4.1 Turnover per Technology

A list of turnover potential per technology can be found in Table 9.

TECHNOLOGY	100MWh TURNOVER/y	1GWh TURNOVER/y	10GWh TURNOVER/y
Biogas Production (Anaerobic Digestion)	€12.000	€120.000	€1.200.000
Bio-Oil Production (Pyrolysis)	€12.000	€120.000	€1.200.000
Green Hydrogen Production (Electrolysis)	€17.500	€175.000	€1.750.000
Aquathermal Energy Systems	€12.000	€120.000	€1.200.000
Sewage Thermal Energy Systems	€12.000	€120.000	€1.200.000
Residual Heat Recovery Systems	€12.000	€120.000	€1.200.000
Geothermal Energy Systems (ATES/BTES)	€12.000	€120.000	€1.200.000
Absorption Cooling			
Air-to-Water Heat Pumps / Drycooler	€12.000	€120.000	€1.200.000
Solar Panels (PV)	€30.000	€300.000	€3.000.000
Solar Panels (PT)	€12.000	€120.000	€1.200.000
Solar Panels (PVT)	€16.500	€165.000	€1.650.000
Solar Panels (PC)			
Concentrated Solar Power (CSP)	€12.000	€120.000	€1.200.000
Wind Energy Systems (Onshore)	€30.000	€300.000	€3.000.000
Small and Medium Wind Turbines (SMWT)	€30.000	€300.000	€3.000.000
Micro Hydropower	€30.000	€300.000	€3.000.000
Ocean Power			
Organic Rankine Cycle (ORC) Systems	€30.000	€300.000	€3.000.000
Small Modular Reactors (SMRs) and Micro Reactors	€30.000	€300.000	€3.000.000
District Heating (4th Generation)	€12.000	€120.000	€1.200.000
District Heating and Cooling (5th Generation)	€12.000	€120.000	€1.200.000

Table 9: Turnover potential for different scales of implementation.

3.4.2 Operational Expenses per Technology

A list of OPEX per technology can be found in Table 10.

3.4.3 Payback Capacity per Technology

A list of the payback capacity per technology can be found in Table 11.

TECHNOLOGY	100MWh OPEX/y	1GWh OPEX/y	10GWh OPEX/y
Biogas Production (Anaerobic Digestion)	€35.714,29	€200.000,00	€857.142,86
Bio-Oil Production (Pyrolysis)	€60.000,00	€375.000,00	€2.000.000,00
Green Hydrogen Production (Electrolysis)	€30.303,03	€181.818,18	€909.090,91
Aquathermal Energy Systems	€8.181,82	€39.772,73	€90.909,09
Sewage Thermal Energy Systems	€6.666,67	€41.666,67	€222.222,22
Residual Heat Recovery Systems	€6.000,00	€30.000,00	€100.000,00
Geothermal Energy Systems (ATES/BTES)	€6.000,00	€26.666,67	€66.666,67
Absorption Cooling			
Air-to-Water Heat Pumps / Drycooler	€4.000,00	€27.777,78	€177.777,78
Solar Panels (PV)	€1.764,71	€11.764,71	€70.588,24
Solar Panels (PT)	€2.823,53	€20.588,24	€141.176,47
Solar Panels (PVT)	€4.411,76	€29.411,76	€176.470,59
Solar Panels (PC)			
Concentrated Solar Power (CSP)	€15.000,00	€100.000,00	€600.000,00
Wind Energy Systems (Onshore)	€2.500,00	€16.666,67	€100.000,00
Small and Medium Wind Turbines (SMWT)	€6.000,00	€41.666,67	€266.666,67
Micro Hydropower	€9.333,33	€50.000,00	€200.000,00
Ocean Power			
Organic Rankine Cycle (ORC) Systems	€22.857,14	€128.571,43	€571.428,57
Small Modular Reactors (SMRs) and Micro Reactors	€28.000,00	€180.000,00	€1.000.000,00
District Heating (4th Generation)	€6.000,00	€40.000,00	€240.000,00
District Heating and Cooling (5th Generation)	€2.857,14	€16.071,43	€71.428,57

Table 10: Total operational expenses for scales of implementation.

TECHNOLOGY	100MWh NET PROFIT/y	1GWh NET PROFIT/y	10GWh NET PROFIT/y
Biogas Production (Anaerobic Digestion)	-€23.714,29	-€80.000,00	€342.857,14
Bio-Oil Production (Pyrolysis)	-€48.000,00	-€255.000,00	-€800.000,00
Green Hydrogen Production (Electrolysis)	-€12.803,03	-€6.818,18	€840.909,09
Aquathermal Energy Systems	€3.818,18	€80.227,27	€1.109.090,91
Sewage Thermal Energy Systems	€5.333,33	€78.333,33	€977.777,78
Residual Heat Recovery Systems	€6.000,00	€90.000,00	€1.100.000,00
Geothermal Energy Systems (ATES/BTES)	€6.000,00	€93.333,33	€1.133.333,33
Absorption Cooling			
Air-to-Water Heat Pumps / Drycooler	€8.000,00	€92.222,22	€1.022.222,22
Solar Panels (PV)	€28.235,29	€288.235,29	€2.929.411,76
Solar Panels (PT)	€9.176,47	€99.411,76	€1.058.823,53
Solar Panels (PVT)	€12.088,24	€135.588,24	€1.473.529,41
Solar Panels (PC)			
Concentrated Solar Power (CSP)	-€3.000,00	€20.000,00	€600.000,00
Wind Energy Systems (Onshore)	€27.500,00	€283.333,33	€2.900.000,00
Small and Medium Wind Turbines (SMWT)	€24.000,00	€258.333,33	€2.733.333,33
Micro Hydropower	€20.666,67	€250.000,00	€2.800.000,00
Ocean Power			
Organic Rankine Cycle (ORC) Systems	€7.142,86	€171.428,57	€2.428.571,43
Small Modular Reactors (SMRs) and Micro Reactors	€2.000,00	€120.000,00	€2.000.000,00
District Heating (4th Generation)	€6.000,00	€80.000,00	€960.000,00
District Heating and Cooling (5th Generation)	€9.142,86	€103.928,57	€1.128.571,43

Table 11: Payback capacity for different scales of implementation.

3.4.4 Payback Periods and Scalability Factor

To evaluate how different technologies benefit from economies of scale, we calculated a scalability factor. This factor acts as a type of sensitivity parameter, quantifying the impact of scaling up a technology's deployment on its payback period.

The scalability factor is determined by typically calculating the difference in payback periods between the large community (10 GWh) and the small community (100 MWh), and then dividing this difference by the number of orders of magnitude in scale increase–two in most cases (10 GWh is 100 times the size of 100 MWh).

A higher scalability factor indicates that a technology benefits more from economies of scale, as its payback period decreases significantly with larger installations. Conversely, a low scalability factor suggests that the technology's financial performance is less sensitive to scaling, making it equally viable across different community sizes.

By including this parameter, we can identify which technologies are particularly well-suited for larger communities and which maintain consistent viability regardless of scale. This insight is critical for guiding investment strategies and optimizing technology deployment.

TECHNOLOGY	100MWh PAYBACK	1GWh PAYBACK	10GWh PAYBACK	SCALABILITY	
Biogas Production (Anaerobic Digestion)	x	x	83,3	41,7	BRONZE
Bio-Oil Production (Pyrolysis)	x	x	x	20,8	
Green Hydrogen Production (Electrolysis)	x	x	54,1	27,0	
Aquathermal Energy Systems	71,4	19,8	4,1	33,7	
Sewage Thermal Energy Systems	41,7	21,3	11,4	15,2	
Residual Heat Recovery Systems	50,0	22,2	9,1	20,5	
Geothermal Energy Systems (ATES/BTES)	33,3	14,3	5,9	13,7	
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	16,7	12,0	8,7	4,0	
Solar Panels (PV)	4,2	3,3	2,4	0,9	*unsensitive*
Solar Panels (PT)	15,4	11,8	8,9	3,2	
Solar Panels (PVT)	14,6	10,8	8,0	3,3	
Solar Panels (PC)					
Concentrated Solar Power (CSP)	x	200,0	50,0	75,0	SILVER
Wind Energy Systems (Onshore)	3,6	2,9	2,3	0,7	*unsensitive*
Small and Medium Wind Turbines (SMWT)	8,3	6,5	4,9	1,7	
Micro Hydropower	11,3	6,7	3,6	3,9	
Ocean Power					
Organic Rankine Cycle (ORC) Systems	80,0	25,0	11,8	34,1	
Small Modular Reactors (SMRs) and Micro Reactors	200,0	25,0	10,0	95,0	GOLD
District Heating (4th Generation)	40,0	25,0	16,7	11,7	
District Heating and Cooling (5th Generation)	15,6	10,3	6,3	4,6	

Table 12: Static payback periods for different scales of implementation.

3.4.5 Insights

The analysis of scalability factors reveals some interesting and noteworthy findings regarding which technologies benefit most from economies of scale. Among the technologies analyzed, the top three highest scalability factors are:

- SMRs – Gold Medal: SMRs demonstrate the highest scalability factor, as their payback period improves significantly with larger installations. This is due to their inherent design advantages, which include modular construction and high energy output that efficiently distributes fixed costs over large scales. Although we notice that Small Modular Reactor (SMR) and micro reactors are feasible starting from medium-sized communities (200-300 dwellings), the scalability factor indicates their huge potential for large-sized communities and beyond. **This advocates the use of SMR from medium-sized communities and nuclear energy in general for city-wide energy production**.
- CSP – Silver Medal: CSP systems also benefit strongly from scaling up. Larger installations take advantage of cost efficiencies in solar field deployment, storage integration, and advanced thermal systems, resulting in a substantially lower payback period for larger communities. Nevertheless, a large-sized community of 2000-3000 dwellings seems challenging in getting the payback period under 50 years, **this advocates the use of CSP in very large industrial or city-wide installations**.

- Biogas – Bronze Medal: Biogas production shows significant scalability benefits. Larger installations achieve higher efficiencies in feedstock processing and energy recovery, which drives improved financial performance at scale. Reflecting on the payback periods in the different sized communities, the same conclusion can be made as for CSP; **it advocates for the use of biogas production in industrial, city-wide and transport applications**.

We notice that bio-oil production is not feasible for the use in energy communities and that it needs to find its value in different markets. **These findings advocate bio-oil production for the use in the transport and materials industry**, e.g. within the circular economy like the company Renasci (subsidiary of Borealis) that has developed a process to produce plastics from bio-oil and vice versa.

Another of the key findings of this analysis is the relative insensitivity of PV solar panels and onshore wind turbines (excluding building-integrated SMWT systems) to economies of scale when deployed as local community energy sources. For solar PV systems, their modular design and scalability mean that financial performance remains relatively stable across small, medium, and large community sizes. Their simplicity, low maintenance costs, and straightforward deployment make them equally viable for small-scale installations in local communities or larger-scale systems for regional energy generation. However, their output is inherently limited by the available solar irradiation, making location the most critical factor for their effectiveness rather than the scale of the installation. Similarly, onshore wind turbines, when installed in suitable locations, exhibit minimal variation in financial performance across different scales, considering same wind technologies (height, blade length and power scale). It has to be noted that this does not take into account the benefit that you could have with the so called "super" wind mills that have much larger blades and power. The latter is more akin to offshore wind and is not evaluated in this thesis. Typical onshore wind mills are efficient even at smaller scales, provided the site conditions–such as wind speed, direction, and consistency–are optimal. While economies of scale can reduce costs for larger wind farms, the financial viability of wind energy remains primarily driven by the quality of the location rather than the size of the project. Combined with their low payback periods, **this advocates the use of PV solar panels and regular wind energy systems in all circumstances possible**. Note that conclusion is only valid when the value of the electrical energy is integrally valorized in a decentral system, avoiding the typical costs (and tax) of the national public grid.

The analysis shows that technologies such as aquathermal energy systems, sewage thermal systems, residual heat recovery, geothermal systems, ORC systems, and 4th generation district heating are most financially viable starting from medium-sized communities or those with an annual energy demand of approximately 1 GWh. These systems require sufficient scale to offset higher upfront costs and operational complexity. Medium-sized communities provide the demand needed to fully utilize their capacity and benefit from economies of scale, making them cost-effective. Smaller communities often lack the demand to justify the infrastructure, while medium-scale systems achieve the necessary balance for efficient operation. This highlights their strong potential as sustainable energy solutions for communities with moderate energy needs and beyond.

Finally, **5GDHC can already make financial and operational sense within small communities**, but this is highly dependent on the system's ability to operate without requiring additional active energy generation. The core advantage of 5GDHC lies in its design possibility to maintain a balanced network, where heating and cooling demands are buffered and redistributed efficiently within the system itself, without the need for external buffer systems or additional energy inputs. This balance, however, is only achievable in mixed-use developments with diverse energy demands. For instance, a community with a mix of residential, commercial, and industrial buildings can leverage the natural synergy between heating and cooling loads, ensuring the system remains in equilibrium. In contrast, mono-programmatic developments, such as purely residential communities, lack this diversity. The uniform demand patterns in such areas make it difficult for 5GDHC systems to achieve balance without requiring external energy inputs or additional storage infrastructure, reducing their cost-effectiveness and efficiency. Thus, while 5GDHC already has strong potential for small communities, its success hinges on the presence of diverse energy demands within the network, enabling it to operate as a self-regulating and balanced system.

3.5 Dynamic Turnover over 50 Years

3.5.1 Inflation and Discount Rate in the Dynamic Simulation

To ensure a realistic and commercially relevant analysis, we apply a 3% yearly price inflation for market prices and an 8% discount rate in our dynamic simulation. These parameters reflect both economic trends and the expectations of private investors, creating a robust framework for evaluating the financial potential of energy technologies over time.

The 3% yearly price inflation accounts for the steady increase in the value of energy outputs such as heat, electricity, hydrogen, and water. This rate is based on historical inflation trends in Europe and projections for the energy sector. It reflects the anticipated growth in energy prices driven by increasing demand for renewables, rising costs of fossil fuels due to decarbonization policies like the EU Emissions Trading System 2 (ETS2), and general economic inflation. This ensures our analysis captures long-term pricing realities in a future-proof manner.

The 8% discount rate is chosen to align with commercial viability and competitiveness in the global market. This rate reflects the opportunity cost of capital, where investments in energy technologies must deliver returns comparable to other commercial ventures. The global stock index, for instance, has historically averaged an 8% annual return, making this a logical benchmark for evaluating energy projects. Additionally, the discount rate accounts for the risks inherent in energy investments, including market fluctuations, policy changes, and technological adoption uncertainties. By setting the rate at 8%, the analysis remains grounded in real-world investment expectations.

Together, the 3% inflation rate and 8% discount rate provide a balanced and practical approach to dynamic financial modeling. They allow us to account for the rising value of energy outputs while ensuring the economic viability of investments, making this analysis a strong foundation for assessing the long-term potential of sustainable energy technologies.

3.5.2 Turnover Tables

The dynamic turnover potential in such a market, over 50 years, for the small-sized (100 MWh) communities, listed per year for heating/cooling, electricity and hydrogen, can be found in Table 13. The medium-sized, found in Table 14, and large-sized communities, found in Table 15, show a 10-, or 100-fold dynamic turnover potential respectively compared to the listed small-sized community.

ENERGY FORM	1	2	3	4	5	6	7	8	9	10
Heat/Cooling	€12.000	€11.444	€10.915	€10.409	€9.927	€9.468	€9.029	€8.611	€8.213	€7.833
Electricity	€30.000	€28.611	€27.287	€26.023	€24.818	€23.669	€22.574	€21.529	€20.532	€19.581
Hydrogen	€17.500	€16.690	€15.917	€15.180	€14.477	€13.807	€13.168	€12.558	€11.977	€11.422
	11	12	13	14	15	16	17	18	19	20
Heat/Cooling	€7.470	€7.124	€6.794	€6.480	€6.180	€5.894	€5.621	€5.361	€5.112	€4.876
Electricity	€18.675	€17.810	€16.986	€16.199	€15.449	€14.734	€14.052	€13.401	€12.781	€12.189
Hydrogen	€10.894	€10.389	€9.908	€9.450	€9.012	€8.595	€8.197	€7.817	€7.456	€7.110
	21	22	23	24	25	26	27	28	29	30
Heat/Cooling	€4.650	€4.435	€4.229	€4.034	€3.847	€3.669	€3.499	€3.337	€3.182	€3.035
Electricity	€11.625	€11.087	€10.573	€10.084	€9.617	€9.172	€8.747	€8.342	€7.956	€7.588
Hydrogen	€6.781	€6.467	€6.168	€5.882	€5.610	€5.350	€5.103	€4.866	€4.641	€4.426
	31	32	33	34	35	36	37	38	39	40
Heat/Cooling	€2.895	€2.761	€2.633	€2.511	€2.395	€2.284	€2.178	€2.077	€1.981	€1.889
Electricity	€7.236	€6.901	€6.582	€6.277	€5.987	€5.709	€5.445	€5.193	€4.953	€4.723
Hydrogen	€4.221	€4.026	€3.839	€3.662	€3.492	€3.331	€3.176	€3.029	€2.889	€2.755
	41	42	43	44	45	46	47	48	49	50
Heat/Cooling	€1.802	€1.718	€1.639	€1.563	€1.491	€1.422	€1.356	€1.293	€1.233	€1.176
Electricity	€4.505	€4.296	€4.097	€3.908	€3.727	€3.554	€3.390	€3.233	€3.083	€2.940
Hydrogen	€2.628	€2.506	€2.390	€2.279	€2.174	€2.073	€1.977	€1.886	€1.798	€1.715

Table 13: Dynamic turnover for five decades in a small community.

ENERGY FORM	1	2	3	4	5	6	7	8	9	10
Heat/Cooling	€120.000	€114.444	€109.146	€104.093	€99.274	€94.678	€90.295	€86.114	€82.128	€78.325
Electricity	€300.000	€286.111	€272.865	€260.233	€248.185	€236.695	€225.737	€215.286	€205.319	€195.813
Hydrogen	€175.000	€166.898	€159.171	€151.802	€144.774	€138.072	€131.680	€125.583	€119.769	€114.225
	11	12	13	14	15	16	17	18	19	20
Heat/Cooling	€74.699	€71.241	€67.943	€64.797	€61.797	€58.936	€56.208	€53.606	€51.124	€48.757
Electricity	€186.748	€178.102	€169.857	€161.993	€154.493	€147.341	€140.520	€134.014	€127.810	€121.893
Hydrogen	€108.936	€103.893	€99.083	€94.496	€90.121	€85.949	€81.970	€78.175	€74.556	€71.104
	21	22	23	24	25	26	27	28	29	30
Heat/Cooling	€46.500	€44.347	€42.294	€40.336	€38.468	€36.687	€34.989	€33.369	€31.824	€30.351
Electricity	€116.249	€110.867	€105.735	€100.840	€96.171	€91.719	€87.472	€83.423	€79.561	€75.877
Hydrogen	€67.812	€64.673	€61.679	€58.823	€56.100	€53.503	€51.026	€48.663	€46.410	€44.262
	31	32	33	34	35	36	37	38	39	40
Heat/Cooling	€28.946	€27.606	€26.328	€25.109	€23.946	€22.838	€21.780	€20.772	€19.810	€18.893
Electricity	€72.364	€69.014	€65.819	€62.772	€59.866	€57.094	€54.451	€51.930	€49.526	€47.233
Hydrogen	€42.213	€40.258	€38.395	€36.617	€34.922	€33.305	€31.763	€30.293	€28.890	€27.553
	41	42	43	44	45	46	47	48	49	50
Heat/Cooling	€18.019	€17.184	€16.389	€15.630	€14.906	€14.216	€13.558	€12.930	€12.332	€11.761
Electricity	€45.046	€42.961	€40.972	€39.075	€37.266	€35.541	€33.895	€32.326	€30.830	€29.402
Hydrogen	€26.277	€25.061	€23.900	€22.794	€21.739	€20.732	€19.772	€18.857	€17.984	€17.151

Table 14: Dynamic turnover for five decades in a medium community.

3.6 Dynamic Expenses over 50 Years

3.6.1 Replacement Costs

To streamline the dynamic simulation, we have chosen not to include replacement costs as separate expenditures. Instead, we have encapsulated these costs within the OPEX, which are subject to the same 3% yearly price inflation as other market parameters.

ENERGY FORM	1	2	3	4	5	6	7	8	9	10
Heat/Cooling	k€1144	k€1091	k€1041	k€993	k€947	k€903	k€861	k€821	k€783	k€747
Electricity	k€2861	k€2729	k€2602	k€2482	k€2367	k€2257	k€2153	k€2053	k€1958	k€1867
Hydrogen	k€1669	k€1592	k€1518	k€1448	k€1381	k€1317	k€1256	k€1198	k€1142	k€1089
	11	12	13	14	15	16	17	18	19	20
Heat/Cooling	k€712	k€679	k€648	k€618	k€589	k€562	k€536	k€511	k€488	k€465
Electricity	k€1781	k€1699	k€1620	k€1545	k€1473	k€1405	k€1340	k€1278	k€1219	k€1162
Hydrogen	k€1039	k€991	k€945	k€901	k€859	k€820	k€782	k€746	k€711	k€678
	21	22	23	24	25	26	27	28	29	30
Heat/Cooling	k€443	k€423	k€403	k€385	k€367	k€350	k€334	k€318	k€304	k€289
Electricity	k€1109	k€1057	k€1008	k€962	k€917	k€875	k€834	k€796	k€759	k€724
Hydrogen	k€647	k€617	k€588	k€561	k€535	k€510	k€487	k€464	k€443	k€422
	31	32	33	34	35	36	37	38	39	40
Heat/Cooling	k€276	k€263	k€251	k€239	k€228	k€218	k€208	k€198	k€189	k€180
Electricity	k€690	k€658	k€628	k€599	k€571	k€545	k€519	k€495	k€472	k€450
Hydrogen	k€403	k€384	k€366	k€349	k€333	k€318	k€303	k€289	k€276	k€263
	41	42	43	44	45	46	47	48	49	50
Heat/Cooling	k€172	k€164	k€156	k€149	k€142	k€136	k€129	k€123	k€118	k€112
Electricity	k€430	k€410	k€391	k€373	k€355	k€339	k€323	k€308	k€294	k€280
Hydrogen	k€251	k€239	k€228	k€217	k€207	k€198	k€189	k€180	k€172	k€164

Table 15: Dynamic turnover for five decades in a large community.

This approach simplifies the simulation by avoiding the need to account for specific replacement events, such as the renewal of components or subsystems, which can vary significantly depending on the technology and operational conditions. By embedding replacement costs into OPEX, we ensure these expenses are accounted for consistently over the lifetime of the project without adding unnecessary complexity to the model.

Additionally, since OPEX is subject to yearly price inflation, this method indirectly reflects the rising costs associated with future replacements. It provides a practical yet comprehensive way to account for ongoing operational and maintenance expenses while keeping the simulation manageable and focused on the overall economic feasibility of each technology.

This simplification does not compromise the accuracy of the analysis but rather aligns with the objective of providing a clear and efficient framework for evaluating the long-term payback potential of sustainable energy technologies.

3.6.2 Discounting Consequences

By applying an 8% discount rate in our dynamic simulation, the importance of future turnover diminishes over time, as does the significance of future costs. This is because, with a high discount rate, the present value of cash flows in the distant future becomes relatively small compared to those in the near term. As a result, business cases for energy technologies tend to have a limited time horizon when viewed purely from a financial profits perspective.

However, this financial perspective can be nuanced when incorporating ecological benefits into an Social Cost Benefit Analysis (SCBA). While financial models emphasize short-to medium-term viability, an SCBA accounts for the broader societal value of environmental benefits, such as reduced carbon emissions, energy independence, and long-term sustainability. These ecological advantages often extend beyond the immediate profitability window and can justify investments with longer time horizons.

We therefore analyze the minimum time horizon required for financial viability in this dynamic context. By identifying the point at which a project becomes profitable from a purely financial standpoint, we establish a baseline for evaluating the economic potential of each technology. This provides valuable insight into how financial and ecological considerations interact, helping decision-makers balance profitability with sustainability goals.

3.7 Total DCF-results and Dynamic Payback Periods

To evaluate the financial performance of each technology, we calculated the dynamic payback period using a comprehensive Discounted Cash Flow (DCF) model. This approach accounts for the time value of money by discounting both turnover and expenses to their present value, providing a realistic view of profitability over time.

In the DCF model:

- Yearly net profits are calculated as the difference between discounted turnover and discounted expenses.
- These yearly net profits are accumulated to calculate the Net Present Value (NPV).
- The dynamic payback period is identified as the point where the cumulative NPV equals 0, meaning the initial investment has been fully recovered under the assumed rate of return.

We used an 8% discount rate, reflecting commercial investment expectations and aligning with typical returns in global markets. Additionally, the NPV at the end of the 50-year time horizon provides further insights [64]:

- A positive NPV at the end of 50 years indicates the viability of the technology and its potential to generate returns above the required rate.
- A negative NPV would suggest that the technology may not be financially sustainable under the given conditions, with expanding to an SCBA context.

This method not only determines the payback period but also highlights the long-term profitability of each technology, offering a robust framework for evaluating their financial viability and potential for higher returns.

The findings of the dynamic simulation align closely with those of the static payback period analysis, confirming the overall trends in financial viability across the technologies. However, the results from the dynamic simulation are generally more conservative, reflecting the influence of the 8% discount rate used to account for the time value of money and commercial expectations. In the static analysis, payback periods are calculated without considering discounting, providing a straightforward measure of how quickly the initial investment is recovered. In contrast, the dynamic simulation incorporates the opportunity cost of capital, making it more representative of a real-world commercial perspective. As a result, the dynamic payback periods are slightly longer, particularly for technologies with significant returns in later years, as future profits are discounted and carry less weight in the analysis. This consistency between the two approaches strengthens the reliability of the findings, while the dynamic simulation adds depth by highlighting the financial viability of the technologies in a commercial context. This perspective is crucial for guiding invest-

TECHNOLOGY	100MWh PAYBACK	1GWh PAYBACK	10GWh PAYBACK
Biogas Production (Anaerobic Digestion)	SCBA	SCBA	SCBA
Bio-Oil Production (Pyrolysis)	SCBA	SCBA	SCBA
Green Hydrogen Production (Electrolysis)	SCBA	SCBA	SCBA
Aquathermal Energy Systems	SCBA	SCBA	5
Sewage Thermal Energy Systems	SCBA	SCBA	18
Residual Heat Recovery Systems	SCBA	SCBA	13
Geothermal Energy Systems (ATES/BTES)	SCBA	23	8
Absorption Cooling			
Air-to-Water Heat Pumps / Drycooler	32	18	12
Solar Panels (PV)	5	4	3
Solar Panels (PT)	27	17	13
Solar Panels (PVT)	24	15	11
Solar Panels (PC)			
Concentrated Solar Power (CSP)	SCBA	SCBA	SCBA
Wind Energy Systems (Onshore)	4	4	3
Small and Medium Wind Turbines (SMWT)	11	8	6
Micro Hydropower	16	8	5
Ocean Power			
Organic Rankine Cycle (ORC) Systems	SCBA	SCBA	19
Small Modular Reactors (SMRs) and Micro Reactors	SCBA	SCBA	15
District Heating (4th Generation)	SCBA	SCBA	37
District Heating and Cooling (5th Generation)	28	14	8

Table 16: Dynamic payback potential for different scales of implementation.

ment decisions, ensuring a realistic understanding of the long-term economic performance of each technology.

3.8 Energy Storage or Buffer Systems

We evaluate energy buffer systems independently of community size. These systems, such as Thermal Energy Storage (TES) and BESS, typically account for only a fraction of the total energy consumption of a community. Despite their smaller scale relative to energy production, they still benefit from economies of scale, as larger installations often achieve lower costs per unit of capacity, leading to better payback periods.

3.8.1 Neutral Energy Cost

Since buffers do not produce energy but only store it, their financial feasibility is highly dependent on the cost of storing or purchasing energy. For the purposes of this analysis, we assume that energy is only stored when it is available at no cost (i.e., "free" surplus energy). This is a realistic standpoint for most energy systems, as effective energy management seeks to utilize excess energy from renewable sources or other low-, or negative-cost periods. However, it is important to note that there are scenarios where buffers must store energy regardless of cost, particularly when tied to specific Service Level Agreements (SLAs). For example, if a buffer system is part of critical infrastructure, it may need to maintain a minimum energy reserve, even if it requires purchasing energy at prevailing market rates. Conversely, effective energy management can turn buffers into assets. For instance, during periods of negative electricity prices–an increasingly common phenomenon in energy markets due to renewable overproduction–buffer systems can store energy and even be paid to consume it. This capability highlights the dual financial potential of energy buffers: they can reduce costs by storing surplus energy and generate revenue under favorable market conditions.

3.8.2 Usage Cycles

A critical factor influencing the financial performance of buffer systems is the number of cycles they complete each year. The frequency of charge and discharge cycles directly affects the system's ability to generate value by storing and releasing energy. Important examples are:

- For STES systems, such as pit thermal storage or rock cavern storage, cycling is typically limited to one or two times per year, aligning with seasonal heating and cooling demands. Their financial viability is therefore more constrained and heavily dependent on the cost-effectiveness of storing energy over long durations.
- In contrast, BESS, when managed effectively, can cycle daily–achieving up to 365 cycles per year. This high cycle frequency allows BESS to generate consistent value, either by participating in grid services (e.g., frequency regulation [120]) or through energy arbitrage (storing cheap energy and discharging during peak price periods).

The difference in cycle frequency highlights why some buffer systems, like BESS, are more versatile and can achieve faster payback periods, while others, like STES systems, are more suited for specific, long-term applications. By integrating cycle usage into our analysis, we ensure that the financial viability of each buffer system is evaluated within the context of its intended use case and operational dynamics. This comprehensive perspective emphasizes the importance of smart energy management and application-specific strategies in optimizing buffer performance.

3.8.3 Findings

Under the conditions outlined in our analysis, sand thermal energy storage emerges as a technology with significant untapped potential. Its simplicity, cost-effectiveness, and scalability make it a promising solution for thermal energy storage. A notable example is the sand battery pilot project in Finland, developed by Polar Night Energy. In this project, sand is heated using electrical resistance heating during periods when electricity prices are negative or exceptionally low, storing thermal energy for later use. The sand battery, installed in a district heating network, can reach temperatures of up to 500–600°C and stores energy with minimal losses for extended periods. This stored heat is then used to supply district heating during colder months, effectively balancing the system. The project demonstrates how sand storage can efficiently transform surplus renewable energy, such as wind or solar power, into a valuable resource for heating, reducing waste and increasing energy system resilience. The combination of low material costs, high-temperature capability, and straightforward design positions sand storage as an ideal technology for buffering renewable energy surpluses, especially in regions with frequent overproduction. The ability to store energy during off-peak periods and release it when needed offers a practical and financially viable solution for balancing energy systems.

For other TES technologies, our findings reveal that payback periods increase with system complexity:

TECHNOLOGY	CYCLES	TYPE	TURNOVER/MWh	CAPEX (€/kWh)	OPEX in %	COST/MWh	PAYBACK
Seasonal Thermal Energy Storage (PTES)	2	heat/cooling	€240	4	0,50%	€4.020	17
Seasonal Thermal Energy Storage (Tank)	2	heat/cooling	€240	8	1,00%	€8.080	34
Seasonal Thermal Energy Storage (Rock Cavern)	2	heat/cooling	€240	3	0,50%	€3.015	13
Thermal Buffer (Ice Storage)	50	heat/cooling	€6.000	250	1,50%	€253.750	42
Thermal Buffer (Sand Storage)	100	heat	€12.000	20	1,00%	€20.200	2
Thermal Buffer (Molten Salt)	50	heat	€6.000	50	1,50%	€50.750	8
Thermal Buffer (PCMs)	200	heat/cooling	€24.000	150	2,00%	€153.000	6
Battery Energy Storage Systems (BESS)	365	electricity	€109.500	900	2,00%	€918.000	8

Table 17: Static payback of energy storage and buffer systems.

- Ice Storage and TTES, while versatile and well-suited to specific applications, involve higher costs for materials, insulation, and advanced integration. These added complexities drive up upfront investments and operational expenses, leading to longer payback periods.
- In contrast, sand storage benefits from its low-cost materials and relatively simple system design, resulting in shorter payback periods and higher financial viability.

The example of the sand battery from Polar Night Energy underscores the scalability and practicality of sand storage for addressing energy storage needs. Its ability to harness negative electricity prices, reduce reliance on fossil fuels, and seamlessly integrate with district heating systems highlights its broad potential. As the global energy transition accelerates, sand storage presents a cost-effective and scalable solution for optimizing renewable energy use and balancing thermal energy systems.

3.9 Greywater Regeneration

In Flanders, the average person uses approximately 119 liters of water per day, according to data from *Vlaams kenniscentrum en overlegplatform voor water*
Flemish knowledge centre and discussion platform for water (VLARIO). However, a detailed breakdown of this consumption reveals a striking opportunity for resource optimization through water reuse, particularly in the context of decentralized water systems.

A significant share of this daily use–up to 64 liters per person per day–is for non-potable purposes such as toilet flushing, laundry, and cleaning. These uses do not require drinking-quality water and could therefore be supplied by regenerated greywater or harvested rainwater. Meanwhile, only 3 liters per day, or roughly 2,5% of total consumption, are used for cooking and drinking, which truly necessitate high-quality potable water.

In terms of greywater regeneration, activities like personal hygiene (showers, baths, sinks) and, to a lesser extent, dishwashing, can produce an estimated 47 liters of reusable water per person per day. When appropriately filtered and treated, this water can be repurposed to meet much of the non-potable demand–especially for toilet flushing, which alone accounts for 43 liters per day and is typically discharged as black water. While toilet flushing itself creates black water, it does not require potable input and is ideally suited to be supplied by treated greywater or rainwater, reducing the burden on the drinking water network.

This clear separation between water quality needs and usage types opens up a compelling business case for Water Service Companies (WASCOs). These companies can provide on-site greywater recycling systems–such as compact Membrane Bio Reactors (MBRs)–to treat and redistribute greywater within residential buildings. By doing so, WASCOs not only support sustainable water use but also reduce operational costs for residents and municipalities, alleviate pressure on public water infrastructure, and contribute to climate resilience in urban environments.

As regulatory frameworks increasingly recognize the need for circular water systems, and with technologies reaching commercial maturity, WASCOs are positioned to play a pivotal role in transforming the built environment. Their services can bridge the gap between traditional centralized utilities and the need for decentralized, adaptable, and environmentally responsible water solutions [39].

3.9.1 CAPEX

Greywater regeneration systems are gaining traction as a practical and sustainable way to reduce drinking water use and promote circularity in residential developments. These systems, often based on MBR technology, enable treated wastewater from showers, sinks, and laundry to be reused for non-potable purposes such as toilet flushing, irrigation, or cleaning. While the core technology is well-established, the CAPEX varies considerably depending on the scale of the community and the volume of greywater to be treated daily.

For a small-sized community of approximately 20 to 30 dwellings, the expected volume of greywater generation and treatment is around 3 cubic meters per day. At this scale, the system typically consists of a compact, pre-assembled MBR unit with minimal automation, suitable for installation in a shared technical room or outdoor enclosure. These small systems are ideal for cohousing projects, eco-villages, or off-grid developments focused on water self-sufficiency. However, due to limited economies of scale, the CAPEX tends to be relatively high–ranging from €50.000 to €80.000, or approximately €16.000 to €27.000 per m^3/day of capacity. Despite the higher unit costs, the value lies in independence, reduced water bills, and alignment with sustainability goals.

A medium-sized community, comprising 200 to 300 dwellings, would generate and need to treat around 30 cubic meters of greywater per day. This corresponds to a population of roughly 500 to 750 residents. At this level, the greywater system benefits significantly from scale: modular, containerized MBR units are typically used, often equipped with automated controls, Ultraviolet (UV) disinfection, and buffer tanks. These systems are centrally located and can be integrated into new development master plans. CAPEX for such systems ranges between €250.000 and €450.000, bringing the cost per m^3/day down to €8.000 to €15.000. This scale is ideal for new residential zones, apartment complexes, or mixed-use developments aiming for circular water strategies.

For a large-scale community of 2.000 to 3.000 dwellings, the daily greywater volume reaches around 300 cubic meters. At this scale, industrial-grade MBR systems are custom engineered to meet higher reliability, treatment quality, and capacity needs. The system may also include features such as SCADA monitoring, energy-efficient aeration, sludge handling, and integration with rainwater harvesting or district energy systems. CAPEX for such large-scale installations typically ranges from €1,8 million to €3 million, with a cost per m^3/day of just €6.000 to €10.000. These large systems are economically efficient and well-suited for urban districts, institutional campuses, or Public Private Partnership (PPP) developments.

In conclusion, as greywater volumes scale with community size, the unit cost of treatment decreases, making large and medium-sized systems significantly more cost-effective per cubic meter of water processed. While small-scale systems offer flexibility and independence, larger systems benefit from integration and efficiency. This creates a clear business case for WASCOs to develop greywater regeneration services as part of future-proof infrastructure. By tailoring system design to the specific needs of small, medium, or large communities, WASCOs can deliver water solutions that are not only environmentally responsible but also financially viable–paving the way for more circular and resilient urban development.

3.9.2 OPEX

In addition to capital costs, the OPEX of greywater regeneration systems plays a key role in long-term feasibility–especially for WASCOs operating under service-based models. As systems scale up, OPEX per cubic meter of treated water tends to decrease significantly due to automation and economies of scale.

For a small-scale system treating around 3 m^3/day (20–30 dwellings), annual OPEX typically ranges from €1.500 to €3.000, or roughly €1,40 to €2,70 per m^3. These costs cover periodic maintenance, energy use, and basic monitoring. While unit costs are higher due to the smaller volume, the simplicity of these systems helps keep operational demands relatively low.

At the medium scale (30 m^3/day, serving 200–300 dwellings), centralized systems with automated controls can operate for €8.000 to €15.000 per year, translating to €0,70 to €1,40 per m^3. These systems are more efficient, with longer membrane lifespans, lower labor input per unit of water, and improved energy use.

For large-scale systems treating 300 m^3/day (2.000–3.000 dwellings), OPEX can be as low as €0,50 to €1,00 per m^3, or €55.000 to €110.000 per year. These installations are typically fully automated, remotely monitored, and integrated into broader facility or district management systems, which allows for high reliability at low marginal cost.

In summary, as with CAPEX, OPEX improves significantly with scale. For WASCOs, this creates opportunities to offer competitively priced services in larger developments, while still maintaining viable models for smaller communities through simplified system design and optimized maintenance. Low and predictable OPEX is key to ensuring that greywater reuse becomes a practical and affordable part of sustainable urban living.

3.9.3 Findings

Assuming a resale or offset value of €4 per cubic meter, the static payback period for greywater systems varies significantly with scale.

For a small system treating 3 m^3/day (20–30 dwellings), annual net savings are around €2.130, resulting in a payback period of 23,5 years. This makes it borderline financially viable, and its justification often relies more on sustainability goals or regulatory incentives than pure return on investment. However, if the effective value of reused water increases to €5/m^3, the payback period improves to 15,5 years, making it more acceptable for long-term community-focused developments.

Medium systems (30 m^3/day) reach a payback in just 3,7 years, while large-scale systems (300 m^3/day) pay back in only 1,7 years–highlighting strong economies of scale. These figures confirm that while small systems remain marginal, medium and large greywater installations are clearly financially attractive, especially within decentralized WASCO-operated service models.

3.10 Financing

Securing financing is a critical step in the development and scaling of USCOs, especially as they aim to implement capital-intensive infrastructure like greywater systems, heating networks, and decentralized utilities. The financial structure must balance upfront investment, operational income, and long-term returns–while remaining compliant with regulatory frameworks.

This subsection outlines three key aspects of financing: the use of bank loans, the role and sources of equity contributions, and the challenges USCOs face in aligning financial models with both lender expectations and legal constraints. Together, these topics provide a foundation for understanding how USCOs can structure financially viable, scalable, and socially inclusive projects.

3.10.1 Bank Loans

For USCOs, financing through a bank loan is often a strategically sound decision, particularly when the non-financed Internal Rate of Return (IRR) is already around or above 8%. While a bank loan does not reduce the static payback period–which is still determined by the full capital cost and annual net savings–it can improve the dynamic payback period and significantly enhance return on equity [118].

In today's financial context, this makes even more sense. With current interest rates at approximately 3,5%, and the project already delivering an unleveraged IRR of 8%, there is clear room to improve financial performance through the use of debt. By substituting part of the upfront equity investment with bank loans, USCOs can retain more capital, improve capital efficiency, and boost the leveraged IRR well above 8%, depending on the financing structure.

This approach also brings operational advantages. In service-based models, financing enables USCOs to align debt repayments with incoming revenue streams from end-users. This can produce positive cash flow from year one, and in many cases, shorten the dynamic payback period when measured in discounted cash flow terms.

Moreover, financing provides an opportunity to scale faster, deploying multiple systems in parallel without overextending equity. This is particularly important in the utility sector, where infrastructure investments are capital-intensive but yield relative predictable, long-term returns.

3.10.2 Equity

When financing a project through a bank loan, it is always necessary to provide an equity contribution. Banks require this as a sign of financial commitment and to reduce their risk exposure. This equity is typically used to cover a portion of the total project cost–often between 10% and 30%–before the bank will release loan funds.

This equity contribution doesn't have to come solely from the USCO's own cash reserves. While self-financing is the most straightforward option, it is not the only one. USCOs can also raise this equity portion through alternative financial instruments, though each comes with its own implications.

One option is to use subordinated loans or subordinated bonds. These are forms of debt that rank below the senior bank loan in case of default. Because of the higher risk involved for the lender, subordinated financing usually carries higher interest rates than senior loans–often well above the typical 3,5% bank rate.

A more collaborative and often socially aligned alternative is to structure the USCO as a (partially) cooperative entity. In this model, end users–such as residents or building owners–become co-owners of the USCO by purchasing a small share [89]. Their investment can be counted as equity, reducing the need for internal capital or subordinated debt. In return, they benefit not only from cheaper and more sustainable utility services (e.g. water, energy, mobility), but also from a share in the profits generated by the USCO. This fosters long-term engagement, democratic oversight, and aligns user and operator interests.

Beyond equity requirements, banks place significant emphasis on a project's Debt Service Coverage Ratio (DSCR)–arguably the most important financial metric in project finance. DSCR measures the project's ability to generate sufficient cash flow to meet its debt obligations and is defined as:

$$\text{DSCR} = \frac{\text{CFADS}}{\text{Debt Service}} = \frac{\text{Cash Flow Available for Debt Service}}{\text{Interest Payments} + \text{Principal Repayments}}$$

Banks typically require a minimum DSCR of 1,2, meaning the project must generate at least 20% more cash than is needed to cover scheduled debt payments. This provides a cushion to absorb unforeseen operational or market disruptions and ensures that debt service remains secure even in suboptimal conditions.

To assess this, lenders analyze the project's free cash flows over time. From these cash flows, they deduct interest and principal obligations, and apply the DSCR threshold to determine how much debt the project can realistically support. This process, known as debt sizing, essentially works backward: starting from projected cash flows, the bank calculates the maximum debt capacity the project can sustain while maintaining a minimum DSCR. If the repayment is structured as annuities or linear principal payments, this directly shapes the loan amount that can be offered.

Assuming tax is optimized, i.e. taxes become negligible through depreciation and "upstreaming profits" to a parent holding (of course compliant to Base Erosion and Profit Shifting frameworks), and working capital changes are minimal, the Net Operating Income we see in the static payback tables are basically equal to the Cash Flow Available for Debt Service (CFADS).

Ultimately, while equity sources define the initial financial structure, it is the project's ability to reliably service debt from operating cash flow that determines how much financing is feasible. A strong DSCR not only improves bankability but may also allow for more favorable loan terms, such as lower interest rates or longer maturities–both of which reduce the financial burden on the USCO and improve long-term viability.

3.10.3 Weighted Average Cost of Capital

When evaluating an investment project, the Weighted Average Cost of Capital (WACC) represents the average rate the USCO must pay to finance its assets, weighted by the proportion of each capital component–typically equity, subordinated debt, and senior debt. It reflects the minimum return a project must generate to satisfy all capital providers.

In a situation where a project is fully equity-financed, meaning no debt is used, the WACC is simply equal to the required return on equity. This is because the entire capital base comes from equity holders, and thus no weighting is applied to cheaper sources of funding such as bank debt. For example, if the investor demands an 8% return on equity and uses only their own capital, the project's WACC is also 8%. Important to mention is that many investors will demand higher than 8% return, as the USCO is exposed to a higher risk than the global market, like the MSCI world index or FTSE.

However, introducing leverage–for instance, by financing part of the investment with bank debt–can reduce the WACC, provided the cost of debt is lower than the cost of equity. Bank loans typically carry lower returns (e.g., 4–6%) compared to equity, due to lower risk and seniority in repayment. By replacing part of the expensive equity with cheaper debt, the overall weighted cost of capital is reduced. This means the same project cash flows are now being discounted at a lower rate, increasing the project's NPV and potentially improving the return on equity (equity IRR), as less capital is invested for the same or greater financial benefit. This allows to target higher returns, often going to 10–15% equity IRR.

The WACC reflects the average rate a company is expected to pay to finance its assets, weighted by the proportion of each source of capital. When the capital structure includes equity, subordinated debt, and senior debt, the WACC is calculated as follows:

$$\text{WACC} = \left(\frac{E}{V} \times r_e\right) + \left(\frac{SD}{V} \times r_{sd} \times (1-T)\right) + \left(\frac{D}{V} \times r_d \times (1-T)\right)$$

Where:

- E: Market value of equity (common shareholders' capital)
- SD: Market value of subordinated debt (e.g., mezzanine financing or shareholder loans)
- D: Market value of senior debt (typically bank loans)
- $V = E + SD + D$: Total capital (sum of all financing sources)
- r_e: Required return on equity
- r_{sd}: Cost of subordinated debt
- r_d: Cost of senior debt
- T: Corporate tax rate (applied as a shield on interest expenses)

As a realistic example at current times, in case we finance 70% at an interest rate of 3,5%, 2/3rd of the equity (20% of the total volume) as subordinated bonds/loans at 8%, the shareholders equity at 12%, and assuming 25% of tax rate, we are able to reduce the WACC from 8 to 5,25%.

$$\text{WACC} = \left(\frac{10}{100} \times 12\%\right) + \left(\frac{20}{100} \times 8\% \times (1 - 25\%)\right) + \left(\frac{70}{100} \times 3.5\% \times (1 - 25\%)\right) = 5.25\%$$

Getting subordinated bonds or loans for a USCO at 8% (in Belgium) is realistic in the form of crowd funding. If you step to private equity, this will more be in the range of 12% minimum. If the USCO sets the project up as a (partial) cooperative Special Purpose Vehicle (SPV), the cooperants (shareholding members) will typically be satisfied with a return slightly above the return of government bonds, i.e. currently 4%. Participation of the end-user is often a good idea, not only for optimizing the WACC, but also to create a sense of community and gain widespread support for the project.

3.10.4 Challenges

Creating a complete financing plan for a USCO project involves a number of structural challenges, particularly when engaging with banks. In most cases, banks assess USCOs as "cash flow projects", meaning they focus less on the asset itself and more on whether the expected cash flow from users will reliably cover operating costs and loan repayments. This typically requires the USCO to sign contracts with end users that include predictable, fixed monthly fees, which provide the stable income stream banks expect.

However, this clashes with Flemish regulations on thermal energy and hot water billing. According to *Vlaamse Nutsregulator*
Flemish Utility Regulator (VNR) (new name since Jan 1st 2025), at least 40% and up to 90% of the cost charged to end users must be variable, based on actual consumption. The remaining portion–between 10% and 60%–can be fixed. This regulatory requirement ensures fairness and incentivizes efficient energy use, but it limits the extent to which USCOs can rely on fixed income, thereby making financing through banks more complex.

For smaller-scale projects, this creates a particular difficulty. With lower loan amounts, banks are often unwilling to conduct detailed due diligence and tend to apply rigid cash flow criteria, insisting on strong, fixed income contracts to reduce risk. The *VNR* restriction thus directly impairs the project's financeability at small scales.

In contrast, larger projects–with higher capital needs–tend to attract more detailed scrutiny from financial institutions. Banks are more willing to assess the entire business model, beyond just fixed versus variable income. In these cases, the project is treated more as a business case rather than a pure cash flow project, and the regulatory constraint becomes less critical.

3.10.5 Leveraged Return Example

In this example, we assess the financial structure of a medium-scale geothermal energy project designed to serve a community of approximately 200 to 300 dwellings, with an expected annual energy demand of around 1 GWh. The total investment cost is estimated at €1.333.333. When financed entirely with equity, the project generates an annual net cash flow, or CFADS, of €93.333, resulting in a project IRR of 8% over a period of 23 years.

$$\text{IRR} = 8\%, \quad \text{CFADS} = €93.333$$

This IRR aligns with the required return used to discount future cash flows, meaning the NPV of the project over 23 years is zero:

$$\text{NPV} = \sum_{t=1}^{23} \frac{\text{CFADS}_t}{(1+r)^t} - I_0 = 0, \quad \text{where } r = 8\%,\ I_0 = €1.333.333$$

At this point, the return reflects the opportunity cost of capital without any financial leverage.

To improve the capital efficiency of the project, we introduce a typical project finance structure, leveraging future cash flows through a combination of senior bank debt and subordinated cooperative capital. With a conservative DSCR of 1,25 and a bank interest rate of 3,5%, the project can support approximately €1.166.320 in senior debt:

$$\text{DSCR} = \frac{\text{CFADS}}{\text{Debt Service}} = 1,25 \quad \Rightarrow \quad \text{Debt Service} = \frac{€93.333}{1,25} = €74.666$$

Using the annuity formula to solve for the loan amount L:

$$A = L \cdot \frac{r(1+r)^n}{(1+r)^n - 1} \quad \Rightarrow \quad L = \frac{A}{\frac{r(1+r)^n}{(1+r)^n - 1}}$$

$$\text{With } A = €74.666,\ r = 3,5\%,\ n = 23 \Rightarrow L \approx €1.166.320$$

This covers about 87,5% of the total investment, leaving the remaining 12,5%–roughly €167.000–to be covered by equity-like contributions.

To satisfy this equity requirement in a socially inclusive way, the structure assumes that half of the remaining capital–about €83.500–is provided by end users in the form of subordinated cooperative loans at a fixed return of 5%. The final €83.500 is contributed by the main shareholders as pure equity.

Thanks to this layered financing model, the main equity holders benefit from significantly leveraged returns. Although the overall project IRR remains 8%, the effect of replacing a large portion of expensive equity with lower-cost senior and subordinated debt leads to a much higher return on the actual equity at risk. In this case, the equity IRR for the main shareholders increases to:

$$\text{Equity IRR (main shareholders)} = 16,3\%$$

–more than double the return they would have achieved under a fully equity-financed scenario. This illustrates a fundamental principle of project finance: if a project generates stable and predictable cash flows, financial leverage can dramatically improve equity returns, as long as debt service obligations are carefully structured within acceptable DSCR limits. Moreover, by incorporating cooperative capital from future users as subordinated obligations, the project not only becomes more financially viable, but also fosters user ownership, social inclusion, and long-term alignment between the community and the project's financial structure.

4 Political and Legal Context

As the transition to sustainable urban utility services accelerates, navigating the political and legal framework becomes increasingly complex. This chapter explores the regulatory environment in Flanders and the broader European context, with a focus on how it affects the development and deployment of USCOs. It examines critical legal challenges related to energy, water, mobility, and materials, and highlights the tensions between outdated regulatory structures and emerging decentralized, multi-utility models. While the chapter provides an in-depth analysis, it should be noted that the overview is far from exhaustive, reflecting the rapidly evolving nature of the legal landscape in this field.

4.1 Permit Complexity

Table 18 provides an overview of various renewable and sustainable energy technologies, detailing their associated permit complexity, types of required permits, relevant legislation or standards, and the key agencies involved in the permitting or advisory processes. It serves as a general guide to the regulatory landscape for these technologies. However, it is important to note that this list is far from exhaustive and may not in all situations capture all possible requirements.

4.2 Legal Issues for Energy

Establishing an Energy Service Company (ESCO) or USCO in Flanders (Belgium) involves navigating a complex and often outdated legal framework, particularly when the focus is on private energy distribution and decentralized infrastructure. This is especially relevant in cases involving private distribution networks (*privédistributienetten*), where energy is generated and consumed locally–typically within the same residential or commercial development. While such local systems offer clear technical and ecological advantages, they clash with existing Flemish and European regulatory structures, which are largely designed for centralized, utility-driven models.

4.2.1 Local Energy Production

A typical example illustrates the core of the problem: An ESCO installs a large PV installation on a multi-unit residential building, combined with a collective heat pump for shared heating and cooling. During daylight hours, the PV panels often generate excess electricity, which–technically–could be redistributed among the building's residents.

However, under current Flemish and EU legislation, this internal redistribution is legally complex or outright forbidden. Without being a licensed energy supplier or grid operator, the ESCO is not permitted to distribute electricity to multiple end-users, even within the same physical structure. In practice, this means that excess locally generated electricity cannot be shared, even though no external grid infrastructure is used.

4.2.2 Energy Communities

One alternative permitted under the EU Clean Energy Package and Flemish transpositions is the creation of a formal energy community (*energiegemeenschap*) [32]. Through coordination of several connection IDs (EAN numbers) of digital meters with Fluvius, the regional Distribution System Operator (DSO), local actors can collectively share energy.

While this theoretically enables internal sharing of energy, it comes with a significant caveat: distribution and transmission tariffs still apply, even when the energy remains physically inside the building. This creates a paradox: local energy is economically treated as if it had traveled through the public grid, despite using none of its infrastructure. As a result, the economic case for such community energy models is weakened.

4.2.3 Closed Distribution Networks

A rarely applied legal construct that could potentially address this issue is the closed distribution network (*Gesloten Distributienet*). This status allows for private distribution of electricity within a confined, functionally integrated area–such as an industrial zone or hospital campus–without needing to follow the same regulations as public Distribution System Operators (DSOs).

While conceptually useful, this model is difficult to obtain for residential or mixed-use developments. The approval process is strict, the operational requirements are high, and regulators are cautious to avoid the fragmentation of grid oversight. For most ESCO and USCO initiatives, especially those that are residential or semi-public, this legal route is impractical.

4.2.4 Legal Complications of Ground Infrastructure

Adding another layer of complexity, many new developments involve the transformation of private land into public domain–particularly for roads, parks, sidewalks, and public utilities. This introduces significant legal and operational challenges for ESCOs and USCOs seeking to lay cables, heating pipes, or borehole infrastructure in these areas.

4.2.5 KLIP and KLB Obligations

Once any infrastructure (such as a district heating pipe or a geothermal borehole field) passes through public domain, the ESCO or USCO becomes subject to obligations under the *Kabels, Leidingen en Informatieportaal*
Cables, Pipes and Information Portal (KLIP) framework [63]. They must:

- Register as a *Kabels en Leidingbeheerder*
  Cables and Pipes Manager (KLB),
- Provide detailed maps and technical plans of their underground infrastructure,
- Respond to information requests whenever public works are planned near their installations,
- Bear liability for damages or interference with public projects.

This transforms the ESCO from a technical facilitator into a regulated utility infrastructure operator, with all the administrative burdens that entails.

4.2.6 The Borehole Dilemma

One of the most pressing cases involves geothermal borehole fields used in collective heat pump systems. These fields cannot always be located beneath buildings, due to space, structural, water or timing constraints. As a result, they must be installed in surrounding ground, which in new developments often becomes public domain (e.g., under roads or sidewalks).

This leads to legal and operational conflicts:

- Municipalities are hesitant to allow borehole installations under public domain due to liability concerns [111].
- If a road subsides, it becomes difficult to determine whether the issue stems from public infrastructure failure or e.g. a leak in the private borehole field.
- Responsibility for repair costs in such scenarios is often disputed.

- When the borehole system needs maintenance or repair, the public domain must be opened, raising further complications:
  - If the private party performs the works, the municipality questions whether the repair is done professionally and whether the public domain is restored to its original quality.
  - If the public authority carries out the works, a public procurement process is typically required, resulting in significant delays for the ESCO or USCO.

To mitigate this, some legal experts propose a "horizontal property split", where private rights only start from a certain depth below the public domain (e.g., one meter underground), allowing private infrastructure ownership without affecting the surface. However, this solution is often met with resistance by municipalities, due to the potential for entanglement with existing public utilities and the aforementioned complex liability scenarios.

4.2.7 Broader Regulatory Hurdles

In addition to the above, USCOs in Flanders face a multitude of additional regulatory issues:

- Licensing as Energy Supplier: Legal access to supply energy to third parties is strictly regulated and typically reserved for entities licensed by *VNR*.
- Grid Connection Complexity: The limited flexibility of Fluvius in enabling custom grid arrangements hampers innovation in local systems.
- Billing and Taxation: Shared systems need to manage individual billing, smart metering, and Value Added Tax (VAT) compliance, often without access to necessary metering infrastructure.
- Consumer Rights Legislation: Any service provided to end-users must comply with strict consumer protection rules, even within a single building or community.
- State Aid and Market Distortion Risks: When municipalities or public actors support these initiatives, EU competition law may trigger scrutiny.

4.2.8 Future Outlook

Since January 1st, 2025, the *Vlaamse Regulator van de Elektriciteits- en Gasmarkt Flemish Regulator for the Electricity and Gas market (VREG)* has officially evolved into the *VNR* [110]. This change significantly broadens the scope of its authority. No longer limited to overseeing just the electricity and gas markets, the *VNR* now also holds regulatory power over thermal energy networks, including district heating and cooling systems. This marks a major milestone in Flanders' energy transition, as heating and cooling–responsible for a large share of emissions–begin to receive the same institutional attention as electricity and gas.

On April 4th, 2025, the newly empowered regulator held its first official meeting to initiate the development of a technical regulation for heating networks. This process will lead to new, formalized legislation covering crucial aspects such as pricing structures, technical standards, operational procedures, and user protections for district heating and cooling systems. The aim is to create a clear, transparent framework that ensures fairness, reliability, and long-term sustainability for both operators and end users.

A key feature of this upcoming legislation is the important role reserved for municipalities. While the Flemish regulator will set out general rules and minimum requirements, local governments will be granted the power to further define and enforce specific conditions within their territories. Municipalities will, for example, be able to introduce additional sustainability criteria for heat sources, establish local quality norms, or even decide whether connection to a heating network is mandatory for certain types of buildings or zones.

This last point – the potential for mandatory connection to district heating or cooling networks – is particularly significant. Until now, one of the main barriers for ESCOs has been the fragmented nature of ownership in existing residential areas, where hundreds of individual homeowners each make separate decisions about their energy supply. Without a guaranteed number of connections, ESCOs could not justify the high upfront investment required to build local heat networks.

The ability for municipalities to legally require end-users to connect changes this dynamic completely. It enables the creation of a secure customer base, making it financially viable to roll out heating grids in established neighborhoods–something that was previously close to impossible. This shift opens the door for ESCOs to deliver decarbonized heat at scale, even in districts that were once seen as commercially unfeasible.

In sum, the transformation of *VREG* into the *VNR*, combined with the start of the technical regulation process for heating networks, sets the stage for a new era in local energy systems. The increased autonomy for municipalities, including the power to impose connection obligations, will play a crucial role in unlocking the potential of district heating and cooling. For ESCOs, this could be the breakthrough needed to extend their services into complex, multi-owner residential areas–bringing the energy transition into the very heart of Flanders' built environment.

4.3 Legal Issues for Water

As USCOs expand their scope beyond electricity and heat to offer integrated utility services, a growing area of innovation involves decentralized water management. One of the most promising developments in this domain is the emergence of WASCOs which aim to optimize the use, reuse, and treatment of water at the building or district level. These companies typically focus on sustainable water solutions such as greywater recycling for non-potable uses, including toilet flushing, laundry washing and garden faucets. However, this innovation is increasingly coming into conflict with existing regional water regulations, particularly those surrounding rainwater reuse in Flanders.

4.3.1 Greywater Reuse vs Rainwater Obligation

WASCOs often propose systems that collect, treat, and reuse greywater–wastewater from showers, baths, and sinks–for non-drinking applications. These systems offer clear environmental and logistical benefits: they reduce freshwater demand, lower wastewater output, and enhance resilience in water-scarce urban areas. Yet, under current Flemish building and environmental codes, especially the regional rainwater decree (*Hemelwaterverordening*), there is a legal obligation to reuse rainwater for specific applications such as toilet flushing.

This regulation prioritizes rainwater as the primary alternative water source, and does not explicitly recognize greywater reuse as a legally equivalent substitute. As a result, projects that install advanced greywater recycling systems may still be legally required to install rainwater tanks and plumbing for rainwater use, even if this duplicates infrastructure and contradicts the sustainability logic of their WASCO-led design.

The result is a regulatory mismatch: WASCOs offering greywater reuse solutions are penalized by laws that mandate the use of a less reliable and less consistently available source–rainwater. This not only undermines the environmental potential of water-smart buildings, but also creates redundant costs and design complexity for developers.

4.3.2 Additional Legal Challenges for WASCOs

Beyond the conflict with rainwater regulations, WASCOs face a series of other legal and operational barriers that make implementation difficult:

- Water Quality Standards and Liability: Greywater reuse systems must meet strict water quality standards, especially when used for toilets and washing machines. However, Flanders lacks detailed, specific legal criteria for these intermediate water qualities. This creates legal uncertainty for WASCOs, particularly in terms of liability. If users experience health or hygiene problems due to recycled water, the Water Service Company (WASCO) must demonstrate compliance in a regulatory vacuum–an uncomfortable and risky position.
- Responsibility for Operation and Maintenance: In traditional water systems, utilities are responsible for maintenance up to the meter. In decentralized setups, WASCOs assume responsibility for the entire water loop, including pumps, filters, and storage tanks. This creates a legal grey zone regarding inspections, service obligations, and repair liabilities–especially in multi-user buildings or residential blocks.
- Overlap with Public Water Utilities: Municipal and intermunicipal water companies (e.g., Farys, De Watergroep) hold the legal monopoly over potable water distribution and wastewater collection. Any decentralized system that starts to resemble a parallel utility service can face regulatory pushback, even when the services are non-potable. There is a risk that WASCOs are seen as infringing on regulated territory, leading to legal disputes over jurisdiction and consumer protection.
- Lack of Incentives or Recognition: Unlike energy systems, which benefit from EU-driven frameworks like energy communities or guarantees of origin, there is no formal structure in place to recognize or incentivize decentralized water systems. This means WASCOs must often navigate high capital costs, uncertain returns, and minimal institutional support, making it difficult to attract investment or integrate their services into standard building practices.
- Permitting and Approval Complexity: Installing a greywater system often requires permits for plumbing alterations, environmental assessments, and coordination with public utilities. These permitting processes are not standardized and differ from municipality to municipality, adding further administrative complexity and risk to WASCO business models.

4.3.3 Need for Integrated Regulation

The legal contradictions faced by WASCOs illustrate a broader issue in Flemish utility policy: the lack of regulatory integration between water, energy, and building design. As USCOs move toward multi-utility models, regulations remain siloed, resulting in conflicting obligations and missed opportunities for sustainable development. In the case of water, this is most evident in the tension between mandated rainwater reuse and greywater innovation.

To fully unlock the potential of WASCOs, Flemish policymakers will need to:

- Update the rainwater decree to recognize greywater reuse as an equivalent or complementary practice;
- Define legal water quality tiers for non-potable reuse;
- Clarify responsibilities and liabilities for decentralized water operators;
- Facilitate cooperation between public utilities and private WASCOs;
- Introduce supportive instruments, such as subsidies, recognition schemes, or standard permit procedures.

4.3.4 Future Outlook

Recent years, some municipalities and provinces–the authorities responsible for issuing environmental permits–have begun to take a more flexible and pragmatic approach. They are increasingly willing to grant exceptions to the rainwater reuse obligation, on the condition that the project demonstrates a high-quality and sustainable rainwater management strategy. The central requirement is that rainwater should not end up in the public sewers, which are often under pressure during heavy rainfall.

When a project can convincingly show that it deals with rainwater locally and effectively, authorities may allow greywater to be used for flushing toilets or running washing machines. This prevents unnecessary duplication of infrastructure and allows more space- and cost-efficient designs, particularly in dense urban settings or in buildings striving for circular water use.

To qualify for such exceptions, projects typically include innovative forms of blue infrastructure, which focus on rainwater retention, infiltration, or reuse in the environment. What is emerging, then, is a form of regulatory flexibility within a rigid framework. While the rainwater ordinance remains unchanged at the regional level, municipalities and provinces are using their discretionary power during the permitting process to make room for pioneering water reuse systems, provided that rainwater is still responsibly managed and does not burden the public infrastructure.

This development reflects a growing awareness that the one-size-fits-all approach of past regulations is no longer suitable for the complex sustainability challenges of today. It also highlights the important role that local governments can play in enabling innovation, even in the absence of updated regional legislation.

In conclusion, while greywater reuse is not yet formally embedded in Flemish environmental law, it is increasingly being tolerated and even supported when paired with smart and local rainwater strategies. This evolving practice signals a positive shift toward integrated and circular water systems, where rainwater and greywater are seen not as rivals, but as complementary resources. As the climate changes and urban water challenges grow, such forward-thinking approaches will be essential for building resilient, sustainable cities.

4.4 Legal Issues for Mobility

In the evolving landscape of integrated urban services, Mobility Service Companies (MOSCOs) are emerging as key players in offering shared, sustainable mobility solutions within residential developments, office parks, and mixed-use neighborhoods. A central component of many Mobility Service Company (MOSCO) models is EV charging infrastructure, especially in the context of shared e-mobility, such as e-car sharing, electric bikes, and scooters.

While the technical feasibility of deploying EV infrastructure in buildings has rapidly advanced, legal, spatial, and safety regulations remain a significant barrier–particularly in underground parking structures, where much of the urban parking stock is, or should be, located. The deployment of EV charging systems by MOSCOs touches on several domains of regulation: parking policy, energy systems integration, and critically, fire safety standards.

4.4.1 Parking Norms and Energy Integration

In many new developments, municipalities impose parking standards that not only define the number of required spaces but increasingly also mandate a percentage of EV-ready parking spots. This aligns with European directives on the electrification of transport and pushes building developers and service companies to anticipate future mobility needs.

MOSCOs respond to this trend by offering managed EV charging services that integrate with the building's energy systems, often in coordination with ESCOs. In ideal cases, the charging is smart and dynamic, responding to grid conditions, PV production, or building energy consumption. However, these systems must be compliant with technical regulations, such as those outlined by Synergrid, and may require specific permits if energy is resold to third parties.

4.4.2 Fire Safety in Underground Parking

The biggest challenge for EV infrastructure in underground settings is fire safety [77]. EVs, particularly their lithium-ion batteries, pose specific fire risks that differ from conventional vehicles. These concerns have led to the introduction of strict limitations on the type and capacity of chargers allowed in enclosed parking environments.

In Belgium, it is prohibited to install high-power Direct Current (DC) chargers (fast chargers) in underground parking garages, due to the higher risk of overheating and fire propagation in enclosed, poorly ventilated spaces. Only Alternating Current (AC) chargers (typically up to a maximum of 22 kW) are permitted, and even these are now subject to increasingly detailed safety regulations.

A significant development in this regard is the publication of the *Regels van Goed Vakman-*

schap
Rules of Good Workmanship (RGV), by the Fire Forum Belgium, which offers clear guidelines for the safe installation of EV chargers in buildings [38]. These rules, while not (yet) legally binding, are becoming the de facto standard used by fire services, insurance providers, and building inspectors.

The RGV includes guidance on:

- Placement of AC chargers in relation to walls, exits, and ventilation,
- Monitoring and disconnection systems in case of overheating,
- Fire compartmentalization of EV charging zones,
- Emergency access and signage in underground environments.

Furthermore, a new national standard specifically addressing fire safety for AC chargers in underground parking is currently in development. This will likely formalize many of the practices recommended in the *RGV* and may introduce mandatory risk assessments and certification requirements for charging infrastructure in enclosed spaces.

4.4.3 Implications for MOSCO Business Models

These regulations have a direct impact on how MOSCOs can design and operate their services. To comply with fire safety rules and spatial constraints, MOSCOs must:

- Adapt the type, charging capacity and location of EV infrastructure,
- Work closely with building engineers and fire safety consultants during design,
- Budget for fire safety upgrades, such as fire-resistant cable ducts or additional smoke and heat extraction,
- Navigate the permitting process with local fire departments and city services,
- Coordinate with other service layers (e.g. ESCOs for energy, facility managers for access control).

In practice, this often limits the scale or speed at which EV infrastructure can be deployed in underground settings, especially in existing buildings where retrofitting is complex and costly. For shared mobility services in multi-owner residential buildings, this creates a further legal and operational barrier: installing chargers in a co-owned parking area often requires unanimous consent or changes to the building regulations, adding legal friction.

4.5 Legal Issues for Materials/Waste and Other Utilities

Material Service Companies (MASCOs) are an emerging category within the broader service-based utility model, offering components of the built environment “as-a-service”. This includes offerings such as lighting-as-a-service, facade-as-a-service–e.g. façades with integrated photovoltaics or Building Integrated Photo Voltaics (BIPV), elevators-as-a-service, and similar systems that combine physical infrastructure with long-term service and maintenance contracts.

From a legal perspective, while many of these services touch on building code compliance, warranty obligations, and property law, the most significant emerging theme is their relationship with the circular economy [40]. Regulations are increasingly steering towards the use of environmentally friendly, low-impact materials, with particular attention to reusability, modular construction, and the avoidance of harmful substances, such as Per- and polyfluoroalkyl Substances (PFAS) [33].

In the future, MASCOs will likely need to comply with product traceability, material passports, and life-cycle impact reporting, especially in public or subsidized projects. However, this brief mention is far from exhaustive–the legal landscape for MASCOs is still developing and will evolve alongside EU and Flemish policies on sustainable construction and material reuse.

4.6 Public vs Private Context

In designing future-proof urban utility systems, a key question is whether core infrastructure and technologies within USCOs should be developed and operated by public entities, private companies, or through public-private partnerships. While there is no one-size-fits-all solution, several factors—including legal structure, financial feasibility, innovation potential, and social equity—shape which model is most appropriate for each technology or component. Both public and private entities have essential roles to play in the development of sustainable utilities. Public actors are uniquely equipped to safeguard long-term public interest, manage systemic risk, and address social equity. Meanwhile, private companies excel in speed, innovation, and investment discipline. By designing governance models that combine the strengths of both—and by embedding public safeguards into open markets—Flanders is paving the way for a more balanced and resilient utility landscape.

4.6.1 Public Oversight for Natural Monopolies

As a baseline, governments will always retain control over true monopolies—services for which duplication is inefficient or impossible. In Belgium, for example, Elia is responsible for the transmission of electricity and critical grid balancing, a function that cannot be meaningfully privatized. These kinds of centralized, natural monopolies must remain in public hands to guarantee neutrality, stability, and long-term investment in public interest.

4.6.2 The Dutch Approach

In the Netherlands, the *Wet Collectieve Warmtevoorziening*
Law Collective Heating (WCW) mandates that heating companies or ESCOs maintain a minimum of 51% public ownership, typically by cities or provinces. The goal is to anchor critical infrastructure in democratic accountability. However, this regulation has sparked backlash from private investors, who feel disenfranchised and exposed to political risk. As a result, private capital has largely retreated from new heating projects, threatening to stall the energy transition.

4.6.3 The Flemish Approach

Flanders is opting for a different path. Even for district heating and cooling networks (4G and 5G systems)—a domain traditionally associated with the public Distribution System Operator (DSO) Fluvius—the government is explicitly avoiding monopolization. The rationale is clear: to accelerate deployment and foster innovation by allowing public and private actors to compete.

To manage this competitive environment while maintaining order, Flanders has introduced a mechanism that allows for exclusive development rights–temporarily granted to a single party (public or private) for a specific district or infrastructure project. These rights are time-bound: if the developer fails to meet deadlines, the opportunity reverts to the public domain. In parallel, the government enables "domain reservations," allowing a party exclusive rights to use parts of the public domain, such as roads or underground corridors, for utility development.

4.6.4 Balancing Innovation, Feasibility, and Social Value

While competition is vital, some infrastructure requires long-term foresight and risk-taking–particularly in uncertain or early-phase developments. In cases where projects do not yield sufficiently short payback periods but offer clear environmental and societal benefits, a public actor should either:

- Lead the development and exploitation, absorbing higher risk and accepting longer depreciation periods (e.g., 50 years or more), or
- Provide targeted subsidies to make private participation viable under a SCBA framework, with guarantees that the social benefits (e.g. CO_2 reduction, health improvements) are actually realized.

This public involvement is not about crowding out the market but correcting market failures. For example, Fluvius might develop a heating network in a low-density area where the business case is initially weak but improves over time as user numbers grow.

4.6.5 Legal and Practical Implications

From a regulatory standpoint, public entities like Fluvius often face fewer administrative hurdles when working in the public domain—they may not need permits for excavation or infrastructure installation. In contrast, private developers must navigate a complex and often slow permitting process, which can be a major barrier.

However, the reverse is true on private land: private owners can often install infrastructure on their property without a permit, whereas public entities must seek approval and possibly negotiate easements or access rights. This legal asymmetry has real-world implications for project design and speed.

4.6.6 Ensuring Equity Through Social Tariffs

Regardless of who operates a USCO component, social tariffs must be guaranteed. If private developments restrict the application of these tariffs–either through pricing structures or selective access–they undermine the goal of universal utility access. Such practices should be discouraged or regulated, ensuring that affordability and inclusiveness remain central to utility provision.

4.6.7 Planning for the Future

Recognizing the need for proactive coordination, the Flemish government is preparing further legislation to mandate "heat plans" at the municipal level. These plans will identify where district heating is viable, set local priorities, and enable smoother coordination between public and private actors. In doing so, they aim to create clear frameworks that allow both innovation and accountability to thrive.

4.7 Ethical Considerations

From the vantage point of Stage 6 moral reasoning in the system of Kohlberg, USCOs are more than just market actors; they are ethical institutions with a profound responsibility toward people, the environment, and future generations. At this highest level of moral development, actions are not only guided by regulations, social consensus, or financial incentives, but also by universal ethical principles such as justice, equity, sustainability, and human dignity. For USCOs and their various components–ESCOs (energy), WASCOs (water), MASCOs (materials), and MOSCOs (mobility)–this perspective redefines their role in society.

4.7.1 Equity in Access to Services

One of the central implications is the need for equity in access. A USCO must ensure that its services–whether it's district heating, greywater recycling, e-mobility, or modular building components–are accessible to all, including low-income households and marginalized communities. Profitability cannot be the sole criterion for determining service areas or customer eligibility. True moral commitment lies in creating inclusive systems that support the well-being of everyone, not just those who can afford to participate. Therefore, required technologies or USCO components that have a high payback period, should be considered in a SCBA to make them viable [88], advocating a well thought through PPP [25].

4.7.2 Sustainability as a Moral Obligation

This ethical responsibility also extends to environmental sustainability, not as a branding strategy or market differentiator, but as a moral obligation. The use of circular, low-impact, and non-toxic materials, the prioritization of renewable energy, and the stewardship of water resources are not optional–they are necessary to safeguard the rights of future generations. A Material Service Company (MASCO) that knowingly uses harmful substances like PFAS, even if legally permitted, would fail to meet the ethical standard expected at this level of reasoning. Similarly, a WASCO that ignores long-term ecosystem impact in favor of short-term savings would act against the principles of ecological justice. Another example of this is the use of refrigerants in heat pumps with low Global Warming Potential (GWP) but containing PFAS.

4.7.3 Transparency and Truthfulness

In the realm of truthfulness and transparency, a Stage 6 ethical framework requires USCOs to communicate openly and honestly about the capabilities, limitations, and consequences of their services. Users deserve to know not only what a service offers, but also its environmental footprint, maintenance needs, and social implications. This commitment to truth becomes especially important in sectors like greywater reuse or underground e-mobility infrastructure, where the risks and responsibilities are often poorly understood by end users.

4.7.4 Respect for Autonomy and Consent

A deep respect for autonomy and consent also characterizes this ethical stage. Users should ideally not be forced or manipulated into subscribing to utility systems without meaningful participation and informed decision-making. For example, when a municipality mandates a connection to a district heating grid, the process must include robust engagement with residents, respecting their right to understand and influence the terms of that connection. Ethical service provision does not override individual agency–it collaborates with it. It is therefore good that the public authorities therefore take the lead in these regulations and obligations.

4.7.5 Beyond Compliance

Perhaps most importantly, USCOs acting from Stage 6 must be willing to go beyond legal compliance. Not all laws reflect justice. In fact, some laws–such as those that prohibit local sharing of solar electricity or restrict water reuse innovation–can actively prevent ethical solutions. USCOs committed to universal principles should be prepared to challenge these structures, advocate for reform, and take the moral high ground, even when it is difficult. Their responsibility is not just to operate within the system, but to help transform the system when it stands in the way of equity and sustainability.

4.7.6 Interdependence and Responsibility to the Future

Stage 6 moral reasoning calls for decisions rooted in justice, sustainability, and respect for human dignity–even when those values challenge conventional norms. At the same time, the reality remains that profit is an essential enabler for the required private USCO initiatives. Without some form of economic viability, even the most ethically grounded initiatives cannot be sustained or scaled. But at this advanced ethical level, profit is not pursued in isolation–it is aligned with long-term societal and environmental benefit. It is akin to the concept of **Business as an Agent for World Benefit**, as defined bij the Fowler Center and the international AIM2Flourish program.

To fulfill their responsibility to both present users and future generations, USCOs must recognize the deep interdependence between systems–energy, water, mobility, materials–and between public interest and private enterprise. Infrastructure that is economically viable but socially exclusive, or environmentally efficient but legally inaccessible, cannot serve the common good. Conversely, services that meet high ethical standards but lack financial durability risk becoming short-lived pilot projects, unable to drive structural change.

This is precisely why USCOs must be composed through careful collaboration between public and private actors. The public sector ensures that universal access, long-term planning, and democratic legitimacy are upheld. The private sector brings innovation, operational efficiency, and capital investment. Neither can succeed alone. Together, they can develop service models that are ethically robust, financially sound, and institutionally credible.

When municipalities, citizens, investors, and service providers co-create USCOs–grounded in shared values but responsive to practical realities–they build systems that reward responsibility, scale impact, and build trust. This kind of collaboration does not dilute moral principles in the name of pragmatism; it activates them in the complex world of urban development and climate transition [75].

In this vision, profit becomes not the goal, but the consequence of doing the right thing, in the right way, with the right partners. And ethical responsibility is no longer a constraint–it is the foundation of resilient, future-proof infrastructure.

TECHNOLOGY	PERMIT COMPLEXITY	TYPE OF PERMIT(S)	LEGISLATION / STANDARDS	PERMIT / ADVICE AGENCIES
Biogas Production (Anaerobic Digestion)	Medium	Environmental (noise, emissions water-air-soil, odour), Spatial planning (visual impact), Fire safety	Vlarem II Environmental quality standards for noise in open air, emission limit values for water and air,...	Province (>25tm^3), VMM, OVAM, Department of Care & Health
Bio-Oil Production (Pyrolysis)	Medium	Environmental (noise, emissions), Spatial planning (visual impact), Fire safety, EIA	Vlarem II Environmental quality standards for noise in open air, emission limit values for water and air,...	Province, VMM, OVAM, MER team, VEKA
Green Hydrogen Production (Electrolysis)	Medium to high	Environmental (noise, safety study), Spatial planning (visual impact), Fire safety, EIA	Vlarem II Environmental quality standards for noise in open air, safety study,...	Province, VMM, OVAM, Environmental Impact Assessment Team, External Safety, MER team
Aquathermal Energy Systems	Medium	Environmental (noise), Spatial planning (visual impact), EIA (va5MW)	F-gas regulation	Local government, province (>5MW) VEKA (>5MW)
Sewage Thermal Energy Systems	Medium	Environmental (noise, emissions)	Vlarem II Environmental quality standards for noise in open air, F-gas regulation	Local government, province
Residual Heat Recovery Systems	Low to medium	Environmental (heat exchangers) Spatial planning	Vlarem II Environmental quality standards for noise in open air, F-gas regulation	Local government or province (depending on power heat pumps, volume heat exchanger)
Geothermal Energy Systems (ATES/BTES)	Medium to high for ATES, Very low for BTES	Environmental (soil) if deeper than depth criterion, Spatial planning (visual impact)	Vlarem II, rules about soil and groundwater management, environmental quality standards for noise in open air, F-gas regulation	>500m: province, VMM, department of environment, department responsible for natural resources
Absorption Cooling	Medium	Environmental (noise), Spatial planning (visual impact)	Codex RO	Local government or other (depending on permit site)
Air-to-Water Heat Pumps	Low	Environmental (noise, F-gas, PFAS in F-gas), Spatial planning (visual impact), Fire safety (for some F-gases)	Vlarem II Environmental quality standards for noise in open air, local RUP/PRUP/GRUP, fire safety standards, F-gas regulation	VMM, Municipal spatial planning board, local fire agency
Solar Panels (PV, PT, PVT)	Low	Spatial planning (visual impact) if not on roofs or not linked to community service, Environmental (transfo>1.000kVA)	Codex RO	Local government, province (dependent on situation)
Solar Panels (PC)	Low	Spatial planning (visual impact), Fire safety (for storage)	Codex RO	Local government, province (dependent on situation), local fire agency
Concentrated Solar Power (CSP)	High	Spatial planning (visual impact), Fire safety (for storage)	Codex RO	Local government, province (dependent on situation), local fire agency
Wind Energy Systems (Onshore)	Medium	Environmental (noise, shadow, biodiversity, aviation), Spatial planning (visual impact)	Vlarem II Environmental quality standards for noise in open air, drop shadow standards	Flemish government, VEKA
Small and Medium Wind Turbines (SMWT)	Low to medium	Environmental (noise, shadow), Spatial planning (visual impact)	Vlarem II Environmental quality standards for noise in open air, drop shadow standards	Local government (<1500kW)
Micro Hydropower	High	Environmental (noise), Spatial planning (visual impact)	Vlarem II Environmental quality standards for noise in open air	Local government (<10.000kVA)
Ocean Power	High to very high	Environmental (noise), Spatial planning (visual impact)	Vlarem II Environmental quality standards for noise in open air	Local government (<10.000kVA)
Organic Rankine Cycle (ORC) Systems	Medium to high	Environmental (noise), Spatial planning (visual impact)	Royal Decree of 18 October 1991 concerning steam appliances	Local government (turbine<100MW)
Small Modular Reactors (SMRs) and Micro Reactors	Extremely High	Environmental, Spatial planning (visual impact)	Royal Decree of 20 July 2001 containing general regulations on the protection of the population, workers and the environment against the danger of ionizing radiation	FANC, local government
District Heating (4th Generation)	Medium to High	Environmental (safety study)		Local government
District Heating and Cooling (5th Generation)	Medium	Environmental (safety study)		Local government
Seasonal Thermal Energy Storage (PTES)	Medium	Environmental (safety study)		Local government
Seasonal Thermal Energy Storage (Tank)	Medium	Environmental (safety study)		Local government
Seasonal Thermal Energy Storage (Rock Cavern)	High	Environmental (safety study)		Local government, province (dependent on situation), VMM
Thermal Buffer (Ice Storage)	Medium	Environmental (safety study)		Local government
Thermal Buffer (Sand Storage)	Low	Environmental (safety study)		Local government
Thermal Buffer (Molten Salt)	Medium	Environmental (safety study)	Fire safety standards	Local government, province (dependent on situation), VMM
Thermal Buffer (PCMs)	Low to medium	Environmental (safety study)		Local government
Battery Energy Storage Systems (BESS)	Medium	Spatial planning, Environmental (transfo>1000kVA), Fire safety	Codex RO	Local government, province (dependent on situation), VMM

Table 18: Permit complexity overview.

5 Business Model

To build a future-proof and strategically grounded business model, it is essential to understand the broader external forces that shape the sectors in which we operate. This chapter presents a PESTEL analysis–examining the Political, Economic, Social, Technological, Environmental, and Legal dimensions–of three critical utility domains: energy, water, and mobility.

These sectors are at the core of today's sustainability and infrastructure transitions, facing both significant pressures and unprecedented opportunities. From shifting policies and regulatory frameworks to technological breakthroughs and changing societal values, each domain is influenced by a complex web of external factors.

By exploring these drivers and constraints, the PESTEL analysis lays the groundwork for developing a solid and well-informed business model canvas. It helps identify where risks may emerge, where value can be created, and how integrated utility services can respond to a rapidly evolving landscape with agility and long-term vision.

5.1 Energy

The energy sector is undergoing a structural transformation shaped by the urgent need for decarbonisation, digitalisation, and decentralisation. This PESTEL analysis (see Figure 14) captures the evolving landscape that influence the future of energy systems in Flanders and Europe.

5.1.1 Political

The energy transition is fundamentally shaped by political frameworks at both the European and regional levels [104]. The EU Energy Policy focuses on achieving a secure, competitive, and sustainable energy system. These overarching goals–security of supply, competitiveness, and sustainability–guide national policy development and influence investment incentives across the energy landscape. Belgium's continued push for renewable integration is aligned with these EU objectives, but is also shaped by national challenges such as phasing out nuclear energy.

The nuclear phase-out in Belgium remains one of the most impactful policy shifts. It introduces a risk of supply imbalance, while also opening up space for increased renewable integration and decentralized systems. To manage this, policy instruments like Contracts for Difference (CfDs)–which will be introduced starting December 2023–and capacity remuneration mechanisms are being deployed to reduce investor risk in low-carbon, flexible assets. These policies will define the next generation of large-scale infrastructure and are central to ensuring the grid remains balanced during the energy transition.

5.1.2 Economic

The energy sector is deeply influenced by macroeconomic volatility. Gas and oil prices, especially since recent global geopolitical tensions, have highlighted the vulnerability of fossil fuel-reliant systems and reinforced the urgency of transitioning to local, renewable sources. This volatility affects not only electricity pricing but also consumer trust and long-term economic planning for energy providers and users.

Another significant factor is the manufacturing shift to China, particularly for solar PV, batteries, and critical minerals. This concentration increases exposure to supply chain disruptions and price shocks. In parallel, inflation and declining purchasing power affect consumer investment in energy efficiency (e.g. heat pumps, insulation) and make the affordability of electricity a key political and societal concern.

Interest rates also have a profound impact. As they rise, the cost of financing renewable energy infrastructure grows, potentially delaying projects or increasing the cost of electricity. However, financial instruments are increasingly being linked to sustainability performance, where interest rates on loans depend on the environmental or social outcomes of the project. This creates both pressure and opportunity for energy players to align operations with Environmental, Social and Governance (ESG) principles.

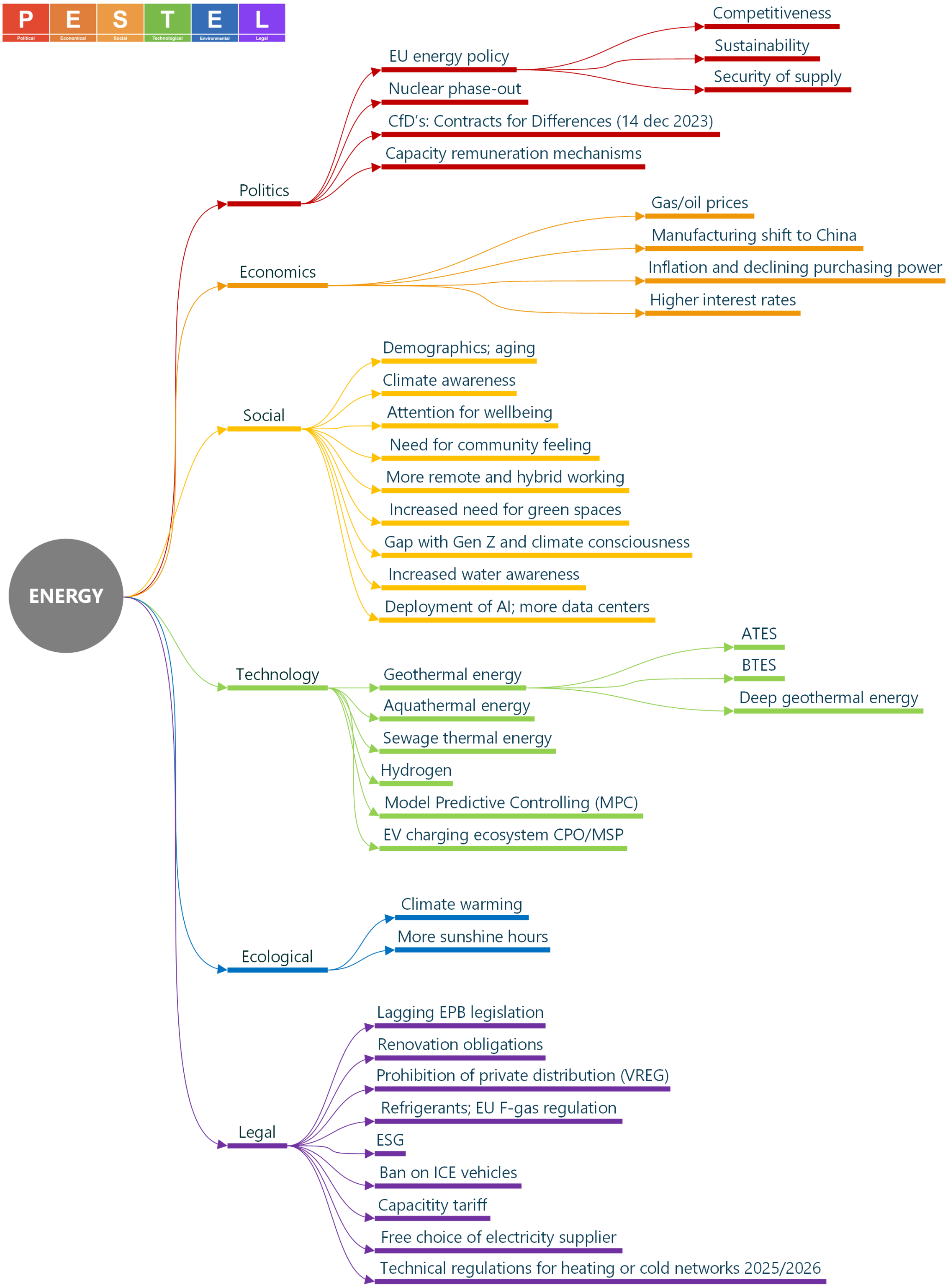

Figure 14: PESTEL analysis of energy. Image ©Sammy Rogmans, composed with Microsoft Visio.

5.1.3 Social

Social dynamics are reshaping how energy is consumed and produced. The aging population requires more predictable, affordable, and uninterrupted energy services, particularly in residential heating and cooling. On the other hand, younger generations (Gen Z and Millennials) demand clean, transparent, and participatory energy systems, giving rise to energy communities, cooperatives, and prosumer models.

There's a growing societal emphasis on climate awareness and wellbeing, leading to more demand for healthy indoor environments, sustainable neighbourhoods, and clean energy sources. Remote and hybrid working has altered daily consumption patterns, shifting peak demand profiles and affecting grid load balancing. Additionally, there's an increasing need for community connection, where decentralised energy systems and cooperative ownership models are seen not just as technical solutions, but also as tools for local empowerment.

New social expectations are also emerging from the rise of AI and data centers, which are energy-intensive and often located near urban hubs. Public scrutiny is increasing around how these facilities manage energy use, and whether their benefits to society justify their consumption profiles.

5.1.4 Technological

Technological innovation is rapidly changing the energy landscape. Geothermal energy, including shallow–i.e. ATES, BTES–and deep variants, is becoming more viable in district heating and large building developments. Aquathermal and sewage thermal energy are emerging as cost-effective, low temperature heat sources for urban areas, especially when integrated with 5GDHC networks.

The development of green hydrogen as a clean energy carrier is progressing, particularly for sectors that are hard to electrify [12]. However, the high costs of electrolysis and limited infrastructure remain barriers to widespread adoption [24]. Alongside this, advanced control systems like Model Predictive Controller (MPC) are enabling smarter building and system management, optimizing energy use and improving flexibility at the grid edge.

Another critical innovation area is the EV charging ecosystem, including Charge Point Operators (CPOs) and Mobility Service Providers (MSPs). The ability to balance electricity demand through smart charging and V2G technologies is key to integrating mobility and energy sectors, especially in dense urban areas where load peaks can strain distribution networks.

5.1.5 Environmental

Climate change directly impacts both energy production and demand. Global warming increases cooling loads, especially in residential and commercial buildings, while slightly reducing heating needs in milder winters. This shift affects grid balancing and seasonal energy planning [98]. Moreover, climate-driven weather variability necessitates stronger system resilience and more flexible generation.

In Flanders, data suggest a trend toward more sunshine hours in summer, which benefits solar PV output but creates new challenges for system congestion and overproduction. This underscores the need for investment in storage and flexible demand solutions. Energy system planning must also consider land use and biodiversity, especially when developing large-scale wind or solar farms.

5.1.6 Legal

The regulatory landscape is evolving to catch up with technology and policy ambition. Lagging Energy Performance of Buildings (EPB) legislation creates uncertainty for investors and builders, while upcoming renovation obligations will drive demand for retrofit solutions–but also raise questions about affordability and social fairness.

Legal conflicts are also emerging around private electricity distribution, particularly for energy communities and smart neighbourhoods, which face constraints under current VNR interpretations. Meanwhile, the ban on Internal Combustion Engine (ICE) vehicles, capacity tariffs, and free supplier choice reshape energy demand and cost distribution.

Regulations around refrigerants (EU F-gas regulation) and technical standards for heating and cooling networks (2025–2026) further underline the growing complexity of compliance in the sector. Lastly, energy providers and infrastructure owners must increasingly align with ESG reporting obligations, integrating social and environmental accountability into their legal and financial models.

5.2 Water

Water is no longer just a utility–it is a strategic resource at the heart of climate adaptation, public health, and regional planning. As pressures from population growth, climate extremes, and aging infrastructure intensify, the sector is undergoing a transformation [41]. This PESTEL analysis explores the complex external forces that shape the future of water management (see Figure 15), supporting the development of forward-looking, integrated utility service models.

5.2.1 Political

Water governance in Flanders is strongly influenced by both regional and European policies that aim to secure long-term availability, protect public health, and improve resilience to climate-related risks. The Third Water Policy Note for Flanders outlines strategic priorities such as integrated water cycle management, protection of groundwater reserves, and climate adaptation, aligning with overarching European directives.

At the EU level, several key regulations shape the landscape. The EU Drinking Water Directive (2023) sets strict standards for water quality and safety, reinforcing monitoring and treatment obligations. The EU Nitrates Directive targets agricultural runoff and its impact on surface and groundwater pollution, demanding closer coordination between environmental and agricultural policies. Meanwhile, the EU Water Framework Directive (WFD 2027) enforces holistic watershed-based planning, requiring countries to achieve “good status” for all water bodies. Together with policies for coastal area management, these frameworks

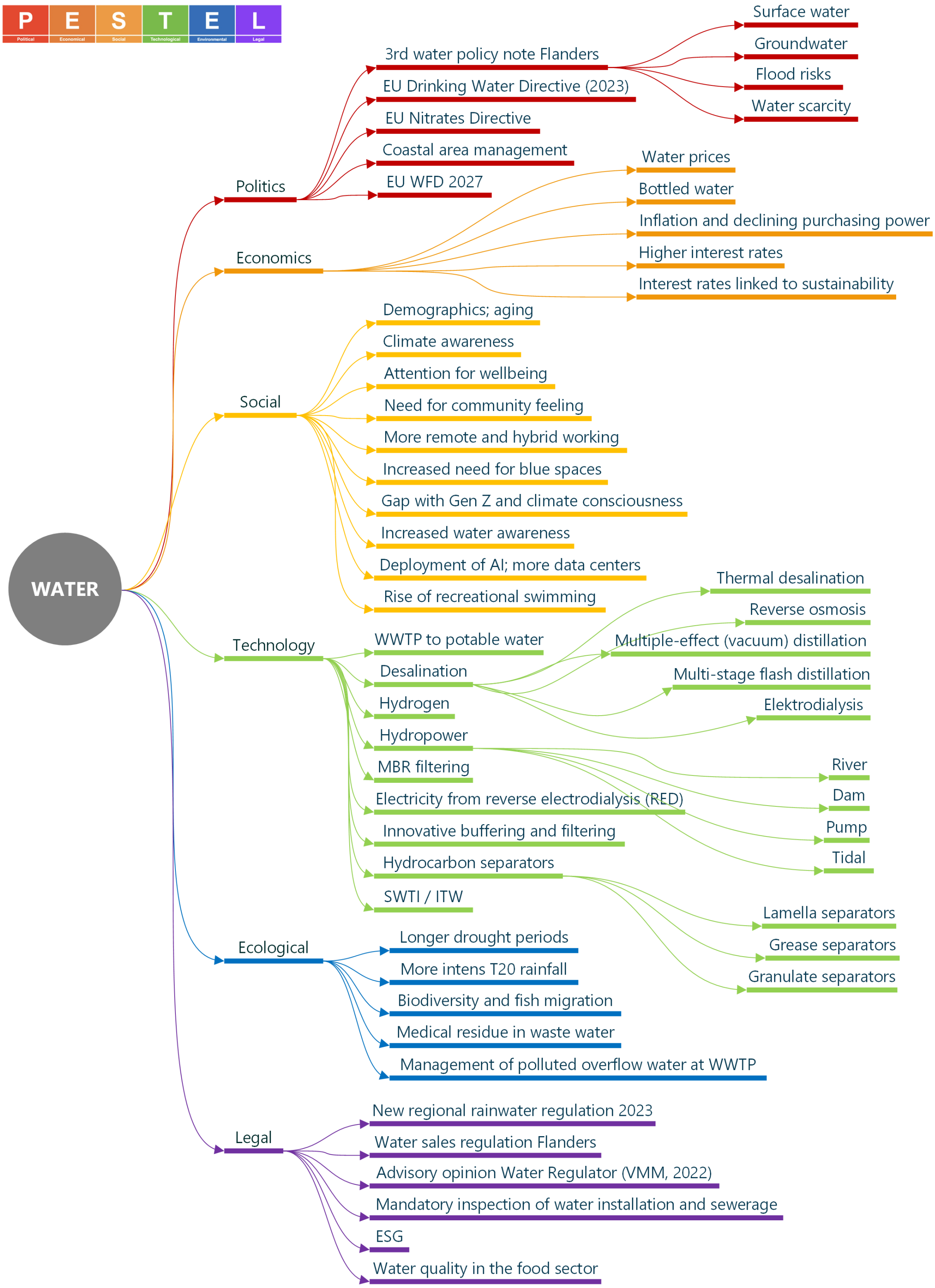

Figure 15: PESTEL analysis of water. Image ©Sammy Rogmans, composed with Microsoft Visio.

add complexity to water infrastructure planning but provide clarity for long-term sustainability goals.

5.2.2 Economic

Water is an essential service, but its economics are becoming increasingly complex. Rising water prices, reflect not just supply constraints but also the growing cost of maintaining infrastructure and complying with new regulatory standards. This creates equity concerns and fuels public debate about the affordability of clean water as a basic right.

Inflation and declining purchasing power impact both households and businesses, challenging water utilities to balance cost recovery with social responsibility. Moreover, higher interest rates increase the cost of financing infrastructure upgrades and innovation in water systems. However, an emerging trend is the rise of sustainability-linked financing, where interest rates are tied to performance on environmental or social targets. For water companies and municipalities, this presents an opportunity to align investment strategies with long-term climate and social objectives.

5.2.3 Social

Society's relationship with water is shifting. Public concern around climate change and water scarcity has made citizens more conscious of how water is used, distributed, and priced. There's a growing expectation that water providers manage resources responsibly and transparently. Demographic changes, particularly aging populations, also drive the demand for accessible and safe water in homes and care facilities.

The trend toward remote and hybrid working is increasing residential water consumption while decreasing usage in traditional office spaces. Meanwhile, the rise of online shopping affects water consumption indirectly through logistics and packaging. Social preferences are also evolving: there's greater appreciation for "blue spaces" (such as rivers, canals, lakes) for recreation and mental health, which influences public investment priorities and urban design.

Generational shifts are evident. The gap between Gen Z and older generations on climate issues extends to water, with younger people demanding stronger sustainability commitments. Water awareness is also rising due to AI-driven data use and more transparent communication from utilities, helping consumers understand their consumption and make informed decisions.

5.2.4 Technological

The water sector is rapidly evolving with new technologies that support circularity, efficiency, and decentralised management. Advances in turning wastewater into potable water, for example, are changing how we define and manage water reuse. Desalination technologies – such as reverse osmosis, electrodialysis, and vacuum distillation – offer new options for augmenting supply in drought-prone areas, though they remain energy-intensive.

MBR filtering, hydrocarbon separation, and smart buffering systems are enabling more precise and localized treatment, ideal for industrial and decentralized municipal applications. Technologies like electricity generation from Reverse Electrodialysis (RED) highlight the increasing overlap between the water and energy sectors, where innovation in one can benefit the other.

Digitalisation also plays a vital role. Smart water networks, powered by AI and IoT, are improving leakage detection, predictive maintenance, and real-time quality control. With rising pressure from urbanisation and climate change, technological integration is becoming central to ensuring efficiency, reliability, and public trust in water services.

5.2.5 Environmental

The water sector is highly vulnerable to ecological disruption. Longer drought periods reduce water availability and lead to increased competition between agricultural, industrial, and domestic users. At the same time, more intense rainfall events (T20) strain drainage systems and result in overflow from Waste Water Treatment Plants (WWTPs), contributing to pollution in rivers and natural ecosystems.

Ecological impacts also include loss of biodiversity and disrupted fish migration, especially due to dams and canalisation. Medical residues in wastewater, including hormones and pharmaceuticals, present growing risks to aquatic life and human health. These challenges call for integrated water management and more stringent filtering and monitoring systems.

Climate-related water stress also affects the energy and food sectors, making water security a cross-cutting issue that intersects with economic productivity, social cohesion, and environmental health. Future-proofing water systems therefore requires an ecological approach that values water not just as a commodity, but as a shared and finite ecosystem service.

5.2.6 Legal

The legal framework governing water in Flanders is becoming more complex and comprehensive. The new regional rainwater regulation (2023) mandates stricter requirements for rainwater buffering, infiltration, and reuse, especially in new developments. These measures aim to prevent flooding, reduce strain on sewage systems, and promote local water resilience.

The Water Sales Regulation enforces rules on fair pricing and transparency, while the water regulator *Vlaamse Mileumaatschappij*
Flemish Environmental Agency (VMM) now plays a stronger advisory and supervisory role in system operation and investment. In addition, mandatory inspection of private installations and sewerage connections helps enforce system integrity and reduce pollution at the household level.

Broader legal frameworks such as ESG obligations and food sector water quality standards also shape the responsibilities of water utilities and industries. As legal scrutiny increases, water actors must not only comply with technical standards, but also demonstrate social and environmental stewardship. This shift will require closer alignment between legal, operational, and communication strategies.

5.3 Mobility

The mobility sector is at the heart of a rapid and far-reaching transition. Driven by climate goals, digitalisation, urbanisation, and evolving societal needs, mobility systems are being reimagined to be cleaner, smarter, and more inclusive. This PESTEL analysis outlines the key external factors shaping mobility today and into the future.

5.3.1 Political

Mobility is increasingly guided by long-term government visions and frameworks. The Flemish Mobility Vision 2040 sets ambitious targets: zero transport emissions, no severe traffic casualties, smooth and seamless mobility, and a 60% reduction in material footprint. Policy efforts focus on both passenger and freight transport, including modal shifts and integrated urban planning. Reforms in the company car policy and the Masterplan Accessibility for Public Transport aim to reduce car dependency and encourage multimodal travel. Investments in smart mobility, such as real-time traffic data, digital ticketing, and vehicle-sharing infrastructure, support a transition toward user-centric, sustainable systems.

5.3.2 Economic

Incentives like the bicycle allowance and subsidies for electric vehicles aim to promote low-carbon transport options, but affordability remains a key challenge. Higher interest rates may slow the uptake of new mobility technologies and infrastructure projects. Meanwhile, rising logistics and energy costs are reshaping supply chains and delivery models, pushing for more efficient and electrified freight solutions. Economic resilience in the mobility sector now hinges on innovation, cost-effective electrification, and flexible Public Private Partnerships.

5.3.3 Social

Societal behaviour and preferences are shifting dramatically. An aging population and growing climate awareness are increasing the demand for safe, accessible, and sustainable transport options. There's greater attention for wellbeing, which includes cleaner air, noise reduction, and reduced commuting stress. Trends like remote and hybrid working and car sharing are reshaping urban mobility patterns and infrastructure demand. The growing divide between generations in climate expectations is pushing for faster action, particularly among younger populations. Meanwhile, the growth of online shopping has increased demand for last-mile logistics, and the deployment of AI and data centers is adding new layers of complexity to urban infrastructure. A broader trend toward urban living is reinforcing the need for walkable, bike-friendly, and public-transit-oriented environments.

5.3.4 Technological

Technological advancements are revolutionizing the mobility ecosystem. From electric bikes to freight electrification (vehicles, planes, ships), electrification is expanding across all transport modes. Hydrogen mobility is emerging for heavier transport segments, while AI and autonomous driving promise to transform safety and efficiency. Data mining and mobility

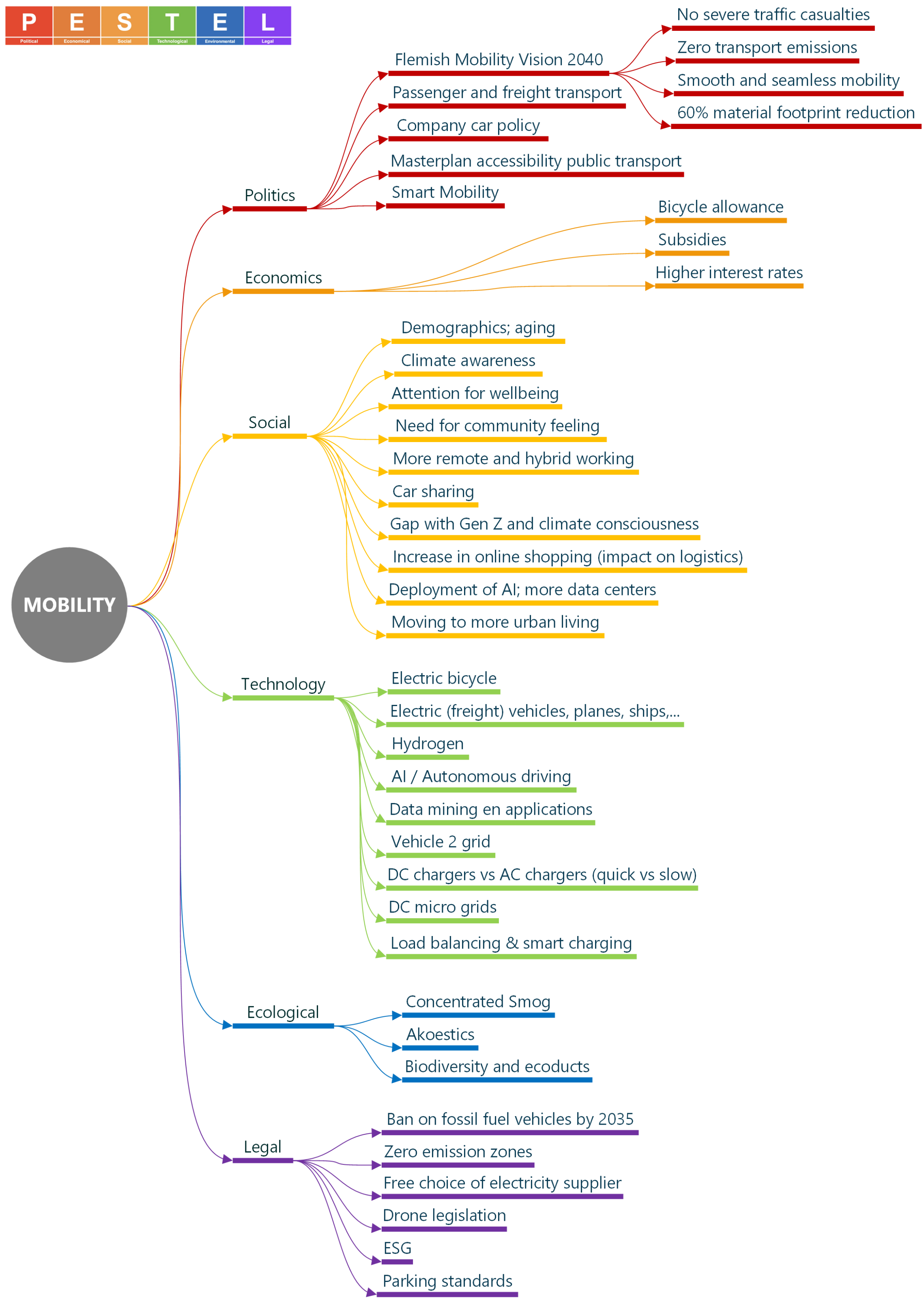

Figure 16: PESTEL analysis of mobility. Image ©Sammy Rogmans, composed with Microsoft Visio.

applications improve route planning, multimodal access, and infrastructure usage. Technologies like Vehicle-to-Grid (V2G) enable cars to act as decentralized energy storage, supporting the grid. The choice between DC and AC chargers (fast vs slow) and the development of DC microgrids influence charging network design [61]. Load balancing and smart charging are essential for managing peak loads and integrating renewable energy into mobility.

5.3.5 Environmental

Mobility remains a major source of air pollution, especially concentrated smog in cities. Noise pollution (acoustics) is also a growing concern, particularly with increased traffic density and the spread of drone technologies. Additionally, the construction of new transport infrastructure can threaten biodiversity and ecological connectivity, prompting greater integration of eco-ducts and green corridors in transport planning. Reducing ecological impact requires not only cleaner vehicles but also sustainable urban design and ecosystem-aware infrastructure.

5.3.6 Legal

The legal environment is evolving quickly. Key shifts include the ban on fossil fuel vehicles by 2035, the creation of zero-emission zones in cities, and evolving parking standards that support new mobility modes. Free choice of electricity supplier affects how charging infrastructure is managed and monetized. Drone legislation is becoming more relevant as aerial logistics and personal mobility drones enter early-stage deployment. Legal expectations around ESG compliance are extending to mobility operators and infrastructure investors. These legal developments shape market access, business models, and technology standards.

5.4 Business Model Canvas

As integrated sustainability challenges increasingly demand cross-sectoral solutions, the USCO model emerges as a powerful framework to deliver energy, water, mobility and other utility services in a cohesive and future-proof way. This business model canvas outlines the key building blocks of a USCO, capturing how it creates, delivers, and captures value through decentralized infrastructure, long-term service models, and strategic partnerships. The canvas is designed to reflect the complexity and opportunity of operating at the intersection of three critical utility domains (i.e. energy, water, and mobility), and serves as a foundation for designing effective, resilient, and scalable USCO initiatives.

5.4.1 Key Partners

A USCO thrives on a wide and strategic ecosystem of partnerships. Its core partners include local governments and municipalities, which often act as anchor clients and facilitators of public space access, permits, and long-term planning alignment. These relationships are foundational, as USCOs contribute to achieving public sustainability goals such as climate neutrality, zero water waste, and congestion reduction.

Equally important are technology providers, supplying the energy, water, and mobility systems that power USCO operations–from solar PV panels and water treatment units to battery storage and shared electric mobility fleets. These partners enable innovation and ensure system upgrades. Maintenance partners take care of continuity. Grid operators (electricity, water, heat) are essential partners for network integration and balancing. Finally, financial institutions and impact investors support the capital-intensive nature of infrastructure projects, often combining commercial and concessionary finance with public grants or green bonds.

A summarized list of key partners:

- Local and regional governments (permits, co-investment, policy alignment).
- Technology providers (solar PV, batteries, greywater systems, EV fleets).
- Grid and network operators (electricity, water, heat).
- Mobility service partners (CPOs, MSPs, e-bike fleets).
- Financial institutions (green loans, ESG-linked financing, impact investors).
- Real estate developers and public infrastructure agencies.
- Citizen cooperatives and community energy groups.

5.4.2 Key Activities

USCOs manage the entire lifecycle of decentralized utility systems. This includes project design, infrastructure financing, construction, and ongoing operation often across three domains: energy, water, and mobility. They integrate hardware (solar panels, heat pumps, smart chargers, etc.) with software systems for smart grid management, consumption tracking, and billing.

In energy, activities may include operating PV and battery systems, managing district heating, grid and energy management, or purchasing green power on behalf of clients. In water, this extends to rainwater harvesting, greywater recycling, water maangement and real-time leak detection. On the mobility side, USCOs manage fleets of electric bikes, cars, or mobility hubs, often through smart-sharing platforms while trying to optimize energy management. Across all activities, customer service, digital interfaces, and data analytics are critical, enabling transparency, optimization, and adaptability to user needs.

A summarized list of key activities:

- Design and engineering of integrated utility systems (energy, water, mobility, etc. ...).
- Financing and co-investment structuring (CAPEX & OPEX models).
- Construction and installation of infrastructure.
- Operation and maintenance of systems (energy plants, EV fleets, water loops).
- Smart metering, data analytics, and consumption optimisation.
- Customer service and long-term contract management.
- Regulatory compliance and performance reporting.

5.4.3 Value Propositions

USCOs offer a powerful value proposition: fully integrated, turnkey utility services that are clean, efficient, and community-oriented. By bundling energy, water, mobility and other utilities into one seamless offering, USCOs reduce administrative burden, simplify user experience, and create synergies between systems (e.g. V2G energy feedback, heat reuse from data centers, or rainwater usage for EV washing stations).

They can deliver predictable and competitive pricing, essential for public clients or housing cooperatives working within tight budgets. Moreover, their services are inherently sustainable, with built-in zero-emission design, resource circularity, and resilience against price shocks or supply interruptions. For real estate developers or municipalities, a USCO de-risks sustainability targets by offering long-term, performance-based contracts that align with ESG goals.

A summarized list of value propositions:

- One-stop service for efficient, decentralized, zero-emission utility systems.
- Long-term performance contracts (ESCO/WASCO/MOSCO/MASCO/X-as-a-Service).
- Lower lifecycle costs and stable pricing for clients.
- Turnkey sustainability and ESG compliance.
- Reduced environmental impact and resource circularity.
- Transparent digital tools for usage, billing, and system health.
- Strong alignment with municipal and real estate climate targets.

5.4.4 Customer Relationships

USCOs build long-term, trust-based relationships with their clients. Most engagements are formalized through multi-year service contracts (10–30 years), often structured as Energy-as-a-Service or Mobility-as-a-Service models. These contracts ensure high service quality, risk-sharing, and alignment on performance Key Performance Indicators (KPIs) like CO_2 reduction, uptime, or user satisfaction.

In many cases, USCOs also foster participative governance. Municipalities or citizen groups may co-own part of the utility, ensuring alignment with public interest. Digital customer platforms offer transparency, real-time tracking of consumption, and accessible support. These channels strengthen engagement and build loyalty, particularly when users can see how their behaviour contributes to community goals or cost savings.

A summarized list of customer relationships:

- Long-term service-level agreements (SLA) and performance-based contracts.
- Co-ownership models or community engagement structures.
- Digital platforms for real-time monitoring and customer support.
- Public workshops and participatory design.
- Clear, transparent communication on impact and costs.

5.4.5 Customer Segments

USCOs target a growing range of institutional, public, and community-scale customers. These include:

- Municipalities looking to decarbonize infrastructure and reduce utility bills.
- Real estate developers and housing cooperatives seeking integrated utilities for new eco-districts or retrofitted neighbourhoods.
- Campuses, hospitals, or business parks with predictable but diverse utility needs.
- Citizen collectives or energy communities desiring ownership and control over local resources.
- Large-scale infrastructure operators (ports, airports, business parks).

These customers share a common desire for sustainability, resilience, cost control, and ease of operation–making them ideal partners for the USCO model.

5.4.6 Key Resources

To operate effectively, USCOs depend on a mix of physical, digital, financial, and human resources. On the physical side, this includes renewable energy assets (solar fields, batteries, microgrids), water systems (treatment units, greywater loops), and mobility infrastructure (charging stations, e-vehicles). These are combined with robust IT systems for monitoring, control, billing, and analytics.

Human capital is equally important. A USCO requires expertise in engineering, urban planning, customer experience, legal compliance, and stakeholder engagement. In terms of financial resources, access to blended capital (equity, debt, subsidies) is critical for infrastructure roll-out. Licensing and regulatory approvals round out the core resource package, especially in sensitive urban and utility environments.

A summarized list of key resources:

- Infrastructure assets (solar PV, battery systems, water treatment, EVs).
- Software and digital platforms (MPC, smart charging, monitoring tools).
- Human expertise (technical, regulatory, project management).
- Licenses and permits (grid access, water management, mobility operations).
- Financial capital (public-private funding, green bonds, subsidies).

5.4.7 Channels

USCOs use several channels to acquire and engage customers. Public tenders and procurement processes are common, especially for municipalities and large infrastructure projects. Direct B2B sales and partnerships are used with developers, utilities, and institutional customers. Co-development models are increasingly popular, where the USCO helps design the utility system during project inception.

Digital channels play a vital role post-acquisition. Online platforms enable contract management, customer service, usage tracking, and reporting, helping customers stay informed and engaged. Community engagement events or co-design workshops also help build trust, particularly in public or co-owned projects.

A summarized list channels:

- Public procurement and tendering platforms.
- Direct partnerships with municipalities and developers.
- Industry events, networks, and urban innovation forums.
- Digital channels for customer onboarding and engagement.
- Pilot projects and co-development initiatives.

5.4.8 Cost Structure

USCOs operate in a capital-intensive environment. The largest costs come from CAPEX– such as energy systems, water piping, or e-mobility stations. OPEX follow, including maintenance, staff, insurance, and technology upgrades. As digital systems become more central, there's also growing investment in platform development, cybersecurity, and data governance.

Regulatory compliance, such as reporting, certification, or grid connection costs, adds another layer of expense. However, through standardisation and modularity, mature USCOs can reduce unit costs over time. As scale increases, economies of scope (serving multiple utility needs together) further improve cost efficiency.

A summarized list of the cost structure:

- Capital expenditures (infrastructure build-out).
- Operational expenses (maintenance, staffing, insurance).
- Platform development and software maintenance.
- Legal, permitting, and regulatory compliance costs.
- Marketing and community engagement efforts.

5.4.9 Revenue Streams

USCOs generate revenue from multi-utility service fees, often in the form of fixed monthly payments tied to usage tiers or service levels. Some charge variable tariffs (e.g. per kWh, m^3 water, km driven) while others offer performance-based pricing, where bonuses or penalties depend on service quality or savings delivered.

Additional revenue can come from Power Purchase Agreements (PPAs), feed-in tariffs, or grid services like demand response or frequency balancing. USCOs may also tap into public funding, innovation grants, or green infrastructure subsidies, especially when helping public partners meet regulatory or climate goals.

A summarized list of the revenue streams:

- Fixed service fees (monthly or annual utility payments)
- Variable usage charges (per kWh, m^3, or km)

- Performance-based incentives (e.g. shared savings)
- Power Purchase Agreements (for surplus energy sold to grid)
- Government subsidies or grants (climate, circular economy, i.e. to carry investments with social profits)

5.5 Possible USCO Configurations and Example

USCOs (Utility Service Companies) can be tailored to serve different types of built environments by integrating modular utility services across the domains of energy, water, mobility, and materials. The following five configurations illustrate how USCOs can adapt to varied contexts:

Figure 17: Possible USCO configurations. Image ©Sammy Rogmans, composed with Microsoft Visio.

1. **Sustainable Operation of Data Centers and Communities**: This configuration links data centers with residential communities. It leverages residual heat from data centers for community heating and optimizes cooling needs. It also includes public EV charging infrastructure and facades with integrated photovoltaics (BIPV), promoting energy efficiency and material innovation.
2. **Smart Management of Residential Buildings**: Focused on delivering cost-effective and sustainable heating, cooling, and electricity (including production and storage), this setup also includes greywater regeneration systems and centralized private parking equipped with EV charging stations.
3. **Smart Management of Commercial Buildings**:Aimed at office or retail spaces, this model integrates thermal and electrical utilities, storm water management (buffer and

infiltration), centralized semi-public parking, and modular interior solutions like lighting and partitions as-a-service.

4. **Smart Management in the Healthcare Sector**: Designed for hospitals and nursing homes, this configuration provides advanced energy systems, waste water treatment, and medical waste separation. Mobility is addressed through semi-public EV-charging-enabled parking infrastructure.
5. **Smart Management of Industrial Sites**:This industrial model focuses on robust and efficient utility systems for thermal and electrical energy, waste water regeneration, and buffer infrastructure. Parking solutions are semi-public and include optional EV infrastructure.

These examples demonstrate the flexibility and scalability of USCOs across sectors, allowing tailored solutions that align with both environmental goals and user-specific needs.

The findings in the thesis allow fast calculation of the potential of such communities. As an example, the sustainable operation of micro data center (1 MW) can be coupled to a contemporary large residential community (about 2500 dwellings), feeding heat from the data center through a 5GDHC with a STES (i.e. implemented as PTES) for thermal buffering, and a combination of BIPV PV solar panels and SMWT to generate renewable energy and a BESS for electrical buffering. The CAPEX for this example are in total about 67 million euros:

- **10 GWh 5GDHC** network for transporting the data center's heat: about 7M EUR, and an estimated static payback time of 6,3 years.
- **4 GWh PTES** for storing the excess heat: about 16M EUR, static payback time of 17 years.
- **10 Gwh PV** solar panels to generate renewable electricity for data center operations and EV charging: about 10M EUR, static payback time of 2,4 years.
- **10 GWh SMWT** as complementary power generation: about 16M EUR, static payback time of 4,9 years.
- **20 MWh BESS** for storing renewable energy and exploiting grid balance: about 18M EUR, static payback time of 8 years.

Where the indicative (static) payback period can be computed by taking the CAPEX-weighted average:

$$\text{PB} = \left(\frac{7}{67} \times 6,3y\right) + \left(\frac{16}{67} \times 17y\right) + \left(\frac{10}{67} \times 2,4y\right) + \left(\frac{16}{67} \times 4,9y\right) + \left(\frac{18}{67} \times 8y\right) = 8,4y$$

Meaning that this example of an energy community composed of a data center linked to residential housing has about CAPEX of 67M EUR, an indicated 8,4 years of static payback and therefore the potential to generate over 166M EUR of added value for its investors over the course of 30 years, while resulting in the sustainable and an advanced autonomous operation of it's community.

6 Conclusion

The transition to a sustainable society requires a radical rethinking of how utilities are produced, managed, and distributed. This thesis has explored the transformative potential of USCOs as a vehicle to enable that transition—particularly by decentralizing critical services such as energy, water, mobility, and even compute power. The USCO model, structured around the three foundational pillars of environmentally aware technology, economic viability, and legal-political feasibility, provides a comprehensive framework for realizing sustainable, scalable, and community-oriented infrastructure.

Technologically, the maturity and diversity of sustainable solutions—ranging from aquathermal systems and solar PV to advanced water regeneration and data center integration–demonstrate that the tools for transformation are not only available but increasingly efficient and adaptable. Economically, our analyses have shown that many of these technologies are not only environmentally sound but also financially viable, especially when deployed at scale and supported by intelligent business models. The introduction of static and dynamic payback models, as well as financing strategies incorporating equity, debt, and cooperative ownership, reveals a pragmatic path toward profitable sustainability.

Legally and politically, however, the path remains more complex. While progressive shifts, such as the expansion of VNR's authority or municipalities' growing flexibility around greywater reuse, indicate momentum, the regulatory landscape still poses significant obstacles. These include outdated utility laws, fragmented responsibilities, and ambiguous governance around infrastructure rights in public spaces. Overcoming these barriers will require coordinated action from policymakers, municipalities, and industry stakeholders.

Ultimately, the success of USCOs hinges on the ability to combine these three dimensions into coherent and adaptive business models. This thesis has presented several viable configurations and use cases, and while not exhaustive, it offers a solid foundation for further exploration and implementation. The findings are clear: USCOs are not merely a theoretical construct—they are a tangible, scalable solution to one of society's most pressing challenges. By aligning technological innovation, economic realism, and legal foresight, USCOs can accelerate our collective transition toward a more sustainable, resilient, and equitable future.

A Further Details on Technological and Environmental Opportunities

A.1 Renewable Fuel Production (Green Molecules)

A.1.1 Biofuels

In the context of renewable energy, biofuels offer versatile, sustainable fuels that can be locally produced or externally supplied. These biofuels can be generated on-site through anaerobic digestion or pyrolysis–two distinct processes that convert organic waste into usable energy sources–or, in some cases, can be supplied by the energy grid.

Anaerobic digestion involves breaking down organic waste, such as food scraps, manure, or agricultural residues, in a low-oxygen environment. This process produces biogas, which is rich in methane and can be used for heating, electricity generation, or as a fuel source. Anaerobic digestion systems are especially beneficial in agricultural or food-processing areas, where organic waste is readily available and can be continuously converted into biogas, promoting a circular approach to waste and energy use.

Pyrolysis is a thermal process that heats organic material to high temperatures in the absence of oxygen, breaking it down into bio-oil along with other byproducts like biochar and syngas. Bio-oil, with properties similar to crude oil, can be used as a fuel for heating or power generation. This process is well-suited for facilities that can access and process large amounts of biomass, such as wood waste or agricultural residues.

In addition to local production, biogas and bio-oil can sometimes be supplied via external sources or the energy grid, providing flexibility to areas without sufficient organic waste for continuous local production. This grid supply can support consistent availability of biofuels for industries or residential areas where biogas and bio-oil demand might fluctuate. First-generation biofuel technologies are generally at Technology Readiness Levels (TRL) 8–9, as they have proven viable on both small and large scales, with commercial facilities successfully operating worldwide. This high TRL indicates that both anaerobic digestion and pyrolysis are mature technologies that can significantly contribute to renewable energy portfolios, supporting sustainable fuel options for heating, power, and transport.

A.1.2 Green Hydrogen

Green hydrogen is a versatile and clean fuel produced through renewable methods and can be used for heating, electricity generation, and as a fuel for transport. It can be created locally via electrolysis, algae-based production, or photo-chemical solar panels, or it may be supplied externally via the energy grid.

Electrolysis splits water into hydrogen and oxygen using electricity, ideally sourced from renewables like solar or wind. This method produces pure hydrogen without emissions and is well-suited for applications where renewable electricity is abundant. Electrolysis is efficient, scalable, and increasingly used in areas aiming to decarbonize industrial processes and energy systems.

Algae-based production involves cultivating specific types of algae that produce hydrogen as a byproduct of photosynthesis under certain conditions. Though still emerging, this approach is promising because it leverages natural biological processes to create hydrogen sustainably. Algae-based systems could be highly beneficial for regions with strong sunlight and access to water, offering a biologically-driven alternative to electrolysis.

PC solar panels, like those developed by Solhyd, are designed to produce hydrogen directly from sunlight and water, skipping the electricity generation step altogether. This innovative technology, still progressing toward commercial readiness, holds significant potential for efficient, on-site hydrogen production and may be particularly useful in areas with limited access to the electrical grid.

Green hydrogen may also be supplied through the grid, allowing consistent access in regions without local production capacity. This grid-supplied hydrogen enables a steady supply for industrial processes or transport, even when local renewable generation may be variable.

The production of green hydrogen through electrolysis and algae is generally at TRL 7–9; electrolysis is widely proven and used commercially, while algae-based production is in the demonstration phase. Photo-chemical solar panels, like those by Solhyd, are around TRL 6–7 as they continue development and field testing. These various green hydrogen production methods offer flexible, scalable options to support clean energy goals and reduce reliance on fossil fuels.

A.2 Sustainable Thermal Energy Sources

A.2.1 Aquathermal Energy

Aquathermal energy from rivers, canals, or lakes is an innovative approach to harnessing natural water warmth for sustainable heating and cooling. This process begins by drawing water from the source and passing it through a heat exchanger, which absorbs heat without consuming the water. This heat is then transferred to a heat pump, which raises the temperature to levels suitable for building heating systems. Even though water temperatures in rivers, canals, and lakes may only reach around 10–20°C, the heat pump efficiently boosts this to a range that can warm buildings. After heat extraction, the water is returned to the source, minimizing environmental impact.

During warmer months, the system can be reversed for cooling, transferring excess heat from buildings back into the water to maintain a comfortable indoor climate. Aquathermal systems offer multiple advantages: they are renewable, produce low carbon emissions, and rely on stable water temperatures, making them reliable throughout the year.

Aquathermal energy technology is generally at TRL 8–9, meaning it is mature, commercially available, and already operational in multiple urban and rural locations. In some cases, newer implementations or high-efficiency systems using advanced materials may still be at TRL 6–7, where they undergo further demonstration and refinement in relevant settings.

This technology is ideal for urban areas near water bodies, allowing cities to reduce fossil fuel reliance and lower greenhouse gas emissions. With its high TRL and proven effectiveness, aquathermal energy from rivers, canals, and lakes is a practical solution for sustainable heating and cooling.

Figure 18: Aquathermal energy concept. Image ©ExtraQT [34]

A.2.2 Sewage Thermal Energy

In sewage thermal energy systems, influent and effluent refer to different stages of wastewater where heat can be effectively captured: Influent sewage thermal energy involves extracting heat from incoming wastewater before it enters the treatment plant. This wastewater, freshly discharged from homes or industrial sites, often retains significant warmth, making it a reliable and consistent source of energy. By capturing heat at this stage, influent systems can provide a steady supply of warmth, particularly useful in densely populated areas with high, stable wastewater flow. The captured heat is then transferred to a heat pump, which raises the temperature to a level suitable for heating buildings or even feeding into district heating networks.

Effluent sewage thermal energy, on the other hand, draws heat from treated wastewater as it leaves the treatment plant and is discharged into nearby rivers, lakes, or the sea. While the effluent is cooler than the influent, it still retains enough thermal energy for effective heat extraction. Capturing heat from effluent offers the added environmental benefit of lowering the temperature of the discharged water, reducing thermal impact on surrounding ecosystems.

Both influent and effluent sewage thermal systems work by using heat exchangers and heat pumps to elevate the captured heat to usable temperatures. The technology is highly mature and proven in many urban areas worldwide, generally at TRL 8–9. This high TRL indicates that sewage thermal energy is a commercially viable and reliable solution, capable of reducing fossil fuel reliance and lowering emissions in cities through renewable heating and cooling.

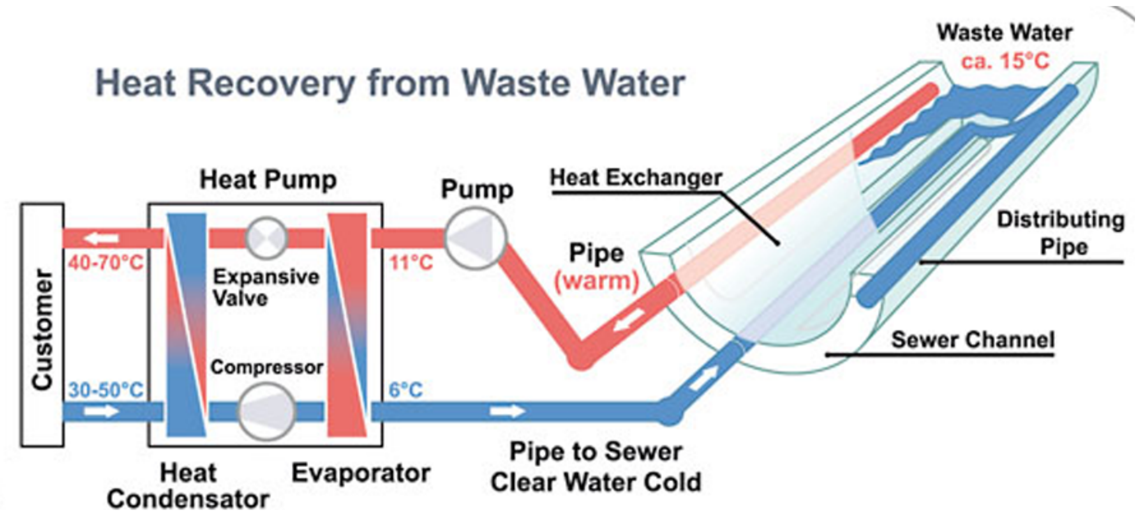

Figure 19: Heat recovery from waste water. Image ©Nedorost, Filip [79]

A.2.3 Residual heat

Residual heat is an untapped source of energy that can be captured from various activities, including industrial processes, CHP generation, exhaust gases, and data centers. This type of heat recovery reduces waste and offsets fossil fuel demand by repurposing heat that would otherwise dissipate unused into the environment.

Industrial processes often produce high levels of waste heat as a byproduct, particularly in sectors like manufacturing, steel production, and cement making. This residual heat, typically at high temperatures, can be recovered and used for other applications, such as heating buildings, driving turbines for electricity generation, or supplying heat to other industrial processes. Capturing residual heat from industries is highly efficient in industrial areas, where there's often a consistent demand for energy.

CHP systems generate both electricity and heat from a single fuel source, making them an efficient option for facilities requiring continuous power and thermal energy. In a CHP system, the residual heat from electricity generation can be captured and used for heating or further energy production, often in district heating networks. This method is commonly implemented in hospitals, industrial complexes, and universities.

Exhaust gases from combustion processes–whether in industrial equipment, transportation, or power plants–are another rich source of residual heat. Using heat exchangers, this heat can be recovered from exhaust streams, allowing it to be repurposed for heating or electricity generation, improving overall efficiency. Exhaust heat recovery is particularly advantageous in transportation or industrial settings with high thermal output.

Data centers, with their extensive server networks, generate significant residual heat as a byproduct of cooling systems. This waste heat can be captured and used to provide heating for nearby buildings or feed into district heating systems. In urban settings, using data center heat for district heating or to supply local buildings offers a practical and low-emission energy solution.

Residual heat recovery technology ranges from TRL 8–9 for well-established methods like CHP and industrial heat recovery, to TRL 7–8 for more specialized applications, such as exhaust heat capture in transportation and heat use from data centers. These technologies are mature, proven, and widely used in commercial and industrial settings, providing a sustainable way to maximize energy efficiency and reduce environmental impact by reusing available heat.

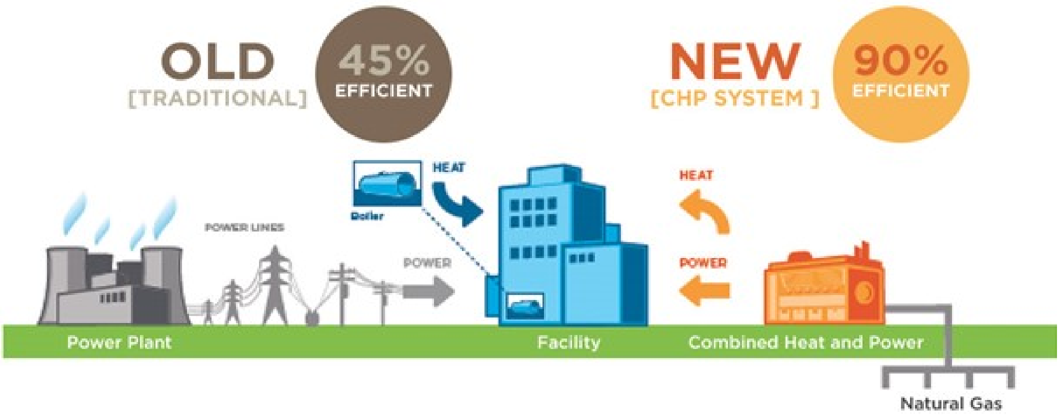

Figure 20: The use of residual heat in a CHP system. Image ©Pace University [82]

A.2.4 Geothermal Energy

Geothermal energy harnesses the Earth's natural heat for sustainable heating and cooling. Two common methods for seasonal geothermal energy storage are ATES and BTES, both of which use underground thermal reservoirs to store heat for later use.

ATES stores thermal energy in natural aquifers–underground layers of water-bearing rock. During summer, warm water is injected into the aquifer, where it is stored for winter heating. In winter, the process reverses, with cool water stored for use in summer cooling. ATES systems are especially suitable for areas with accessible aquifers and are widely used in urban districts and commercial buildings, providing an efficient way to balance seasonal heating and cooling needs.

BTES uses an array of deep boreholes drilled into the ground, where a network of pipes circulates water or a heat-transfer fluid. This fluid exchanges heat with the surrounding soil or rock, storing warmth in summer and extracting it in winter. BTES systems can be used in various geological conditions and are ideal for sites without natural aquifers, offering flexibility for both residential and commercial applications.

Both ATES and BTES systems are considered mature technologies, with ATES generally at TRL 8–9 due to its widespread commercial application, particularly in Europe. BTES is also at a high readiness level, typically TRL 7–9, depending on system size and specific geological requirements. These geothermal methods provide reliable, renewable energy storage solutions that can support year-round heating and cooling needs while significantly reducing reliance on conventional fuels.

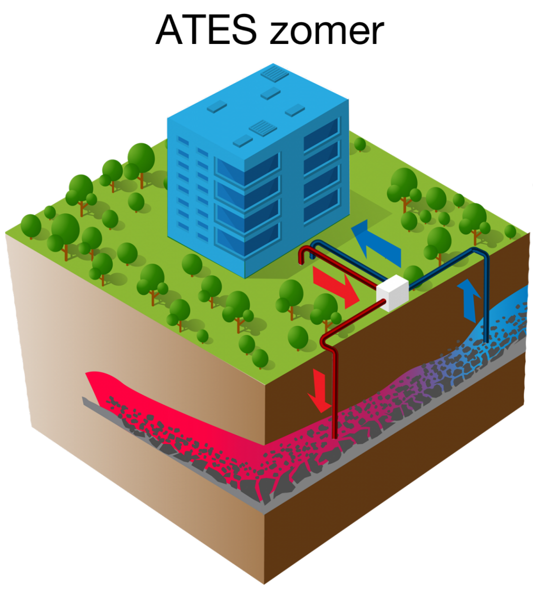

Figure 21: Concept for ATES. Image ©Terra Energy [108]

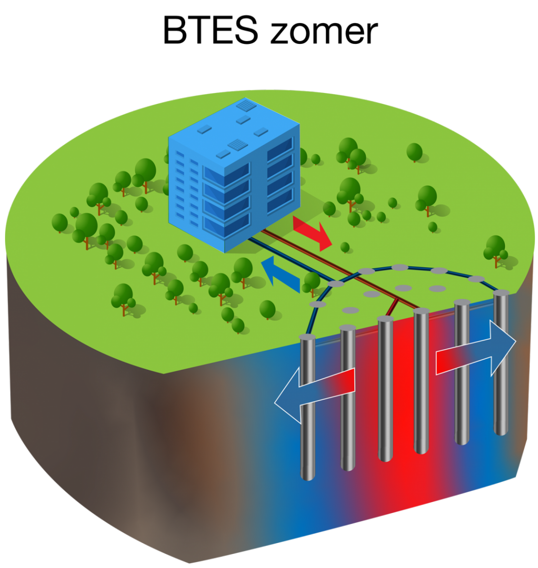

Figure 22: Concept for BTES. Image ©Terra Energy [108]

A.2.5 Air-to-water Heat Pump

Air-to-water heat pumps are efficient, renewable heating and cooling systems that extract heat from the outdoor air and transfer it to water for heating buildings and providing hot water. These systems come in several configurations, including split units, monobloc units, and HT versions, each suited to specific installation and heating requirements.

Split units consist of separate indoor and outdoor units connected by refrigerant lines. The outdoor unit absorbs heat from the air, which is then transferred indoors to heat water for radiators, underfloor heating, or domestic hot water. Split units are versatile and well-suited to residential and commercial applications, especially in areas with mild to moderate winters.

Monobloc units are self-contained systems where all components are housed in a single outdoor unit, simplifying installation and reducing the need for refrigerant handling. Water pipes connect directly from the monobloc unit to the building's heating system, making it ideal for residential use where space indoors may be limited. Monobloc systems are particularly valued for their ease of installation and are effective in a range of climates.

HT air-to-water heat pumps are designed to reach higher output temperatures, typically between 65°C and 90°C, making them suitable for buildings with traditional radiators that require higher water temperatures or the production of domestic hot water. HT versions are a good retrofit option for older buildings that may not have underfloor heating, allowing for efficient heating without requiring extensive changes to the existing heating infrastructure.

Air-to-water heat pumps are generally considered mature technology, with split and monobloc units at TRL 9, as they are commercially available and widely used in residential and commercial settings. HT air-to-water heat pumps are also approaching TRL 9 but may be rated at TRL 8–9, as they continue to gain traction as a retrofit solution. These heat pump options offer adaptable and energy-efficient heating solutions, helping reduce dependence on fossil fuels and supporting the transition to sustainable heating systems.

A.2.6 Absorption cooling

Absorption cooling is a technology that provides cooling using a heat source rather than electricity, making it an energy-efficient solution in settings where waste heat or renewable heat is available. This system is often used in industrial, commercial, and even residential applications to reduce electricity demand for cooling. Key types of absorption cooling systems include single-effect, double-effect, and triple-effect configurations, each offering different levels of efficiency depending on the temperature of the available heat source.

Single-effect absorption cooling uses a single generator to produce cooling and operates efficiently with low-temperature heat sources, such as solar thermal systems or industrial waste heat below 100°C. Single-effect systems are widely used for applications with moderate cooling needs and are generally at TRL 9, fully commercially available and proven in various sectors.

Double-effect absorption cooling incorporates two generators, improving the efficiency and cooling output when higher temperature heat sources are available, typically between 100°C and 200°C. Double-effect systems are well-suited for industrial settings where waste heat from processes such as cogeneration is available, achieving greater energy efficiency. Double-effect absorption cooling is also at TRL 9 and widely implemented in large-scale commercial and industrial applications.

Triple-effect absorption cooling is designed for very high-temperature heat sources, typically over 200°C, and offers the highest efficiency among absorption cooling systems. Although still less common, triple-effect systems are advancing in applications where high-temperature waste heat is abundant, such as in certain heavy industrial processes. These systems are at TRL 7–8, with ongoing developments to improve commercial viability.

Absorption cooling technology overall has a high readiness level, with single- and double-effect systems widely deployed and fully mature. Triple-effect systems, while promising for very high-temperature applications, are still advancing towards full commercial availability. Absorption cooling provides a sustainable alternative to conventional electric cooling, especially in settings with ample waste or renewable heat, helping reduce electricity consumption and supporting energy efficiency goals.

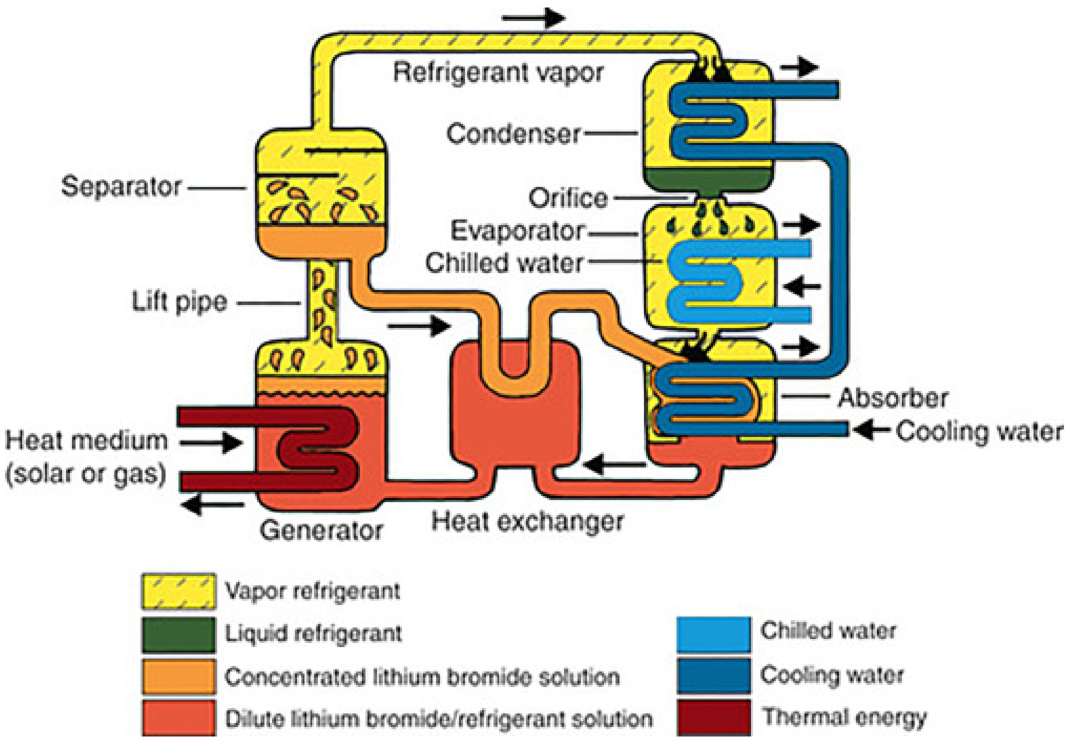

Figure 23: The concept of lithium bromide absorption cooling. Image ©Hoffschmidt, Bernhard [46]

A.3 Renewable Powers

A.3.1 Solar Power

Solar panels capture energy from sunlight, which can be converted to electricity, heat, or even hydrogen, depending on the panel type. Key types include PV, PT, PVT, and PC panels, each suited to specific energy applications.

PV panels are the most common type and convert sunlight directly into electricity using semiconductor materials, typically silicon. PV panels are widely used for residential, commercial, and utility-scale power generation, providing clean, renewable energy for a broad range of needs. With significant advancements over the years, PV technology is at TRL 9, making it fully mature and commercially available.

PT panels capture solar energy as heat, which is typically used to provide hot water or support space heating. PT panels are common in areas with high solar radiation and are an efficient way to produce thermal energy for residential and commercial buildings. PT systems are also at TRL 9, widely deployed, and highly efficient for heating applications.

PVT panels combine the functions of PV and PT panels, simultaneously generating electricity and heat from the same surface area. This dual-function capability makes PVT panels ideal for buildings with limited roof space where both electricity and hot water are needed. PVT panels are approaching TRL 8–9 as they gain popularity, particularly in urban and compact settings where maximizing energy production per square meter is important.

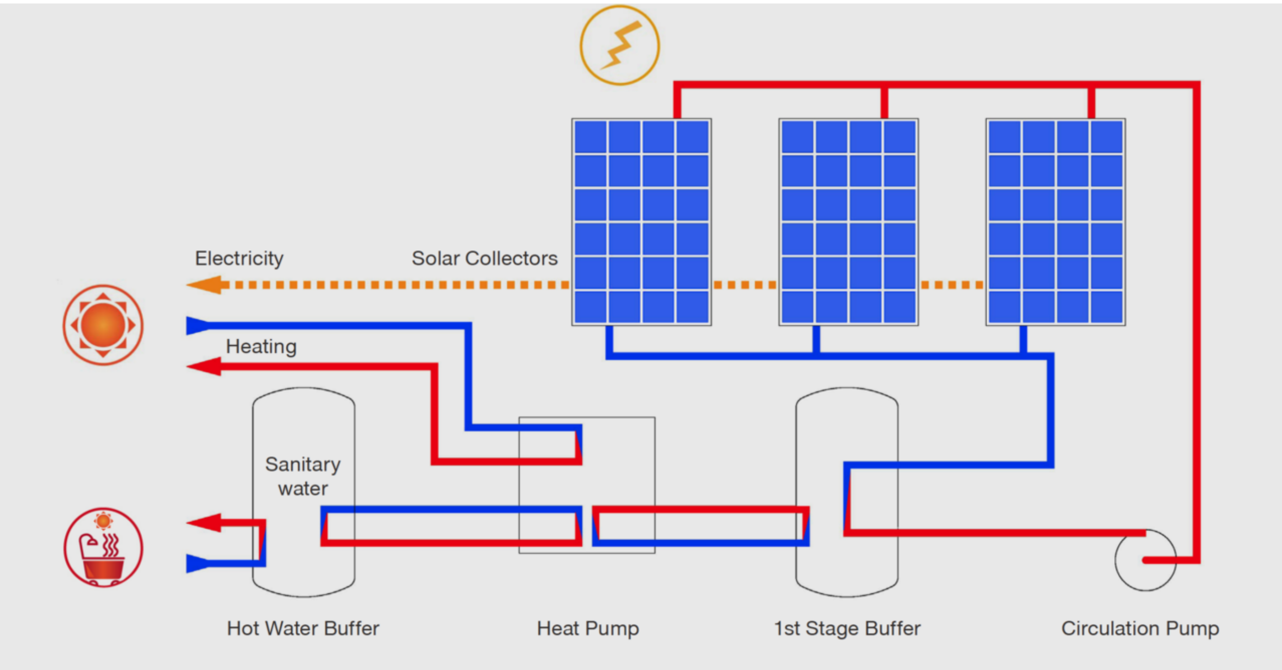

Figure 24: Concept of PVT solar panels that produce both electricity and heat. Image ©[103]

PC panels, which produce hydrogen directly from sunlight and water, are an emerging technology still in development. Although promising for sustainable hydrogen production, PC panels are at an earlier readiness level, typically around TRL 6–7, as they undergo further testing and refinement.

These solar panel types offer various renewable energy solutions, making it possible to meet electricity, heating, and hydrogen needs sustainably. With high readiness levels for PV, PT, and advancing PVT technology, solar panels play a critical role in supporting energy independence and reducing carbon emissions.

A.3.2 Concentrated Solar Power

CSP is a renewable energy technology that generates electricity by focusing sunlight onto a small area to produce high temperatures, which then drive a heat engine connected to an electric generator. CSP systems are particularly effective in sunny, arid regions and are primarily used for utility-scale power generation.

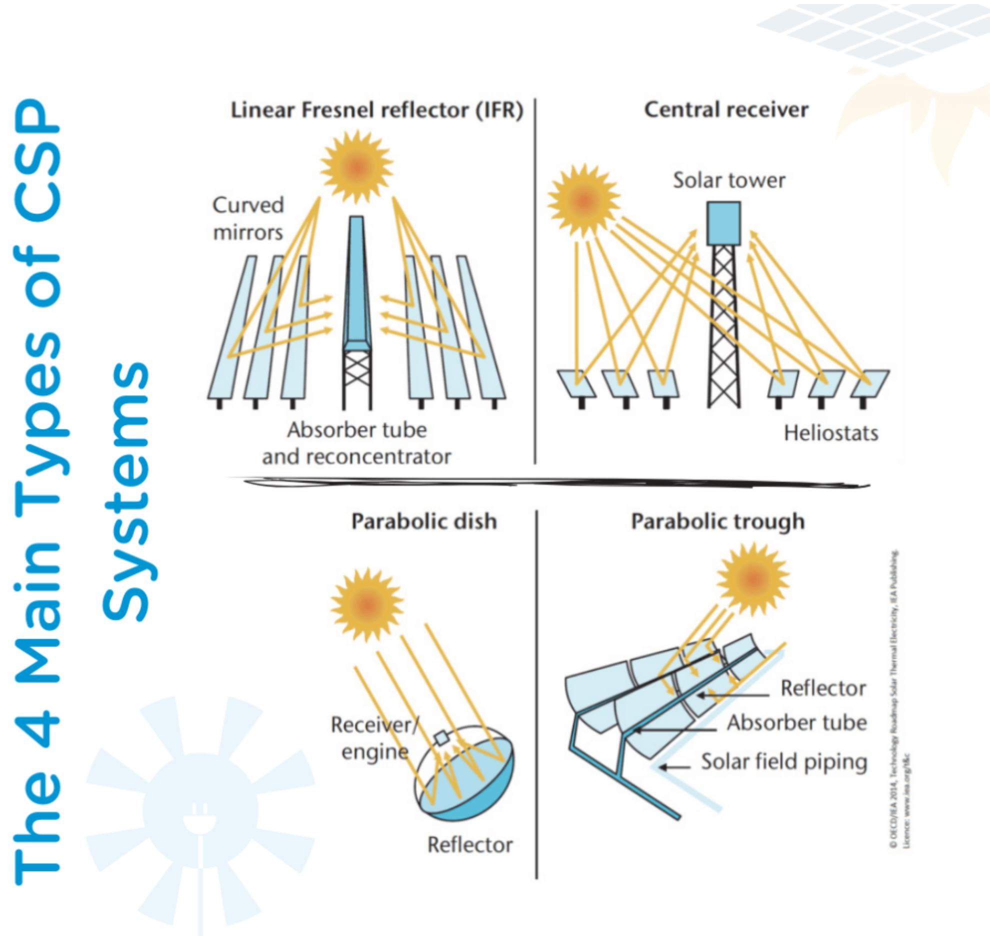

Figure 25: The 4 main types of CSP systems. Image ©Airswift [4]

CSP systems come in several configurations, including parabolic troughs, solar towers, linear Fresnel reflectors, and parabolic dishes, each using mirrors or lenses to concentrate sunlight. Once the sunlight is concentrated, it heats a fluid (often a synthetic oil or molten salt), which is used to produce steam that drives a turbine for electricity generation. The thermal energy can also be stored, allowing CSP plants to continue producing electricity even when the sun isn't shining.

Parabolic troughs use curved mirrors to focus sunlight onto a receiver tube running along the focal line, heating a fluid that powers a turbine. This technology is well-established and at TRL 9, widely used in commercial installations.

Solar towers concentrate sunlight onto a central receiver at the top of a tower. These systems achieve higher temperatures than troughs, improving efficiency and enabling long-term thermal storage with molten salts. Solar towers are also at TRL 8–9, with several large-scale plants in operation globally.

Linear Fresnel reflectors use flat mirrors to focus sunlight onto a series of tubes containing a heat-transfer fluid. This setup is simpler and cost-effective, with commercial applications available at TRL 8–9.

Parabolic dishes concentrate sunlight onto a single point, typically powering a Stirling engine to produce electricity directly. These systems are efficient but more suited to small-scale applications, typically at TRL 7–8, as they are less commonly used on a utility scale.

CSP with thermal storage enables plants to produce electricity even after sunset, offering a unique advantage for grid stability compared to other solar technologies. Overall, CSP is highly mature, especially in parabolic trough and solar tower designs, making it a commercially viable solution for utility-scale power generation in sun-rich areas, helping to reduce fossil fuel reliance and support grid resilience.

A.3.3 Wind Power

Wind energy is a well-established renewable energy technology, with applications ranging from large-scale wind farms to SMWT designed for local power generation. SMWT systems provide a flexible, decentralized approach to wind energy, suited to residential, agricultural, and small commercial settings.

Large-scale wind turbines are widely deployed in onshore and offshore wind farms, where they generate significant amounts of electricity to supply utility grids. These turbines are mature and efficient, with optimized designs that maximize power generation from wind resources. Large wind turbines operate at TRL 9, fully developed and commercially available, and are a central component of renewable energy strategies globally.

SMWT are designed to serve smaller energy needs or support local grids, often in rural or remote locations. SMWT systems can power homes, farms, or small businesses, providing renewable energy independence and reducing reliance on centralized power sources. SMWT units are also at TRL 9, with many models available commercially. They are an effective solution in locations with steady wind resources and suitable for a variety of applications, from residential energy systems to agriculture and off-grid installations.

Both large-scale and SMWT systems benefit from the high TRL and proven reliability of wind technology. Small and Medium Wind Turbines (SMWTs) specifically offer versatile, adaptable renewable energy for areas with moderate wind resources, enabling communities and businesses to harness clean energy locally. As a fully mature technology, wind energy remains one of the most cost-effective and scalable solutions in the transition to sustainable power generation.

A.3.4 Hydropower

Hydropower is a reliable and mature renewable energy source that harnesses the energy of flowing or falling water to generate electricity. While traditional hydropower often requires large dams, micro hydropower systems, like those developed by companies such as Turbulent, focus on providing sustainable energy at a small scale, making them ideal for local and remote applications.

Micro hydropower systems are designed to generate electricity from smaller streams or rivers without the need for large infrastructure. These systems operate at low head (height difference) and flow rates, making them minimally invasive to the natural environment. Micro hydropower systems are suited for rural or off-grid areas, small communities, farms, and individual buildings that need a reliable source of energy independent of the main grid. They are particularly valuable in areas with constant flowing water, even if the flow is modest.

Turbulent micro hydropower systems use a unique vortex technology, which channels water into a spiral to spin a turbine. This design is highly efficient for low-head water sources (e.g. with only a few meters of height difference) and doesn't require large dams or significant structural changes to the river. Turbulent's micro hydropower systems are typically at TRL 8–9, approaching full commercial maturity, with installations successfully deployed worldwide.

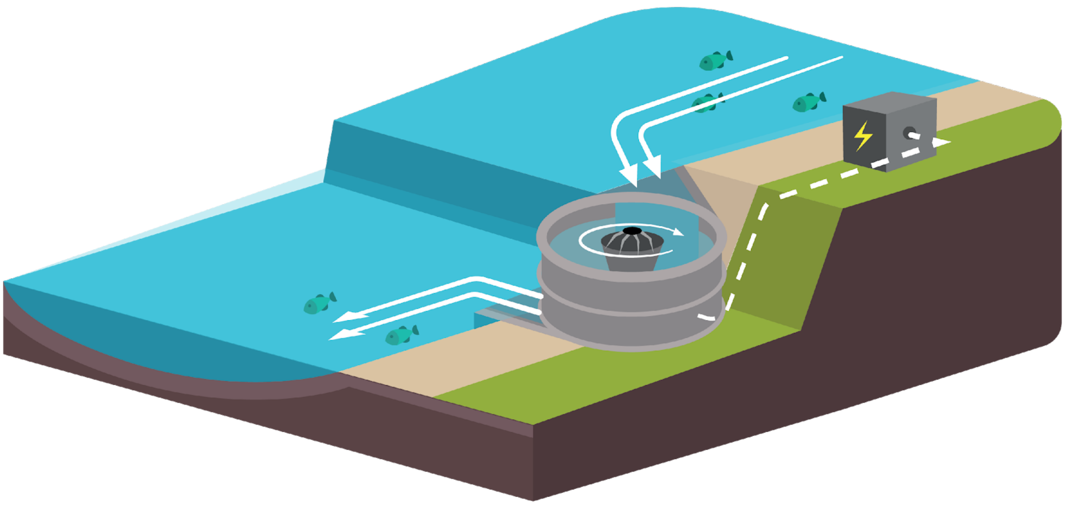

Figure 26: Concept of a damless micro hydro power system.
Image ©Turbulent [112]

Micro hydropower, especially technologies like Turbulent's, offers a scalable, eco-friendly solution for harnessing water energy without major environmental disruption. With its high TRL and commercial availability, micro hydropower is an effective renewable option for local power generation in communities, farms, and small businesses, particularly in remote or off-grid areas with access to flowing water.

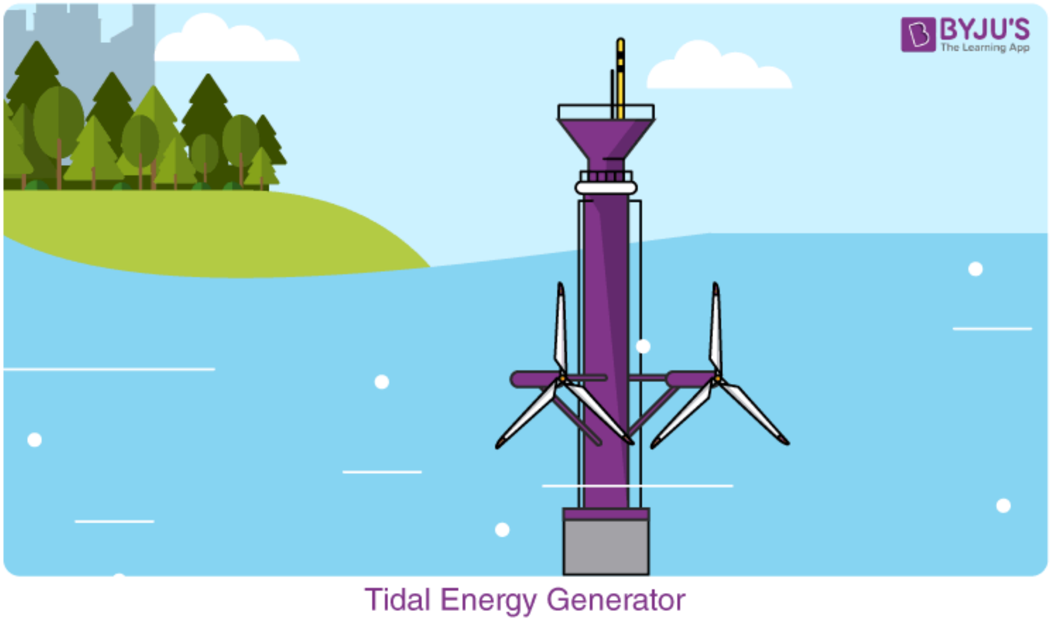

Figure 27: Tidal energy generator. Image ©BYJU'S [19]

A.3.5 Ocean Power

Ocean power harnesses the vast energy potential of oceans to generate electricity, using different forms of ocean movement, such as waves, tides, and ocean currents. This renewable energy source is particularly promising for coastal regions and offers a diverse range of technologies, each targeting specific types of ocean energy. Ocean power is still emerging, with many technologies progressing toward commercial readiness.

Key types of ocean power technologies include wave energy converters, tidal energy turbines, OTEC, and currents-based systems:

- Wave energy converters capture the energy from surface waves. These devices, which can be floating or submerged, use the up-and-down motion of waves to drive generators. Wave energy is promising but generally in the demonstration phase at TRL 5–7, with continued research needed to improve efficiency and cost-effectiveness.
- Tidal energy turbines operate similarly to underwater wind turbines, using tidal currents to turn the blades and generate electricity. Tidal energy is predictable and well-suited for locations with strong tides. Tidal turbines are at a higher readiness level, often TRL 7–8, with some commercially viable projects already operational in areas with significant tidal flow, like the UK and Canada.
- OTEC utilizes the temperature difference between warm surface water and colder deep water to drive a heat engine, generating electricity. OTEC requires specific tropical conditions with a strong thermal gradient and is typically at TRL 6–7, with pilot projects in areas like Hawaii and Japan testing its long-term feasibility.
- Currents-based systems capture energy from consistent, steady ocean currents, like the Gulf Stream. These systems are similar to tidal turbines but are designed to operate in areas with non-tidal, continuous currents. Currents-based ocean power is still in early development, generally at TRL 5–6.

Overall, ocean power holds significant potential, especially in coastal regions. Although still advancing toward higher TRLs, technologies like tidal turbines are approaching commercial maturity, while wave and OTEC systems are actively being tested and improved. Ocean power provides a reliable, renewable energy source that can complement other renewables, supporting energy diversity and resilience in coastal communities.

A.3.6 Heat-to-Power

Innovative heat-to-power systems, such as the ORC, provide an efficient way to convert low- and medium-temperature heat into electricity. ORC technology works similarly to traditional steam cycles but uses organic fluids with lower boiling points than water, making it ideal for waste heat recovery in industrial processes, as well as in geothermal, biomass, and CSP applications.

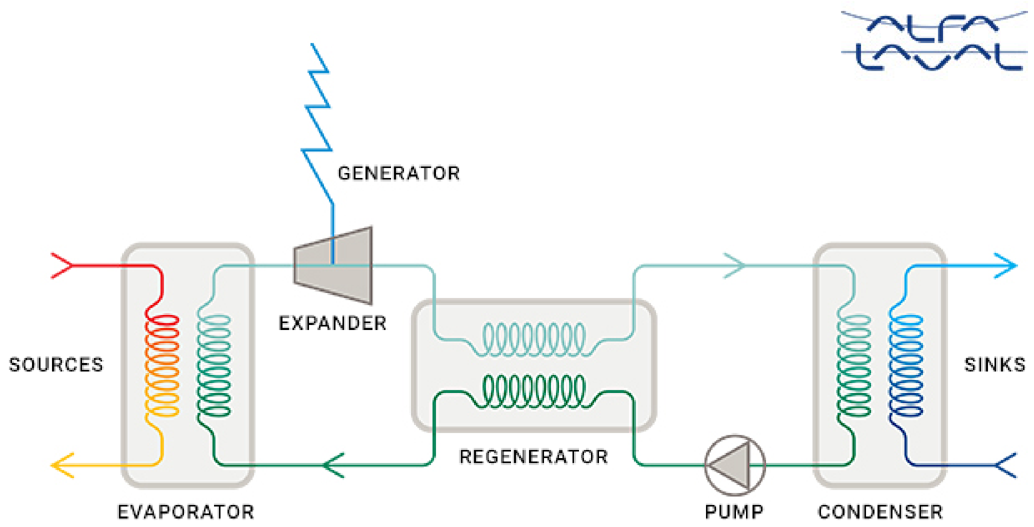

Figure 28: Working concept of an ORC. Image ©Alfa Laval [6]

One of the key advantages of ORC systems is their ability to operate efficiently at temperatures between 80°C and 350°C, capturing energy from low-temperature sources where conventional steam cycles would be less effective. ORC systems use specialized organic fluids, such as refrigerants or hydrocarbons, which evaporate at lower temperatures, enabling them to generate power from a variety of heat sources. This versatility makes ORC systems well-suited for industries like cement, glass, and chemicals, where excess process heat can be converted into electricity rather than wasted. They are also widely used in geothermal plants, tapping into moderate-temperature geothermal resources, and in biomass power plants, where heat from biomass combustion is used to drive ORC turbines.

With a TRL of 8–9, ORC technology is mature and commercially available, with reliable systems operating in diverse industrial and renewable energy settings worldwide. The proven efficiency and adaptability of ORC systems make them a valuable tool in reducing overall energy consumption, increasing the efficiency of industrial processes, and supporting a sustainable energy transition by capturing and repurposing waste heat.

A.3.7 Nuclear Power

SMRs and micro reactors represent a new wave of nuclear technology designed to provide safe, flexible, and low-carbon power on a smaller scale compared to traditional nuclear plants. These reactors are engineered to be compact and modular, offering unique advantages for generating reliable, clean energy in diverse locations, including remote or off-grid areas.

SMRs are typically designed to produce 10–300 MW of power per unit, making them well-suited for smaller grids, industrial sites, and regions with limited power needs. Their modular design allows multiple units to be constructed at a single site or added over time, making them adaptable to changing energy demands. SMRs often incorporate advanced safety features, such as passive cooling systems, which enhance safety by reducing reliance on human intervention or active components in emergencies. SMRs are generally at TRL 7–8, with several designs nearing commercial deployment and regulatory approval in countries like the U.S., Canada, and the UK.

Micro reactors are even smaller, producing between 1–10 MW, and are designed for maximum mobility and quick installation. These reactors can provide stable, continuous power to isolated areas, military bases, or mining operations that require energy independence. Micro reactors are engineered with inherent safety features, ensuring safe operation even in challenging environments. With a TRL of 6–7, micro reactors are in the late development and early demonstration stages, with pilot projects planned to further validate their performance and safety.

Both SMRs and micro reactors offer a promising solution to energy needs in regions with limited infrastructure or where renewable energy may be less feasible. Their small size, modularity, and advanced safety features make them ideal for providing resilient, clean energy, supporting global carbon reduction goals while ensuring energy security in diverse applications.

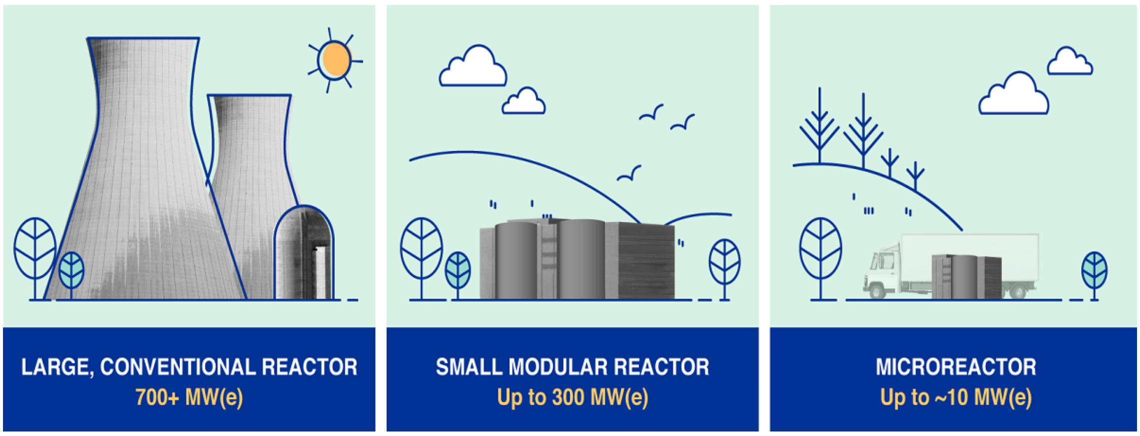

Figure 29: Variations on the scale of nuclear energy. Image ©IAEA [52]

A.4 Sustainable Energy Distribution and Storage

A.4.1 District Heating and Cooling Networks

4GDH and 5GDHC networks are advanced energy systems designed to provide sustainable, low-carbon heating and cooling for urban areas. Both of these systems improve upon traditional district heating by operating at lower temperatures, which reduces energy loss, allows seamless integration with renewable sources, and enhances overall efficiency.

4GDH operates at moderate temperatures, typically between 50–70°C, making it ideal for reducing heat loss and integrating renewable sources such as geothermal energy, solar thermal, waste heat, and heat pumps. These systems are also compatible with low temperature waste heat from data centers, wastewater treatment, and industrial processes, maximizing energy recovery and reducing overall emissions. Designed for modern, energy-efficient buildings that require less heat, 4GDH is fully mature and widely deployed, with a TRL of 8–9, making it a reliable, scalable option for cities focused on reducing their carbon footprint.

5GDHC takes this approach further by operating at ambient or ultra-low temperatures, typically between 10–30°C. Unlike previous generations, 5GDHC systems allow for two-way thermal exchange, enabling buildings within the network to share excess heat or cooling with one another. This setup minimizes waste and maximizes efficiency, making 5GDHC particularly suited for mixed-use urban areas where there are varied and dynamic heating and cooling needs. Buildings use heat pumps within this system to adjust temperatures as needed. With successful implementations across Europe, 5GDHC is also at TRL 8–9, demonstrating commercial maturity and reliability.

Together, 4GDH and 5GDHC networks represent the future of urban energy systems, providing adaptable, efficient, and low-emission solutions for district-wide heating and cooling while supporting climate and sustainability goals.

A.4.2 Innovative Seasonal Thermal Storage

Innovative STES technologies, including PTES, TTES, Rock Cavern Storage, and underground systems like ATES and BTES, are designed to store thermal energy seasonally, balancing heating and cooling demands over the year. These systems collect and retain excess thermal energy in warmer months, which can then be accessed during colder periods, making them valuable for energy efficiency and renewable integration.

PTES uses large, insulated pits filled with water to store heat, typically from sources like solar thermal energy, during summer. This stored heat is then used to meet heating needs in winter. PTES is especially effective in district heating networks, offering a scalable and cost-effective solution with a high TRL of 8–9, indicating full commercial readiness.

Tank Storage involves above-ground or underground insulated tanks filled with water, which serve as thermal storage reservoirs. Tank storage systems are versatile, providing reliable seasonal heat storage for smaller-scale applications or district heating networks, and are fully mature at TRL 8–9.

Rock Cavern Storage utilizes large, underground rock caverns to store thermal energy, often in the form of heated water. The thermal mass of the rock surrounding the cavern enhances storage efficiency, helping retain heat over long periods. Rock cavern storage is particularly suitable for large-scale applications and has proven successful in pilot and commercial projects, positioning it at TRL 7–8. Together with ATES and BTES, these STES solutions offer reliable, adaptable, and sustainable ways to address seasonal heating and cooling needs, optimize renewable energy usage, and reduce fossil fuel reliance in urban and industrial applications.

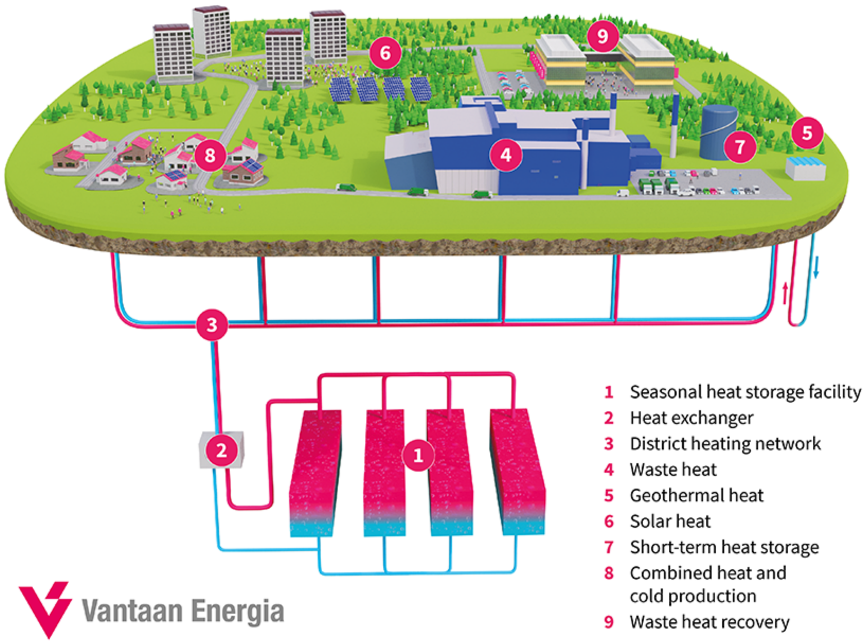

Figure 30: An energy community that uses a STES facility. Image ©Vantaan Energia, AFRY [1]

A.4.3 Innovative Thermal Buffers

Innovative thermal buffers like ice storage, sand thermal storage, molten salt, and PCMs are advanced technologies designed to store thermal energy for short- to medium-term use, effectively acting as energy “buffers.” These systems capture excess heat or cold during low-demand times and release it when needed, helping to balance energy loads, reduce peak demand, and enhance the integration of renewable energy.

Ice Storage works by freezing water into ice during times when electricity is inexpensive or renewable energy is abundant, usually at night or in colder months. This stored cold energy is then used for cooling in warmer periods, often in commercial buildings or industrial applications. Ice storage is a mature technology with a TRL of 8–9 and is widely used to provide energy-efficient cooling. Sand thermal storage uses sand as a high-temperature storage medium, storing heat at temperatures up to 1.000°C from sources like concentrated solar power or excess industrial heat. Sand’s thermal stability and ability to retain heat make it ideal for high-energy applications, such as providing supplemental heating. Currently at TRL 6–7, sand thermal storage is an emerging technology with promising pilot projects underway.

Molten salt storage is commonly used in CSP plants. In this system, sunlight heats molten salt to high temperatures, storing thermal energy that can be converted into steam for electricity generation even when the sun isn't shining. Molten salt storage is highly effective for large-scale renewable energy applications, with a TRL of 8–9 indicating its commercial readiness.

PCMs absorb and release large amounts of heat as they change phases, typically from solid to liquid and back. PCMs are particularly useful for applications that require a steady temperature, as they release heat gradually. These materials are versatile and can be applied in building materials, refrigeration, and industrial processes. With a TRL of 8–9, PCMs are commercially available in various products, offering adaptable thermal storage solutions.

Together, these innovative thermal buffers provide efficient, flexible options for managing short- and medium-term energy demands. They are critical in supporting grid stability, optimizing renewable energy use, and providing reliable heating and cooling in residential, commercial, and industrial applications.

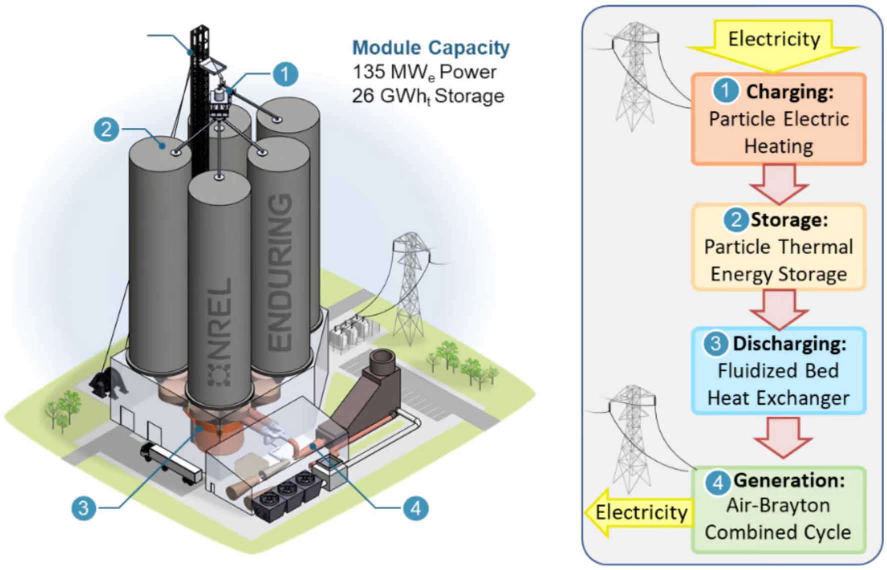

Figure 31: Concept of sand thermal storage using electricity.
Image ©Zhiwen Ma [71]

A.4.4 Battery Energy Storage Systems

BESS are vital components of modern power systems, acting as robust buffers for electricity. BESS store electrical energy in batteries and release it when needed, helping balance grid supply and demand, supporting renewable energy integration, and providing reliable backup power. This ability to store and dispatch power on demand makes BESS crucial for applications that need rapid response and reliable energy over short to medium durations, such as grid stabilization, peak demand management, and supporting renewable sources like solar and wind. BESS employ various types of battery technologies, each suited to specific applications:

- Lithium-Ion BESS are the most widely used, known for their high energy density, fast charging, and long cycle life. They're ideal for high-demand applications, including balancing the grid and addressing the variability of solar and wind power. As a mature technology with TRL 9, lithium-ion BESS have seen extensive commercial deployment worldwide.
- Flow Battery BESS use liquid electrolytes stored in external tanks, which makes it easy to scale storage capacity. This design is particularly suited for long-duration storage and high-frequency cycling, such as for grid-scale applications that require consistent energy output. Flow batteries are advancing steadily, typically at TRL 7–8, with successful pilot projects showcasing their potential.
- Lead-Acid BESS are among the oldest battery technologies and are commonly used for backup applications. Although they have a lower energy density and shorter cycle life than lithium-ion batteries, lead-acid systems remain valuable in settings where cost-effectiveness and reliability are key, such as emergency power for hospitals. These systems are highly mature and widely used, with a TRL of 9.

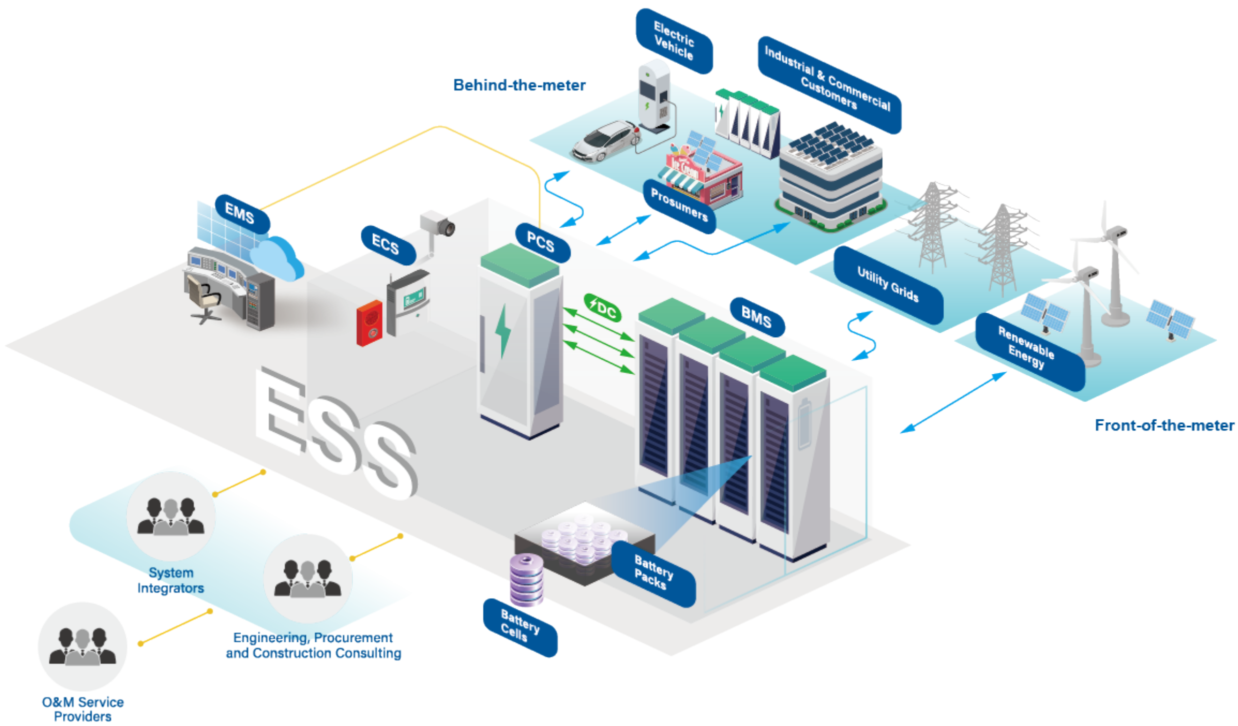

Figure 32: Concept of a Battery Energy Storage System. Image ©Energy Storage News [31]

A.5 Sustainable Water Production

A.5.1 Water Harvesting

Rainwater harvesting is a technique that involves capturing, storing, and using rainwater that falls on surfaces like rooftops and paved areas, instead of allowing it to run off. This harvested water can be filtered and used for drinking, irrigation, household cleaning, and even industrial applications. In regions facing water scarcity, rainwater harvesting is an invaluable method to conserve water, reduce demand on groundwater, and provide an alternative water source.

The process begins with collection surfaces–usually rooftops, as they are easy to install collection systems on and provide a relatively clean surface for capturing rain. From the rooftop, rainwater is directed into gutters and downspouts, which guide the water toward storage tanks or reservoirs. Along the way, screens and filters are installed to keep out leaves, dust, and other debris that might contaminate the water.

Many systems include a first-flush diverter, which channels away the initial flow of rainwater since this first runoff may carry accumulated dirt, pollutants, and other impurities from the collection surface. By discarding this initial water, the diverter helps ensure that the stored water remains cleaner and safer to use.

Once filtered, the rainwater flows into storage tanks or underground reservoirs, which can be made from materials like plastic, metal, or concrete depending on storage needs. The tanks are typically covered to prevent contamination from debris and insects. Some systems also include overflow pipes to handle excess water during heavy rainfall, ensuring that no water is wasted.

Rainwater harvesting is a sustainable, low-cost solution that can significantly reduce demand on local water supplies. It conserves groundwater, lessens the impact on municipal water systems, and provides a dependable water source during dry periods. By capturing rainwater, households and communities can contribute to water conservation, enhance resilience to water shortages, and help ensure that clean, usable water is available for future generations.

A.5.2 Membrane Bioreactor

Wastewater regeneration using MBR technology is an advanced and efficient process that enables the treatment and reuse of wastewater from sources like showers, sinks, and washing machines. This treated water, known as regenerated wastewater, can be used for non-potable purposes such as toilet flushing, landscape irrigation, and cooling systems, significantly reducing the demand for fresh water.

In an MBR system, wastewater undergoes two main stages of treatment:

- Biological Treatment: First, wastewater passes through a biological treatment stage where bacteria break down organic matter and pollutants, reducing contaminants by natural microbial processes.
- Membrane Filtration: After biological treatment, the water is filtered through microfiltration or ultrafiltration membranes. These membranes act as physical barriers, trapping particles, pathogens, and suspended solids, resulting in highly purified water that meets stringent health and environmental standards.

Thanks to its compact and modular design, MBR technology is ideal for decentralized, on-site black and grey wastewater recycling, making it suitable for use in residential buildings, commercial complexes, and even industrial sites.

MBR technology for wastewater regeneration is well-established and operates at a TRL of 8–9. This means it is mature, with widespread commercial deployment in buildings, commercial sites, and industrial facilities around the world.

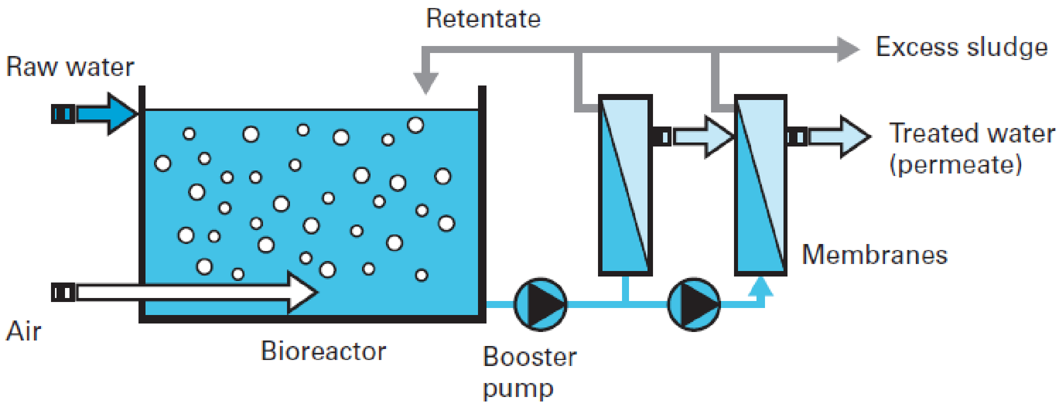

Figure 33: Workings of a Membrane Bioreactor. Image ©IconicTech [51]

A.5.3 Innovative Desalination and Filtration

Innovative desalination and filtration techniques are paving the way for sustainable, efficient, and advanced water treatment solutions. These methods aim to provide clean water with minimal environmental impact, addressing global water scarcity. Here's a closer look at some of the leading technologies and their current stages of development.

Solar-powered desalination using CSP harnesses solar energy to generate heat or steam for seawater desalination in a multistage evaporator (see Figure 34). This method leverages abundant sunlight, especially in arid, sunny regions, reducing dependency on fossil fuels. Ideal for remote coastal areas, CSP-driven desalination provides a renewable solution for clean water. Currently, this technology is at TRL 7–8, with some commercial installations but still advancing in efficiency and scalability for broader use.

Graphene-based filtration utilizes ultra-thin graphene membranes that allow water molecules to pass through while blocking contaminants and salts. Due to graphene's nanoscale structure, this method offers exceptionally high permeability, making filtration both efficient and effective. Graphene filtration shows strong potential for industrial and municipal applications, though it is currently at TRL 5–6. While it has undergone promising lab and pilot tests, large-scale implementation is still in its early stages.

Forward osmosis uses natural osmotic pressure to draw water through a membrane, leaving salts and impurities behind. By employing biodegradable draw solutions, this technique minimizes chemical waste, enhancing sustainability. It's particularly useful for treating brackish water and wastewater, especially in settings where waste disposal options are limited. This technology is progressing at TRL 6–7, with prototypes and pilot projects in operation but requiring further steps for full commercialization.

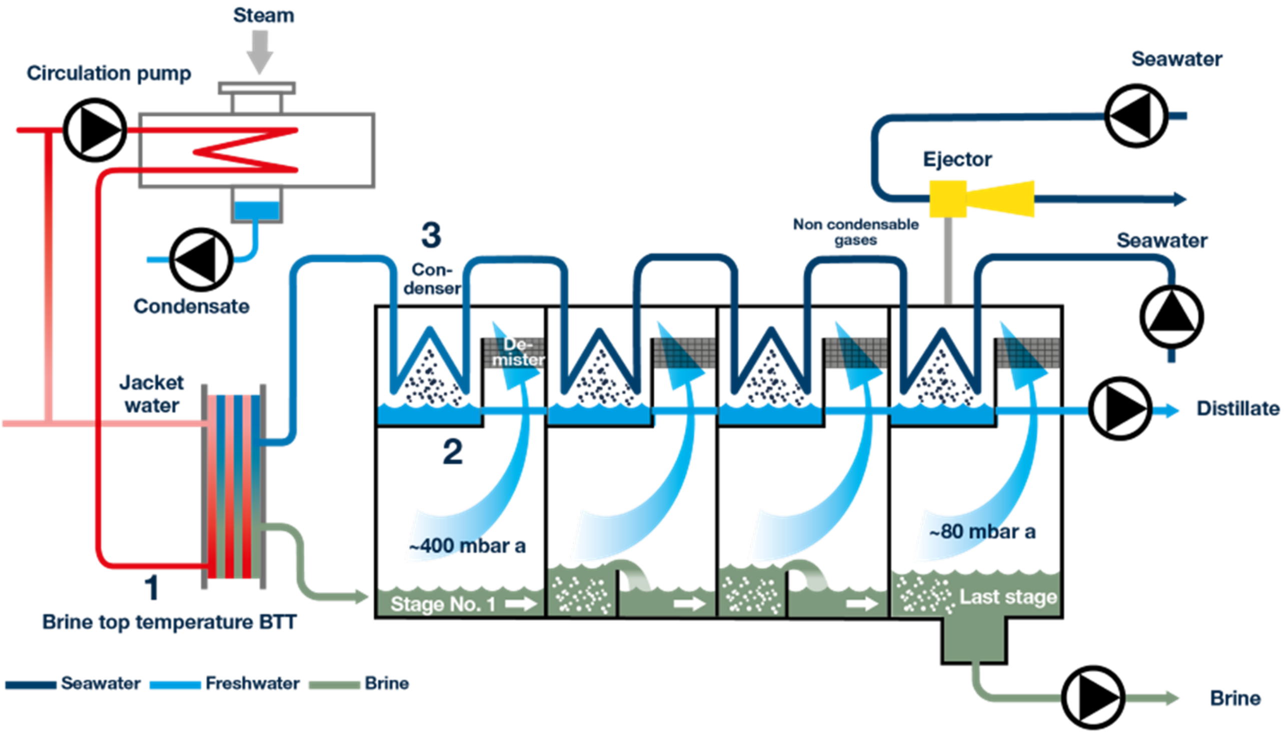

Figure 34: Desalination proces from seawater to clean distilate. Image ©Wartsila [114]

Biomimetic membranes are inspired by natural cellular processes, mimicking selective permeability to achieve desalination with lower energy requirements. These membranes hold promise for revolutionary, low-energy desalination solutions that could significantly benefit water-scarce regions. However, biomimetic membrane technology is currently at TRL 4–5, making it largely experimental. While there is significant potential, more research and development are needed for large-scale applications.

CDI uses electrodes to attract and remove charged ions from water, offering an energy-efficient method for desalinating low-salinity brackish water. CDI is particularly advantageous due to its low energy input and is suitable for regions with brackish groundwater sources. Currently, CDI technology is at TRL 7, with several operational pilots demonstrating its potential, though further advancements are necessary for widespread deployment.

These innovative desalination and filtration techniques represent a range of approaches to sustainable water treatment. While they are at different stages of readiness, each offers unique benefits, from reduced energy use to enhanced filtration efficiency. As these technologies mature, they have the potential to play a critical role in addressing water scarcity worldwide.

A.5.4 Atmospheric Water Generation

AWG technologies offer innovative solutions for extracting water from the air, tapping into a resource often overlooked in water-scarce regions. By drawing moisture from the atmosphere, these methods provide clean, renewable water with minimal environmental impact. Here's an overview of key AWG techniques and their current TRL.

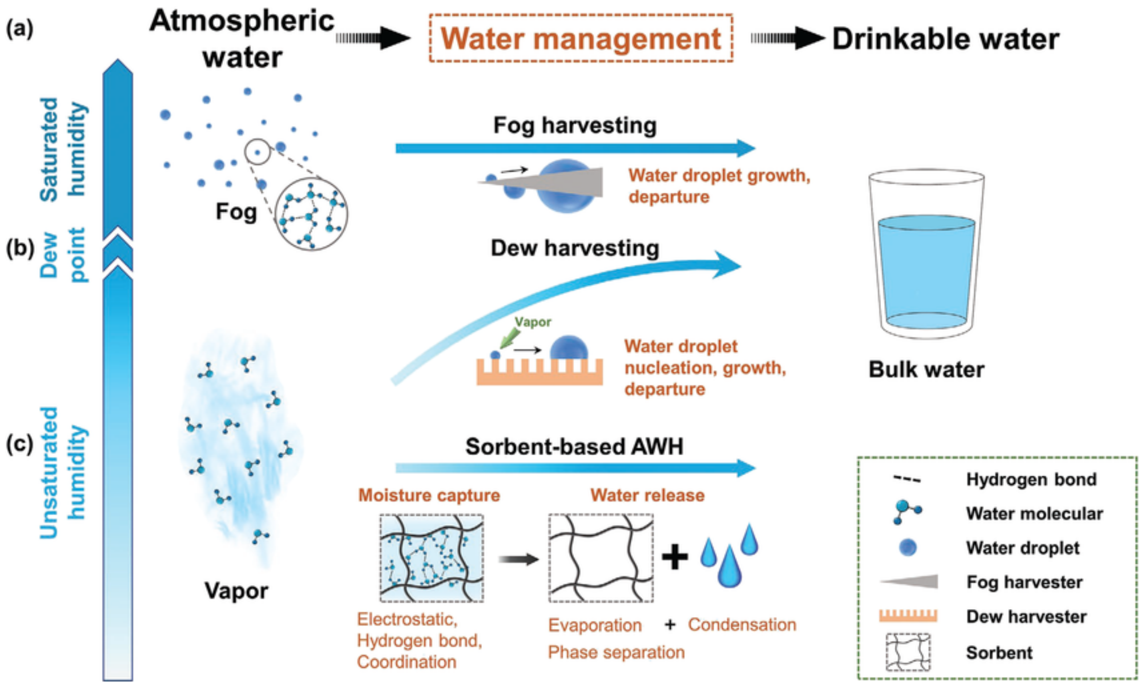

Figure 35: The proces of generating drinkable water from atmospheric water. Image ©Hengyi Lu [69]

Fog and dew harvesting uses specially designed mesh materials to capture tiny droplets from the air, channeling them into collection reservoirs. Advanced mesh technology enhances this process by increasing water capture efficiency, even in arid regions with low humidity. This method is especially useful in coastal or mountainous areas where fog is frequent. Fog and dew harvesting systems are generally at TRL 8–9, as they are already operational in several regions worldwide, though ongoing innovations in mesh design continue to improve efficiency.

Hydrogel-based water harvesting employs superabsorbent materials, or hydrogels, that capture moisture from the air. Once collected, this water can be released from the hydrogel through gentle heating or exposure to sunlight. Hydrogels are highly effective in low-humidity environments, making them valuable for arid climates. Currently, hydrogel water harvesting is at TRL 5–6, with significant progress in lab testing and prototype development, though commercial applications are still in early stages.

Hydropanels, or solar-powered atmospheric water generators, use solar energy to drive moisture condensation from the air. This AWG method generates clean water in areas with abundant sunlight but limited water access, making it ideal for remote and off-grid locations. Hydropanels are self-contained and modular, allowing easy deployment in diverse environments. These systems are at TRL 7–8, with successful pilot projects and growing commercial adoption, especially in arid and semi-arid regions.

Biomimetic membranes, inspired by natural biological processes, are engineered to capture and release water molecules selectively. These membranes mimic the function of natural cell membranes, optimizing water extraction from humid air with minimal energy. Biomimetic membrane technology is especially promising for low-energy, efficient AWG, though it is currently at TRL 4–5. This field is still experimental, with ongoing research needed to advance these membranes to large-scale applications.

These Atmospheric Water Generation techniques present promising solutions for sustainable water access, particularly in regions with limited groundwater or surface water sources. While some, like fog and dew harvesting, are already mature and operational, others, like hydrogel and biomimetic membranes, are still developing. Each technology's potential lies in its unique approach to harnessing atmospheric moisture, offering environmentally friendly ways to secure water in challenging climates.

B Dynamic OPEX Tables over 50 Years

B.1 Small-sized Communities (100 MWh, 20–30 dwellings)

DYNAMIC OPEX PER TECHNOLOGY	1	2	3	4	5
Biogas Production (Anaerobic Digestion)	-€35.714	-€34.061	-€32.484	-€30.980	-€29.546
Bio-Oil Production (Pyrolysis)	-€60.000	-€57.222	-€54.573	-€52.047	-€49.637
Green Hydrogen Production (Electrolysis)	-€30.303	-€28.900	-€27.562	-€26.286	-€25.069
Aquathermal Energy Systems	-€8.182	-€7.803	-€7.442	-€7.097	-€6.769
Sewage Thermal Energy Systems	-€6.667	-€6.358	-€6.064	-€5.783	-€5.515
Residual Heat Recovery Systems	-€6.000	-€5.722	-€5.457	-€5.205	-€4.964
Geothermal Energy Systems (ATES/BTES)	-€6.000	-€5.722	-€5.457	-€5.205	-€4.964
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€4.000	-€3.815	-€3.638	-€3.470	-€3.309
Solar Panels (PV)	-€1.765	-€1.683	-€1.605	-€1.531	-€1.460
Solar Panels (PT)	-€2.824	-€2.693	-€2.568	-€2.449	-€2.336
Solar Panels (PVT)	-€4.412	-€4.208	-€4.013	-€3.827	-€3.650
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€15.000	-€14.306	-€13.643	-€13.012	-€12.409
Wind Energy Systems (Onshore)	-€2.500	-€2.384	-€2.274	-€2.169	-€2.068
Small and Medium Wind Turbines (SMWT)	-€6.000	-€5.722	-€5.457	-€5.205	-€4.964
Micro Hydropower	-€9.333	-€8.901	-€8.489	-€8.096	-€7.721
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€22.857	-€21.799	-€20.790	-€19.827	-€18.909
Small Modular Reactors (SMRs) and Micro Reactors	-€28.000	-€26.704	-€25.467	-€24.288	-€23.164
District Heating (4th Generation)	-€6.000	-€5.722	-€5.457	-€5.205	-€4.964
District Heating and Cooling (5th Generation)	-€2.857	-€2.725	-€2.599	-€2.478	-€2.364

Table 19: Dynamic opex in a small community, year 1–5.

DYNAMIC OPEX PER TECHNOLOGY	6	7	8	9	10
Biogas Production (Anaerobic Digestion)	-€28.178	-€26.873	-€25.629	-€24.443	-€23.311
Bio-Oil Production (Pyrolysis)	-€47.339	-€45.147	-€43.057	-€41.064	-€39.163
Green Hydrogen Production (Electrolysis)	-€23.909	-€22.802	-€21.746	-€20.739	-€19.779
Aquathermal Energy Systems	-€6.455	-€6.156	-€5.871	-€5.600	-€5.340
Sewage Thermal Energy Systems	-€5.260	-€5.016	-€4.784	-€4.563	-€4.351
Residual Heat Recovery Systems	-€4.734	-€4.515	-€4.306	-€4.106	-€3.916
Geothermal Energy Systems (ATES/BTES)	-€4.734	-€4.515	-€4.306	-€4.106	-€3.916
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€3.156	-€3.010	-€2.870	-€2.738	-€2.611
Solar Panels (PV)	-€1.392	-€1.328	-€1.266	-€1.208	-€1.152
Solar Panels (PT)	-€2.228	-€2.125	-€2.026	-€1.932	-€1.843
Solar Panels (PVT)	-€3.481	-€3.320	-€3.166	-€3.019	-€2.880
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€11.835	-€11.287	-€10.764	-€10.266	-€9.791
Wind Energy Systems (Onshore)	-€1.972	-€1.881	-€1.794	-€1.711	-€1.632
Small and Medium Wind Turbines (SMWT)	-€4.734	-€4.515	-€4.306	-€4.106	-€3.916
Micro Hydropower	-€7.364	-€7.023	-€6.698	-€6.388	-€6.092
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€18.034	-€17.199	-€16.403	-€15.643	-€14.919
Small Modular Reactors (SMRs) and Micro Reactors	-€22.092	-€21.069	-€20.093	-€19.163	-€18.276
District Heating (4th Generation)	-€4.734	-€4.515	-€4.306	-€4.106	-€3.916
District Heating and Cooling (5th Generation)	-€2.254	-€2.150	-€2.050	-€1.955	-€1.865

Table 20: Dynamic opex in a small community, year 6–10.

DYNAMIC OPEX PER TECHNOLOGY	11	12	13	14	15
Biogas Production (Anaerobic Digestion)	-€22.232	-€21.203	-€20.221	-€19.285	-€18.392
Bio-Oil Production (Pyrolysis)	-€37.350	-€35.620	-€33.971	-€32.399	-€30.899
Green Hydrogen Production (Electrolysis)	-€18.863	-€17.990	-€17.157	-€16.363	-€15.605
Aquathermal Energy Systems	-€5.093	-€4.857	-€4.632	-€4.418	-€4.213
Sewage Thermal Energy Systems	-€4.150	-€3.958	-€3.775	-€3.600	-€3.433
Residual Heat Recovery Systems	-€3.735	-€3.562	-€3.397	-€3.240	-€3.090
Geothermal Energy Systems (ATES/BTES)	-€3.735	-€3.562	-€3.397	-€3.240	-€3.090
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€2.490	-€2.375	-€2.265	-€2.160	-€2.060
Solar Panels (PV)	-€1.099	-€1.048	-€999	-€953	-€909
Solar Panels (PT)	-€1.758	-€1.676	-€1.599	-€1.525	-€1.454
Solar Panels (PVT)	-€2.746	-€2.619	-€2.498	-€2.382	-€2.272
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€9.337	-€8.905	-€8.493	-€8.100	-€7.725
Wind Energy Systems (Onshore)	-€1.556	-€1.484	-€1.415	-€1.350	-€1.287
Small and Medium Wind Turbines (SMWT)	-€3.735	-€3.562	-€3.397	-€3.240	-€3.090
Micro Hydropower	-€5.810	-€5.541	-€5.284	-€5.040	-€4.806
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€14.228	-€13.570	-€12.941	-€12.342	-€11.771
Small Modular Reactors (SMRs) and Micro Reactors	-€17.430	-€16.623	-€15.853	-€15.119	-€14.419
District Heating (4th Generation)	-€3.735	-€3.562	-€3.397	-€3.240	-€3.090
District Heating and Cooling (5th Generation)	-€1.779	-€1.696	-€1.618	-€1.543	-€1.471

Table 21: Dynamic opex in a small community, year 11–15.

DYNAMIC OPEX PER TECHNOLOGY	16	17	18	19	20
Biogas Production (Anaerobic Digestion)	-€17.541	-€16.729	-€15.954	-€15.215	-€14.511
Bio-Oil Production (Pyrolysis)	-€29.468	-€28.104	-€26.803	-€25.562	-€24.379
Green Hydrogen Production (Electrolysis)	-€14.883	-€14.194	-€13.537	-€12.910	-€12.312
Aquathermal Energy Systems	-€4.018	-€3.832	-€3.655	-€3.486	-€3.324
Sewage Thermal Energy Systems	-€3.274	-€3.123	-€2.978	-€2.840	-€2.709
Residual Heat Recovery Systems	-€2.947	-€2.810	-€2.680	-€2.556	-€2.438
Geothermal Energy Systems (ATES/BTES)	-€2.947	-€2.810	-€2.680	-€2.556	-€2.438
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€1.965	-€1.874	-€1.787	-€1.704	-€1.625
Solar Panels (PV)	-€867	-€827	-€788	-€752	-€717
Solar Panels (PT)	-€1.387	-€1.323	-€1.261	-€1.203	-€1.147
Solar Panels (PVT)	-€2.167	-€2.066	-€1.971	-€1.880	-€1.793
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€7.367	-€7.026	-€6.701	-€6.390	-€6.095
Wind Energy Systems (Onshore)	-€1.228	-€1.171	-€1.117	-€1.065	-€1.016
Small and Medium Wind Turbines (SMWT)	-€2.947	-€2.810	-€2.680	-€2.556	-€2.438
Micro Hydropower	-€4.584	-€4.372	-€4.169	-€3.976	-€3.792
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€11.226	-€10.706	-€10.211	-€9.738	-€9.287
Small Modular Reactors (SMRs) and Micro Reactors	-€13.752	-€13.115	-€12.508	-€11.929	-€11.377
District Heating (4th Generation)	-€2.947	-€2.810	-€2.680	-€2.556	-€2.438
District Heating and Cooling (5th Generation)	-€1.403	-€1.338	-€1.276	-€1.217	-€1.161

Table 22: Dynamic opex in a small community, year 16–20.

DYNAMIC OPEX PER TECHNOLOGY	21	22	23	24	25
Biogas Production (Anaerobic Digestion)	-€13.839	-€13.199	-€12.587	-€12.005	-€11.449
Bio-Oil Production (Pyrolysis)	-€23.250	-€22.173	-€21.147	-€20.168	-€19.234
Green Hydrogen Production (Electrolysis)	-€11.742	-€11.199	-€10.680	-€10.186	-€9.714
Aquathermal Energy Systems	-€3.170	-€3.024	-€2.884	-€2.750	-€2.623
Sewage Thermal Energy Systems	-€2.583	-€2.464	-€2.350	-€2.241	-€2.137
Residual Heat Recovery Systems	-€2.325	-€2.217	-€2.115	-€2.017	-€1.923
Geothermal Energy Systems (ATES/BTES)	-€2.325	-€2.217	-€2.115	-€2.017	-€1.923
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€1.550	-€1.478	-€1.410	-€1.345	-€1.282
Solar Panels (PV)	-€684	-€652	-€622	-€593	-€566
Solar Panels (PT)	-€1.094	-€1.043	-€995	-€949	-€905
Solar Panels (PVT)	-€1.710	-€1.630	-€1.555	-€1.483	-€1.414
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€5.812	-€5.543	-€5.287	-€5.042	-€4.809
Wind Energy Systems (Onshore)	-€969	-€924	-€881	-€840	-€801
Small and Medium Wind Turbines (SMWT)	-€2.325	-€2.217	-€2.115	-€2.017	-€1.923
Micro Hydropower	-€3.617	-€3.449	-€3.290	-€3.137	-€2.992
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€8.857	-€8.447	-€8.056	-€7.683	-€7.327
Small Modular Reactors (SMRs) and Micro Reactors	-€10.850	-€10.348	-€9.869	-€9.412	-€8.976
District Heating (4th Generation)	-€2.325	-€2.217	-€2.115	-€2.017	-€1.923
District Heating and Cooling (5th Generation)	-€1.107	-€1.056	-€1.007	-€960	-€916

Table 23: Dynamic opex in a small community, year 21–25.

DYNAMIC OPEX PER TECHNOLOGY	26	27	28	29	30
Biogas Production (Anaerobic Digestion)	-€10.919	-€10.413	-€9.931	-€9.472	-€9.033
Bio-Oil Production (Pyrolysis)	-€18.344	-€17.494	-€16.685	-€15.912	-€15.175
Green Hydrogen Production (Electrolysis)	-€9.265	-€8.836	-€8.427	-€8.036	-€7.664
Aquathermal Energy Systems	-€2.501	-€2.386	-€2.275	-€2.170	-€2.069
Sewage Thermal Energy Systems	-€2.038	-€1.944	-€1.854	-€1.768	-€1.686
Residual Heat Recovery Systems	-€1.834	-€1.749	-€1.668	-€1.591	-€1.518
Geothermal Energy Systems (ATES/BTES)	-€1.834	-€1.749	-€1.668	-€1.591	-€1.518
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€1.223	-€1.166	-€1.112	-€1.061	-€1.012
Solar Panels (PV)	-€540	-€515	-€491	-€468	-€446
Solar Panels (PT)	-€863	-€823	-€785	-€749	-€714
Solar Panels (PVT)	-€1.349	-€1.286	-€1.227	-€1.170	-€1.116
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€4.586	-€4.374	-€4.171	-€3.978	-€3.794
Wind Energy Systems (Onshore)	-€764	-€729	-€695	-€663	-€632
Small and Medium Wind Turbines (SMWT)	-€1.834	-€1.749	-€1.668	-€1.591	-€1.518
Micro Hydropower	-€2.853	-€2.721	-€2.595	-€2.475	-€2.361
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€6.988	-€6.665	-€6.356	-€6.062	-€5.781
Small Modular Reactors (SMRs) and Micro Reactors	-€8.560	-€8.164	-€7.786	-€7.426	-€7.082
District Heating (4th Generation)	-€1.834	-€1.749	-€1.668	-€1.591	-€1.518
District Heating and Cooling (5th Generation)	-€874	-€833	-€795	-€758	-€723

Table 24: Dynamic opex in a small community, year 26–30.

DYNAMIC OPEX PER TECHNOLOGY	31	32	33	34	35
Biogas Production (Anaerobic Digestion)	-€8.615	-€8.216	-€7.836	-€7.473	-€7.127
Bio-Oil Production (Pyrolysis)	-€14.473	-€13.803	-€13.164	-€12.554	-€11.973
Green Hydrogen Production (Electrolysis)	-€7.310	-€6.971	-€6.648	-€6.341	-€6.047
Aquathermal Energy Systems	-€1.974	-€1.882	-€1.795	-€1.712	-€1.633
Sewage Thermal Energy Systems	-€1.608	-€1.534	-€1.463	-€1.395	-€1.330
Residual Heat Recovery Systems	-€1.447	-€1.380	-€1.316	-€1.255	-€1.197
Geothermal Energy Systems (ATES/BTES)	-€1.447	-€1.380	-€1.316	-€1.255	-€1.197
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€965	-€920	-€878	-€837	-€798
Solar Panels (PV)	-€426	-€406	-€387	-€369	-€352
Solar Panels (PT)	-€681	-€650	-€619	-€591	-€563
Solar Panels (PVT)	-€1.064	-€1.015	-€968	-€923	-€880
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€3.618	-€3.451	-€3.291	-€3.139	-€2.993
Wind Energy Systems (Onshore)	-€603	-€575	-€548	-€523	-€499
Small and Medium Wind Turbines (SMWT)	-€1.447	-€1.380	-€1.316	-€1.255	-€1.197
Micro Hydropower	-€2.251	-€2.147	-€2.048	-€1.953	-€1.862
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€5.513	-€5.258	-€5.015	-€4.783	-€4.561
Small Modular Reactors (SMRs) and Micro Reactors	-€6.754	-€6.441	-€6.143	-€5.859	-€5.587
District Heating (4th Generation)	-€1.447	-€1.380	-€1.316	-€1.255	-€1.197
District Heating and Cooling (5th Generation)	-€689	-€657	-€627	-€598	-€570

Table 25: Dynamic opex in a small community, year 31–35.

DYNAMIC OPEX PER TECHNOLOGY	36	37	38	39	40
Biogas Production (Anaerobic Digestion)	-€6.797	-€6.482	-€6.182	-€5.896	-€5.623
Bio-Oil Production (Pyrolysis)	-€11.419	-€10.890	-€10.386	-€9.905	-€9.447
Green Hydrogen Production (Electrolysis)	-€5.767	-€5.500	-€5.245	-€5.003	-€4.771
Aquathermal Energy Systems	-€1.557	-€1.485	-€1.416	-€1.351	-€1.288
Sewage Thermal Energy Systems	-€1.269	-€1.210	-€1.154	-€1.101	-€1.050
Residual Heat Recovery Systems	-€1.142	-€1.089	-€1.039	-€991	-€945
Geothermal Energy Systems (ATES/BTES)	-€1.142	-€1.089	-€1.039	-€991	-€945
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€761	-€726	-€692	-€660	-€630
Solar Panels (PV)	-€336	-€320	-€305	-€291	-€278
Solar Panels (PT)	-€537	-€512	-€489	-€466	-€445
Solar Panels (PVT)	-€840	-€801	-€764	-€728	-€695
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€2.855	-€2.723	-€2.597	-€2.476	-€2.362
Wind Energy Systems (Onshore)	-€476	-€454	-€433	-€413	-€394
Small and Medium Wind Turbines (SMWT)	-€1.142	-€1.089	-€1.039	-€991	-€945
Micro Hydropower	-€1.776	-€1.694	-€1.616	-€1.541	-€1.469
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€4.350	-€4.149	-€3.957	-€3.773	-€3.599
Small Modular Reactors (SMRs) and Micro Reactors	-€5.329	-€5.082	-€4.847	-€4.622	-€4.408
District Heating (4th Generation)	-€1.142	-€1.089	-€1.039	-€991	-€945
District Heating and Cooling (5th Generation)	-€544	-€519	-€495	-€472	-€450

Table 26: Dynamic opex in a small community, year 36–40.

DYNAMIC OPEX PER TECHNOLOGY	41	42	43	44	45
Biogas Production (Anaerobic Digestion)	-€5.363	-€5.114	-€4.878	-€4.652	-€4.436
Bio-Oil Production (Pyrolysis)	-€9.009	-€8.592	-€8.194	-€7.815	-€7.453
Green Hydrogen Production (Electrolysis)	-€4.550	-€4.339	-€4.139	-€3.947	-€3.764
Aquathermal Energy Systems	-€1.229	-€1.172	-€1.117	-€1.066	-€1.016
Sewage Thermal Energy Systems	-€1.001	-€955	-€910	-€868	-€828
Residual Heat Recovery Systems	-€901	-€859	-€819	-€782	-€745
Geothermal Energy Systems (ATES/BTES)	-€901	-€859	-€819	-€782	-€745
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€601	-€573	-€546	-€521	-€497
Solar Panels (PV)	-€265	-€253	-€241	-€230	-€219
Solar Panels (PT)	-€424	-€404	-€386	-€368	-€351
Solar Panels (PVT)	-€662	-€632	-€603	-€575	-€548
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€2.252	-€2.148	-€2.049	-€1.954	-€1.863
Wind Energy Systems (Onshore)	-€375	-€358	-€341	-€326	-€311
Small and Medium Wind Turbines (SMWT)	-€901	-€859	-€819	-€782	-€745
Micro Hydropower	-€1.401	-€1.337	-€1.275	-€1.216	-€1.159
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€3.432	-€3.273	-€3.122	-€2.977	-€2.839
Small Modular Reactors (SMRs) and Micro Reactors	-€4.204	-€4.010	-€3.824	-€3.647	-€3.478
District Heating (4th Generation)	-€901	-€859	-€819	-€782	-€745
District Heating and Cooling (5th Generation)	-€429	-€409	-€390	-€372	-€355

Table 27: Dynamic opex in a small community, year 41–45.

DYNAMIC OPEX PER TECHNOLOGY	46	47	48	49	50
Biogas Production (Anaerobic Digestion)	-€4.231	-€4.035	-€3.848	-€3.670	-€3.500
Bio-Oil Production (Pyrolysis)	-€7.108	-€6.779	-€6.465	-€6.166	-€5.880
Green Hydrogen Production (Electrolysis)	-€3.590	-€3.424	-€3.265	-€3.114	-€2.970
Aquathermal Energy Systems	-€969	-€924	-€882	-€841	-€802
Sewage Thermal Energy Systems	-€790	-€753	-€718	-€685	-€653
Residual Heat Recovery Systems	-€711	-€678	-€647	-€617	-€588
Geothermal Energy Systems (ATES/BTES)	-€711	-€678	-€647	-€617	-€588
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€474	-€452	-€431	-€411	-€392
Solar Panels (PV)	-€209	-€199	-€190	-€181	-€173
Solar Panels (PT)	-€335	-€319	-€304	-€290	-€277
Solar Panels (PVT)	-€523	-€498	-€475	-€453	-€432
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€1.777	-€1.695	-€1.616	-€1.541	-€1.470
Wind Energy Systems (Onshore)	-€296	-€282	-€269	-€257	-€245
Small and Medium Wind Turbines (SMWT)	-€711	-€678	-€647	-€617	-€588
Micro Hydropower	-€1.106	-€1.055	-€1.006	-€959	-€915
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€2.708	-€2.583	-€2.463	-€2.349	-€2.240
Small Modular Reactors (SMRs) and Micro Reactors	-€3.317	-€3.164	-€3.017	-€2.877	-€2.744
District Heating (4th Generation)	-€711	-€678	-€647	-€617	-€588
District Heating and Cooling (5th Generation)	-€338	-€323	-€308	-€294	-€280

Table 28: Dynamic opex in a small community, year 46–50.

B.2 Medium-sized Communities (1 GWh, 200–300 dwellings)

DYNAMIC OPEX PER TECHNOLOGY	1	2	3	4	5
Biogas Production (Anaerobic Digestion)	-€200.000	-€190.741	-€181.910	-€173.488	-€165.457
Bio-Oil Production (Pyrolysis)	-€375.000	-€357.639	-€341.082	-€325.291	-€310.231
Green Hydrogen Production (Electrolysis)	-€181.818	-€173.401	-€165.373	-€157.717	-€150.415
Aquathermal Energy Systems	-€39.773	-€37.931	-€36.175	-€34.501	-€32.903
Sewage Thermal Energy Systems	-€41.667	-€39.738	-€37.898	-€36.143	-€34.470
Residual Heat Recovery Systems	-€30.000	-€28.611	-€27.287	-€26.023	-€24.818
Geothermal Energy Systems (ATES/BTES)	-€26.667	-€25.432	-€24.255	-€23.132	-€22.061
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€27.778	-€26.492	-€25.265	-€24.096	-€22.980
Solar Panels (PV)	-€11.765	-€11.220	-€10.701	-€10.205	-€9.733
Solar Panels (PT)	-€20.588	-€19.635	-€18.726	-€17.859	-€17.032
Solar Panels (PVT)	-€29.412	-€28.050	-€26.751	-€25.513	-€24.332
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€100.000	-€95.370	-€90.955	-€86.744	-€82.728
Wind Energy Systems (Onshore)	-€16.667	-€15.895	-€15.159	-€14.457	-€13.788
Small and Medium Wind Turbines (SMWT)	-€41.667	-€39.738	-€37.898	-€36.143	-€34.470
Micro Hydropower	-€50.000	-€47.685	-€45.478	-€43.372	-€41.364
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€128.571	-€122.619	-€116.942	-€111.528	-€106.365
Small Modular Reactors (SMRs) and Micro Reactors	-€180.000	-€171.667	-€163.719	-€156.140	-€148.911
District Heating (4th Generation)	-€40.000	-€38.148	-€36.382	-€34.698	-€33.091
District Heating and Cooling (5th Generation)	-€16.071	-€15.327	-€14.618	-€13.941	-€13.296

Table 29: Dynamic opex in a medium community, year 1–5.

DYNAMIC OPEX PER TECHNOLOGY	6	7	8	9	10
Biogas Production (Anaerobic Digestion)	-€157.796	-€150.491	-€143.524	-€136.879	-€130.542
Bio-Oil Production (Pyrolysis)	-€295.868	-€282.171	-€269.107	-€256.649	-€244.767
Green Hydrogen Production (Electrolysis)	-€143.451	-€136.810	-€130.476	-€124.436	-€118.675
Aquathermal Energy Systems	-€31.380	-€29.927	-€28.542	-€27.220	-€25.960
Sewage Thermal Energy Systems	-€32.874	-€31.352	-€29.901	-€28.517	-€27.196
Residual Heat Recovery Systems	-€23.669	-€22.574	-€21.529	-€20.532	-€19.581
Geothermal Energy Systems (ATES/BTES)	-€21.040	-€20.065	-€19.137	-€18.251	-€17.406
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€21.916	-€20.902	-€19.934	-€19.011	-€18.131
Solar Panels (PV)	-€9.282	-€8.852	-€8.443	-€8.052	-€7.679
Solar Panels (PT)	-€16.244	-€15.492	-€14.775	-€14.091	-€13.438
Solar Panels (PVT)	-€23.205	-€22.131	-€21.106	-€20.129	-€19.197
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€78.898	-€75.246	-€71.762	-€68.440	-€65.271
Wind Energy Systems (Onshore)	-€13.150	-€12.541	-€11.960	-€11.407	-€10.879
Small and Medium Wind Turbines (SMWT)	-€32.874	-€31.352	-€29.901	-€28.517	-€27.196
Micro Hydropower	-€39.449	-€37.623	-€35.881	-€34.220	-€32.636
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€101.441	-€96.744	-€92.265	-€87.994	-€83.920
Small Modular Reactors (SMRs) and Micro Reactors	-€142.017	-€135.442	-€129.172	-€123.191	-€117.488
District Heating (4th Generation)	-€31.559	-€30.098	-€28.705	-€27.376	-€26.108
District Heating and Cooling (5th Generation)	-€12.680	-€12.093	-€11.533	-€10.999	-€10.490

Table 30: Dynamic opex in a medium community, year 6–10.

DYNAMIC OPEX PER TECHNOLOGY	11	12	13	14	15
Biogas Production (Anaerobic Digestion)	-€124.499	-€118.735	-€113.238	-€107.995	-€102.996
Bio-Oil Production (Pyrolysis)	-€233.435	-€222.628	-€212.321	-€202.491	-€193.117
Green Hydrogen Production (Electrolysis)	-€113.181	-€107.941	-€102.944	-€98.178	-€93.632
Aquathermal Energy Systems	-€24.758	-€23.612	-€22.519	-€21.476	-€20.482
Sewage Thermal Energy Systems	-€25.937	-€24.736	-€23.591	-€22.499	-€21.457
Residual Heat Recovery Systems	-€18.675	-€17.810	-€16.986	-€16.199	-€15.449
Geothermal Energy Systems (ATES/BTES)	-€16.600	-€15.831	-€15.098	-€14.399	-€13.733
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€17.291	-€16.491	-€15.727	-€14.999	-€14.305
Solar Panels (PV)	-€7.323	-€6.984	-€6.661	-€6.353	-€6.059
Solar Panels (PT)	-€12.816	-€12.223	-€11.657	-€11.117	-€10.602
Solar Panels (PVT)	-€18.309	-€17.461	-€16.653	-€15.882	-€15.146
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€62.249	-€59.367	-€56.619	-€53.998	-€51.498
Wind Energy Systems (Onshore)	-€10.375	-€9.895	-€9.436	-€9.000	-€8.583
Small and Medium Wind Turbines (SMWT)	-€25.937	-€24.736	-€23.591	-€22.499	-€21.457
Micro Hydropower	-€31.125	-€29.684	-€28.309	-€26.999	-€25.749
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€80.035	-€76.330	-€72.796	-€69.426	-€66.211
Small Modular Reactors (SMRs) and Micro Reactors	-€112.049	-€106.861	-€101.914	-€97.196	-€92.696
District Heating (4th Generation)	-€24.900	-€23.747	-€22.648	-€21.599	-€20.599
District Heating and Cooling (5th Generation)	-€10.004	-€9.541	-€9.099	-€8.678	-€8.276

Table 31: Dynamic opex in a medium community, year 11–15.

DYNAMIC OPEX PER TECHNOLOGY	16	17	18	19	20
Biogas Production (Anaerobic Digestion)	-€98.227	-€93.680	-€89.343	-€85.206	-€81.262
Bio-Oil Production (Pyrolysis)	-€184.176	-€175.649	-€167.518	-€159.762	-€152.366
Green Hydrogen Production (Electrolysis)	-€89.298	-€85.163	-€81.221	-€77.460	-€73.874
Aquathermal Energy Systems	-€19.534	-€18.629	-€17.767	-€16.944	-€16.160
Sewage Thermal Energy Systems	-€20.464	-€19.517	-€18.613	-€17.751	-€16.930
Residual Heat Recovery Systems	-€14.734	-€14.052	-€13.401	-€12.781	-€12.189
Geothermal Energy Systems (ATES/BTES)	-€13.097	-€12.491	-€11.912	-€11.361	-€10.835
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€13.643	-€13.011	-€12.409	-€11.834	-€11.286
Solar Panels (PV)	-€5.778	-€5.511	-€5.255	-€5.012	-€4.780
Solar Panels (PT)	-€10.112	-€9.643	-€9.197	-€8.771	-€8.365
Solar Panels (PVT)	-€14.445	-€13.776	-€13.139	-€12.530	-€11.950
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€49.114	-€46.840	-€44.671	-€42.603	-€40.631
Wind Energy Systems (Onshore)	-€8.186	-€7.807	-€7.445	-€7.101	-€6.772
Small and Medium Wind Turbines (SMWT)	-€20.464	-€19.517	-€18.613	-€17.751	-€16.930
Micro Hydropower	-€24.557	-€23.420	-€22.336	-€21.302	-€20.315
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€63.146	-€60.223	-€57.435	-€54.776	-€52.240
Small Modular Reactors (SMRs) and Micro Reactors	-€88.405	-€84.312	-€80.408	-€76.686	-€73.136
District Heating (4th Generation)	-€19.645	-€18.736	-€17.869	-€17.041	-€16.252
District Heating and Cooling (5th Generation)	-€7.893	-€7.528	-€7.179	-€6.847	-€6.530

Table 32: Dynamic opex in a medium community, year 16–20.

DYNAMIC OPEX PER TECHNOLOGY	21	22	23	24	25
Biogas Production (Anaerobic Digestion)	-€77.500	-€73.912	-€70.490	-€67.226	-€64.114
Bio-Oil Production (Pyrolysis)	-€145.312	-€138.584	-€132.168	-€126.049	-€120.214
Green Hydrogen Production (Electrolysis)	-€70.454	-€67.192	-€64.082	-€61.115	-€58.286
Aquathermal Energy Systems	-€15.412	-€14.698	-€14.018	-€13.369	-€12.750
Sewage Thermal Energy Systems	-€16.146	-€15.398	-€14.685	-€14.005	-€13.357
Residual Heat Recovery Systems	-€11.625	-€11.087	-€10.573	-€10.084	-€9.617
Geothermal Energy Systems (ATES/BTES)	-€10.333	-€9.855	-€9.399	-€8.964	-€8.549
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€10.764	-€10.266	-€9.790	-€9.337	-€8.905
Solar Panels (PV)	-€4.559	-€4.348	-€4.146	-€3.954	-€3.771
Solar Panels (PT)	-€7.978	-€7.609	-€7.256	-€6.920	-€6.600
Solar Panels (PVT)	-€11.397	-€10.869	-€10.366	-€9.886	-€9.429
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€38.750	-€36.956	-€35.245	-€33.613	-€32.057
Wind Energy Systems (Onshore)	-€6.458	-€6.159	-€5.874	-€5.602	-€5.343
Small and Medium Wind Turbines (SMWT)	-€16.146	-€15.398	-€14.685	-€14.005	-€13.357
Micro Hydropower	-€19.375	-€18.478	-€17.622	-€16.807	-€16.029
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€49.821	-€47.515	-€45.315	-€43.217	-€41.216
Small Modular Reactors (SMRs) and Micro Reactors	-€69.750	-€66.520	-€63.441	-€60.504	-€57.703
District Heating (4th Generation)	-€15.500	-€14.782	-€14.098	-€13.445	-€12.823
District Heating and Cooling (5th Generation)	-€6.228	-€5.939	-€5.664	-€5.402	-€5.152

Table 33: Dynamic opex in a medium community, year 21–25.

DYNAMIC OPEX PER TECHNOLOGY	26	27	28	29	30
Biogas Production (Anaerobic Digestion)	-€61.146	-€58.315	-€55.615	-€53.040	-€50.585
Bio-Oil Production (Pyrolysis)	-€114.648	-€109.341	-€104.279	-€99.451	-€94.847
Green Hydrogen Production (Electrolysis)	-€55.587	-€53.014	-€50.559	-€48.219	-€45.986
Aquathermal Energy Systems	-€12.160	-€11.597	-€11.060	-€10.548	-€10.059
Sewage Thermal Energy Systems	-€12.739	-€12.149	-€11.587	-€11.050	-€10.539
Residual Heat Recovery Systems	-€9.172	-€8.747	-€8.342	-€7.956	-€7.588
Geothermal Energy Systems (ATES/BTES)	-€8.153	-€7.775	-€7.415	-€7.072	-€6.745
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€8.492	-€8.099	-€7.724	-€7.367	-€7.026
Solar Panels (PV)	-€3.597	-€3.430	-€3.271	-€3.120	-€2.976
Solar Panels (PT)	-€6.294	-€6.003	-€5.725	-€5.460	-€5.207
Solar Panels (PVT)	-€8.992	-€8.576	-€8.179	-€7.800	-€7.439
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€30.573	-€29.157	-€27.808	-€26.520	-€25.292
Wind Energy Systems (Onshore)	-€5.095	-€4.860	-€4.635	-€4.420	-€4.215
Small and Medium Wind Turbines (SMWT)	-€12.739	-€12.149	-€11.587	-€11.050	-€10.539
Micro Hydropower	-€15.286	-€14.579	-€13.904	-€13.260	-€12.646
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€39.308	-€37.488	-€35.753	-€34.097	-€32.519
Small Modular Reactors (SMRs) and Micro Reactors	-€55.031	-€52.483	-€50.054	-€47.736	-€45.526
District Heating (4th Generation)	-€12.229	-€11.663	-€11.123	-€10.608	-€10.117
District Heating and Cooling (5th Generation)	-€4.914	-€4.686	-€4.469	-€4.262	-€4.065

Table 34: Dynamic opex in a medium community, year 26–30.

DYNAMIC OPEX PER TECHNOLOGY	31	32	33	34	35
Biogas Production (Anaerobic Digestion)	-€48.243	-€46.010	-€43.879	-€41.848	-€39.911
Bio-Oil Production (Pyrolysis)	-€90.456	-€86.268	-€82.274	-€78.465	-€74.832
Green Hydrogen Production (Electrolysis)	-€43.857	-€41.827	-€39.890	-€38.044	-€36.282
Aquathermal Energy Systems	-€9.594	-€9.150	-€8.726	-€8.322	-€7.937
Sewage Thermal Energy Systems	-€10.051	-€9.585	-€9.142	-€8.718	-€8.315
Residual Heat Recovery Systems	-€7.236	-€6.901	-€6.582	-€6.277	-€5.987
Geothermal Energy Systems (ATES/BTES)	-€6.432	-€6.135	-€5.851	-€5.580	-€5.321
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€6.700	-€6.390	-€6.094	-€5.812	-€5.543
Solar Panels (PV)	-€2.838	-€2.706	-€2.581	-€2.462	-€2.348
Solar Panels (PT)	-€4.966	-€4.736	-€4.517	-€4.308	-€4.108
Solar Panels (PVT)	-€7.095	-€6.766	-€6.453	-€6.154	-€5.869
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€24.121	-€23.005	-€21.940	-€20.924	-€19.955
Wind Energy Systems (Onshore)	-€4.020	-€3.834	-€3.657	-€3.487	-€3.326
Small and Medium Wind Turbines (SMWT)	-€10.051	-€9.585	-€9.142	-€8.718	-€8.315
Micro Hydropower	-€12.061	-€11.502	-€10.970	-€10.462	-€9.978
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€31.013	-€29.578	-€28.208	-€26.902	-€25.657
Small Modular Reactors (SMRs) and Micro Reactors	-€43.419	-€41.409	-€39.491	-€37.663	-€35.920
District Heating (4th Generation)	-€9.649	-€9.202	-€8.776	-€8.370	-€7.982
District Heating and Cooling (5th Generation)	-€3.877	-€3.697	-€3.526	-€3.363	-€3.207

Table 35: Dynamic opex in a medium community, year 31–35.

DYNAMIC OPEX PER TECHNOLOGY	36	37	38	39	40
Biogas Production (Anaerobic Digestion)	-€38.063	-€36.301	-€34.620	-€33.017	-€31.489
Bio-Oil Production (Pyrolysis)	-€71.368	-€68.064	-€64.913	-€61.907	-€59.041
Green Hydrogen Production (Electrolysis)	-€34.603	-€33.001	-€31.473	-€30.016	-€28.626
Aquathermal Energy Systems	-€7.569	-€7.219	-€6.885	-€6.566	-€6.262
Sewage Thermal Energy Systems	-€7.930	-€7.563	-€7.213	-€6.879	-€6.560
Residual Heat Recovery Systems	-€5.709	-€5.445	-€5.193	-€4.953	-€4.723
Geothermal Energy Systems (ATES/BTES)	-€5.075	-€4.840	-€4.616	-€4.402	-€4.198
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€5.287	-€5.042	-€4.808	-€4.586	-€4.373
Solar Panels (PV)	-€2.239	-€2.135	-€2.036	-€1.942	-€1.852
Solar Panels (PT)	-€3.918	-€3.737	-€3.564	-€3.399	-€3.241
Solar Panels (PVT)	-€5.597	-€5.338	-€5.091	-€4.855	-€4.631
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€19.031	-€18.150	-€17.310	-€16.509	-€15.744
Wind Energy Systems (Onshore)	-€3.172	-€3.025	-€2.885	-€2.751	-€2.624
Small and Medium Wind Turbines (SMWT)	-€7.930	-€7.563	-€7.213	-€6.879	-€6.560
Micro Hydropower	-€9.516	-€9.075	-€8.655	-€8.254	-€7.872
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€24.469	-€23.336	-€22.256	-€21.225	-€20.243
Small Modular Reactors (SMRs) and Micro Reactors	-€34.257	-€32.671	-€31.158	-€29.716	-€28.340
District Heating (4th Generation)	-€7.613	-€7.260	-€6.924	-€6.603	-€6.298
District Heating and Cooling (5th Generation)	-€3.059	-€2.917	-€2.782	-€2.653	-€2.530

Table 36: Dynamic opex in a medium community, year 36–40.

DYNAMIC OPEX PER TECHNOLOGY	41	42	43	44	45
Biogas Production (Anaerobic Digestion)	-€30.031	-€28.641	-€27.315	-€26.050	-€24.844
Bio-Oil Production (Pyrolysis)	-€56.308	-€53.701	-€51.215	-€48.844	-€46.583
Green Hydrogen Production (Electrolysis)	-€27.301	-€26.037	-€24.832	-€23.682	-€22.586
Aquathermal Energy Systems	-€5.972	-€5.696	-€5.432	-€5.180	-€4.941
Sewage Thermal Energy Systems	-€6.256	-€5.967	-€5.691	-€5.427	-€5.176
Residual Heat Recovery Systems	-€4.505	-€4.296	-€4.097	-€3.908	-€3.727
Geothermal Energy Systems (ATES/BTES)	-€4.004	-€3.819	-€3.642	-€3.473	-€3.313
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€4.171	-€3.978	-€3.794	-€3.618	-€3.451
Solar Panels (PV)	-€1.767	-€1.685	-€1.607	-€1.532	-€1.461
Solar Panels (PT)	-€3.091	-€2.948	-€2.812	-€2.682	-€2.557
Solar Panels (PVT)	-€4.416	-€4.212	-€4.017	-€3.831	-€3.654
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€15.015	-€14.320	-€13.657	-€13.025	-€12.422
Wind Energy Systems (Onshore)	-€2.503	-€2.387	-€2.276	-€2.171	-€2.070
Small and Medium Wind Turbines (SMWT)	-€6.256	-€5.967	-€5.691	-€5.427	-€5.176
Micro Hydropower	-€7.508	-€7.160	-€6.829	-€6.513	-€6.211
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€19.306	-€18.412	-€17.559	-€16.746	-€15.971
Small Modular Reactors (SMRs) and Micro Reactors	-€27.028	-€25.777	-€24.583	-€23.445	-€22.360
District Heating (4th Generation)	-€6.006	-€5.728	-€5.463	-€5.210	-€4.969
District Heating and Cooling (5th Generation)	-€2.413	-€2.301	-€2.195	-€2.093	-€1.996

Table 37: Dynamic opex in a medium community, year 41–45.

DYNAMIC OPEX PER TECHNOLOGY	46	47	48	49	50
Biogas Production (Anaerobic Digestion)	-€23.694	-€22.597	-€21.551	-€20.553	-€19.602
Bio-Oil Production (Pyrolysis)	-€44.426	-€42.369	-€40.408	-€38.537	-€36.753
Green Hydrogen Production (Electrolysis)	-€21.540	-€20.543	-€19.592	-€18.685	-€17.820
Aquathermal Energy Systems	-€4.712	-€4.494	-€4.286	-€4.087	-€3.898
Sewage Thermal Energy Systems	-€4.936	-€4.708	-€4.490	-€4.282	-€4.084
Residual Heat Recovery Systems	-€3.554	-€3.390	-€3.233	-€3.083	-€2.940
Geothermal Energy Systems (ATES/BTES)	-€3.159	-€3.013	-€2.873	-€2.740	-€2.614
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-€3.291	-€3.138	-€2.993	-€2.855	-€2.722
Solar Panels (PV)	-€1.394	-€1.329	-€1.268	-€1.209	-€1.153
Solar Panels (PT)	-€2.439	-€2.326	-€2.218	-€2.116	-€2.018
Solar Panels (PVT)	-€3.484	-€3.323	-€3.169	-€3.023	-€2.883
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€11.847	-€11.298	-€10.775	-€10.277	-€9.801
Wind Energy Systems (Onshore)	-€1.974	-€1.883	-€1.796	-€1.713	-€1.633
Small and Medium Wind Turbines (SMWT)	-€4.936	-€4.708	-€4.490	-€4.282	-€4.084
Micro Hydropower	-€5.923	-€5.649	-€5.388	-€5.138	-€4.900
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-€15.232	-€14.527	-€13.854	-€13.213	-€12.601
Small Modular Reactors (SMRs) and Micro Reactors	-€21.324	-€20.337	-€19.396	-€18.498	-€17.641
District Heating (4th Generation)	-€4.739	-€4.519	-€4.310	-€4.111	-€3.920
District Heating and Cooling (5th Generation)	-€1.904	-€1.816	-€1.732	-€1.652	-€1.575

Table 38: Dynamic opex in a medium community, year 46–50.

B.3 Large-sized Communities (10 GWh, 2,000–3,000 dwellings)

DYNAMIC OPEX PER TECHNOLOGY	1	2	3	4	5
Biogas Production (Anaerobic Digestion)	-k€857	-k€817	-k€780	-k€744	-k€709
Bio-Oil Production (Pyrolysis)	-k€2000	-k€1907	-k€1819	-k€1735	-k€1655
Green Hydrogen Production (Electrolysis)	-k€909	-k€867	-k€827	-k€789	-k€752
Aquathermal Energy Systems	-k€91	-k€87	-k€83	-k€79	-k€75
Sewage Thermal Energy Systems	-k€222	-k€212	-k€202	-k€193	-k€184
Residual Heat Recovery Systems	-k€100	-k€95	-k€91	-k€87	-k€83
Geothermal Energy Systems (ATES/BTES)	-k€67	-k€64	-k€61	-k€58	-k€55
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€178	-k€170	-k€162	-k€154	-k€147
Solar Panels (PV)	-k€71	-k€67	-k€64	-k€61	-k€58
Solar Panels (PT)	-k€141	-k€135	-k€128	-k€122	-k€117
Solar Panels (PVT)	-k€176	-k€168	-k€161	-k€153	-k€146
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€600	-k€572	-k€546	-k€520	-k€496
Wind Energy Systems (Onshore)	-k€100	-k€95	-k€91	-k€87	-k€83
Small and Medium Wind Turbines (SMWT)	-k€267	-k€254	-k€243	-k€231	-k€221
Micro Hydropower	-k€200	-k€191	-k€182	-k€173	-k€165
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€571	-k€545	-k€520	-k€496	-k€473
Small Modular Reactors (SMRs) and Micro Reactors	-k€1000	-k€954	-k€910	-k€867	-k€827
District Heating (4th Generation)	-k€240	-k€229	-k€218	-k€208	-k€199
District Heating and Cooling (5th Generation)	-k€71	-k€68	-k€65	-k€62	-k€59

Table 39: Dynamic opex in a large community, year 1–5.

DYNAMIC OPEX PER TECHNOLOGY	6	7	8	9	10
Biogas Production (Anaerobic Digestion)	-k€676	-k€645	-k€615	-k€587	-k€559
Bio-Oil Production (Pyrolysis)	-k€1578	-k€1505	-k€1435	-k€1369	-k€1305
Green Hydrogen Production (Electrolysis)	-k€717	-k€684	-k€652	-k€622	-k€593
Aquathermal Energy Systems	-k€72	-k€68	-k€65	-k€62	-k€59
Sewage Thermal Energy Systems	-k€175	-k€167	-k€159	-k€152	-k€145
Residual Heat Recovery Systems	-k€79	-k€75	-k€72	-k€68	-k€65
Geothermal Energy Systems (ATES/BTES)	-k€53	-k€50	-k€48	-k€46	-k€44
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€140	-k€134	-k€128	-k€122	-k€116
Solar Panels (PV)	-k€56	-k€53	-k€51	-k€48	-k€46
Solar Panels (PT)	-k€111	-k€106	-k€101	-k€97	-k€92
Solar Panels (PVT)	-k€139	-k€133	-k€127	-k€121	-k€115
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€473	-k€451	-k€431	-k€411	-k€392
Wind Energy Systems (Onshore)	-k€79	-k€75	-k€72	-k€68	-k€65
Small and Medium Wind Turbines (SMWT)	-k€210	-k€201	-k€191	-k€183	-k€174
Micro Hydropower	-k€158	-k€150	-k€144	-k€137	-k€131
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€451	-k€430	-k€410	-k€391	-k€373
Small Modular Reactors (SMRs) and Micro Reactors	-k€789	-k€752	-k€718	-k€684	-k€653
District Heating (4th Generation)	-k€189	-k€181	-k€172	-k€164	-k€157
District Heating and Cooling (5th Generation)	-k€56	-k€54	-k€51	-k€49	-k€47

Table 40: Dynamic opex in a large community, year 6–10.

DYNAMIC OPEX PER TECHNOLOGY	11	12	13	14	15
Biogas Production (Anaerobic Digestion)	-k€534	-k€509	-k€485	-k€463	-k€441
Bio-Oil Production (Pyrolysis)	-k€1245	-k€1187	-k€1132	-k€1080	-k€1030
Green Hydrogen Production (Electrolysis)	-k€566	-k€540	-k€515	-k€491	-k€468
Aquathermal Energy Systems	-k€57	-k€54	-k€51	-k€49	-k€47
Sewage Thermal Energy Systems	-k€138	-k€132	-k€126	-k€120	-k€114
Residual Heat Recovery Systems	-k€62	-k€59	-k€57	-k€54	-k€51
Geothermal Energy Systems (ATES/BTES)	-k€41	-k€40	-k€38	-k€36	-k€34
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€111	-k€106	-k€101	-k€96	-k€92
Solar Panels (PV)	-k€44	-k€42	-k€40	-k€38	-k€36
Solar Panels (PT)	-k€88	-k€84	-k€80	-k€76	-k€73
Solar Panels (PVT)	-k€110	-k€105	-k€100	-k€95	-k€91
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€373	-k€356	-k€340	-k€324	-k€309
Wind Energy Systems (Onshore)	-k€62	-k€59	-k€57	-k€54	-k€51
Small and Medium Wind Turbines (SMWT)	-k€166	-k€158	-k€151	-k€144	-k€137
Micro Hydropower	-k€124	-k€119	-k€113	-k€108	-k€103
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€356	-k€339	-k€324	-k€309	-k€294
Small Modular Reactors (SMRs) and Micro Reactors	-k€622	-k€594	-k€566	-k€540	-k€515
District Heating (4th Generation)	-k€149	-k€142	-k€136	-k€130	-k€124
District Heating and Cooling (5th Generation)	-k€44	-k€42	-k€40	-k€39	-k€37

Table 41: Dynamic opex in a large community, year 11–15.

DYNAMIC OPEX PER TECHNOLOGY	16	17	18	19	20
Biogas Production (Anaerobic Digestion)	-k€421	-k€401	-k€383	-k€365	-k€348
Bio-Oil Production (Pyrolysis)	-k€982	-k€937	-k€893	-k€852	-k€813
Green Hydrogen Production (Electrolysis)	-k€446	-k€426	-k€406	-k€387	-k€369
Aquathermal Energy Systems	-k€45	-k€43	-k€41	-k€39	-k€37
Sewage Thermal Energy Systems	-k€109	-k€104	-k€99	-k€95	-k€90
Residual Heat Recovery Systems	-k€49	-k€47	-k€45	-k€43	-k€41
Geothermal Energy Systems (ATES/BTES)	-k€33	-k€31	-k€30	-k€28	-k€27
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€87	-k€83	-k€79	-k€76	-k€72
Solar Panels (PV)	-k€35	-k€33	-k€32	-k€30	-k€29
Solar Panels (PT)	-k€69	-k€66	-k€63	-k€60	-k€57
Solar Panels (PVT)	-k€87	-k€83	-k€79	-k€75	-k€72
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€295	-k€281	-k€268	-k€256	-k€244
Wind Energy Systems (Onshore)	-k€49	-k€47	-k€45	-k€43	-k€41
Small and Medium Wind Turbines (SMWT)	-k€131	-k€125	-k€119	-k€114	-k€108
Micro Hydropower	-k€98	-k€94	-k€89	-k€85	-k€81
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€281	-k€268	-k€255	-k€243	-k€232
Small Modular Reactors (SMRs) and Micro Reactors	-k€491	-k€468	-k€447	-k€426	-k€406
District Heating (4th Generation)	-k€118	-k€112	-k€107	-k€102	-k€98
District Heating and Cooling (5th Generation)	-k€35	-k€33	-k€32	-k€30	-k€29

Table 42: Dynamic opex in a large community, year 16–20.

DYNAMIC OPEX PER TECHNOLOGY	21	22	23	24	25
Biogas Production (Anaerobic Digestion)	-k€332	-k€317	-k€302	-k€288	-k€275
Bio-Oil Production (Pyrolysis)	-k€775	-k€739	-k€705	-k€672	-k€641
Green Hydrogen Production (Electrolysis)	-k€352	-k€336	-k€320	-k€306	-k€291
Aquathermal Energy Systems	-k€35	-k€34	-k€32	-k€31	-k€29
Sewage Thermal Energy Systems	-k€86	-k€82	-k€78	-k€75	-k€71
Residual Heat Recovery Systems	-k€39	-k€37	-k€35	-k€34	-k€32
Geothermal Energy Systems (ATES/BTES)	-k€26	-k€25	-k€23	-k€22	-k€21
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€69	-k€66	-k€63	-k€60	-k€57
Solar Panels (PV)	-k€27	-k€26	-k€25	-k€24	-k€23
Solar Panels (PT)	-k€55	-k€52	-k€50	-k€47	-k€45
Solar Panels (PVT)	-k€68	-k€65	-k€62	-k€59	-k€57
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€232	-k€222	-k€211	-k€202	-k€192
Wind Energy Systems (Onshore)	-k€39	-k€37	-k€35	-k€34	-k€32
Small and Medium Wind Turbines (SMWT)	-k€103	-k€99	-k€94	-k€90	-k€85
Micro Hydropower	-k€77	-k€74	-k€70	-k€67	-k€64
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€221	-k€211	-k€201	-k€192	-k€183
Small Modular Reactors (SMRs) and Micro Reactors	-k€387	-k€370	-k€352	-k€336	-k€321
District Heating (4th Generation)	-k€93	-k€89	-k€85	-k€81	-k€77
District Heating and Cooling (5th Generation)	-k€28	-k€26	-k€25	-k€24	-k€23

Table 43: Dynamic opex in a large community, year 21–25.

DYNAMIC OPEX PER TECHNOLOGY	26	27	28	29	30
Biogas Production (Anaerobic Digestion)	-k€262	-k€250	-k€238	-k€227	-k€217
Bio-Oil Production (Pyrolysis)	-k€611	-k€583	-k€556	-k€530	-k€506
Green Hydrogen Production (Electrolysis)	-k€278	-k€265	-k€253	-k€241	-k€230
Aquathermal Energy Systems	-k€28	-k€27	-k€25	-k€24	-k€23
Sewage Thermal Energy Systems	-k€68	-k€65	-k€62	-k€59	-k€56
Residual Heat Recovery Systems	-k€31	-k€29	-k€28	-k€27	-k€25
Geothermal Energy Systems (ATES/BTES)	-k€20	-k€19	-k€19	-k€18	-k€17
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€54	-k€52	-k€49	-k€47	-k€45
Solar Panels (PV)	-k€22	-k€21	-k€20	-k€19	-k€18
Solar Panels (PT)	-k€43	-k€41	-k€39	-k€37	-k€36
Solar Panels (PVT)	-k€54	-k€51	-k€49	-k€47	-k€45
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€183	-k€175	-k€167	-k€159	-k€152
Wind Energy Systems (Onshore)	-k€31	-k€29	-k€28	-k€27	-k€25
Small and Medium Wind Turbines (SMWT)	-k€82	-k€78	-k€74	-k€71	-k€67
Micro Hydropower	-k€61	-k€58	-k€56	-k€53	-k€51
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€175	-k€167	-k€159	-k€152	-k€145
Small Modular Reactors (SMRs) and Micro Reactors	-k€306	-k€292	-k€278	-k€265	-k€253
District Heating (4th Generation)	-k€73	-k€70	-k€67	-k€64	-k€61
District Heating and Cooling (5th Generation)	-k€22	-k€21	-k€20	-k€19	-k€18

Table 44: Dynamic opex in a large community, year 26–30.

DYNAMIC OPEX PER TECHNOLOGY	31	32	33	34	35
Biogas Production (Anaerobic Digestion)	-k€207	-k€197	-k€188	-k€179	-k€171
Bio-Oil Production (Pyrolysis)	-k€482	-k€460	-k€439	-k€418	-k€399
Green Hydrogen Production (Electrolysis)	-k€219	-k€209	-k€199	-k€190	-k€181
Aquathermal Energy Systems	-k€22	-k€21	-k€20	-k€19	-k€18
Sewage Thermal Energy Systems	-k€54	-k€51	-k€49	-k€46	-k€44
Residual Heat Recovery Systems	-k€24	-k€23	-k€22	-k€21	-k€20
Geothermal Energy Systems (ATES/BTES)	-k€16	-k€15	-k€15	-k€14	-k€13
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€43	-k€41	-k€39	-k€37	-k€35
Solar Panels (PV)	-k€17	-k€16	-k€15	-k€15	-k€14
Solar Panels (PT)	-k€34	-k€32	-k€31	-k€30	-k€28
Solar Panels (PVT)	-k€43	-k€41	-k€39	-k€37	-k€35
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€145	-k€138	-k€132	-k€126	-k€120
Wind Energy Systems (Onshore)	-k€24	-k€23	-k€22	-k€21	-k€20
Small and Medium Wind Turbines (SMWT)	-k€64	-k€61	-k€59	-k€56	-k€53
Micro Hydropower	-k€48	-k€46	-k€44	-k€42	-k€40
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€138	-k€131	-k€125	-k€120	-k€114
Small Modular Reactors (SMRs) and Micro Reactors	-k€241	-k€230	-k€219	-k€209	-k€200
District Heating (4th Generation)	-k€58	-k€55	-k€53	-k€50	-k€48
District Heating and Cooling (5th Generation)	-k€17	-k€16	-k€16	-k€15	-k€14

Table 45: Dynamic opex in a large community, year 31–35.

DYNAMIC OPEX PER TECHNOLOGY	36	37	38	39	40
Biogas Production (Anaerobic Digestion)	-k€163	-k€156	-k€148	-k€142	-k€135
Bio-Oil Production (Pyrolysis)	-k€381	-k€363	-k€346	-k€330	-k€315
Green Hydrogen Production (Electrolysis)	-k€173	-k€165	-k€157	-k€150	-k€143
Aquathermal Energy Systems	-k€17	-k€17	-k€16	-k€15	-k€14
Sewage Thermal Energy Systems	-k€42	-k€40	-k€38	-k€37	-k€35
Residual Heat Recovery Systems	-k€19	-k€18	-k€17	-k€17	-k€16
Geothermal Energy Systems (ATES/BTES)	-k€13	-k€12	-k€12	-k€11	-k€10
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€34	-k€32	-k€31	-k€29	-k€28
Solar Panels (PV)	-k€13	-k€13	-k€12	-k€12	-k€11
Solar Panels (PT)	-k€27	-k€26	-k€24	-k€23	-k€22
Solar Panels (PVT)	-k€34	-k€32	-k€31	-k€29	-k€28
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€114	-k€109	-k€104	-k€99	-k€94
Wind Energy Systems (Onshore)	-k€19	-k€18	-k€17	-k€17	-k€16
Small and Medium Wind Turbines (SMWT)	-k€51	-k€48	-k€46	-k€44	-k€42
Micro Hydropower	-k€38	-k€36	-k€35	-k€33	-k€31
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€109	-k€104	-k€99	-k€94	-k€90
Small Modular Reactors (SMRs) and Micro Reactors	-k€190	-k€182	-k€173	-k€165	-k€157
District Heating (4th Generation)	-k€46	-k€44	-k€42	-k€40	-k€38
District Heating and Cooling (5th Generation)	-k€14	-k€13	-k€12	-k€12	-k€11

Table 46: Dynamic opex in a large community, year 36–40.

DYNAMIC OPEX PER TECHNOLOGY	41	42	43	44	45
Biogas Production (Anaerobic Digestion)	-k€129	-k€123	-k€117	-k€112	-k€106
Bio-Oil Production (Pyrolysis)	-k€300	-k€286	-k€273	-k€261	-k€248
Green Hydrogen Production (Electrolysis)	-k€137	-k€130	-k€124	-k€118	-k€113
Aquathermal Energy Systems	-k€14	-k€13	-k€12	-k€12	-k€11
Sewage Thermal Energy Systems	-k€33	-k€32	-k€30	-k€29	-k€28
Residual Heat Recovery Systems	-k€15	-k€14	-k€14	-k€13	-k€12
Geothermal Energy Systems (ATES/BTES)	-k€10	-k€10	-k€9	-k€9	-k€8
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€27	-k€25	-k€24	-k€23	-k€22
Solar Panels (PV)	-k€11	-k€10	-k€10	-k€9	-k€9
Solar Panels (PT)	-k€21	-k€20	-k€19	-k€18	-k€18
Solar Panels (PVT)	-k€26	-k€25	-k€24	-k€23	-k€22
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€90	-k€86	-k€82	-k€78	-k€75
Wind Energy Systems (Onshore)	-k€15	-k€14	-k€14	-k€13	-k€12
Small and Medium Wind Turbines (SMWT)	-k€40	-k€38	-k€36	-k€35	-k€33
Micro Hydropower	-k€30	-k€29	-k€27	-k€26	-k€25
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€86	-k€82	-k€78	-k€74	-k€71
Small Modular Reactors (SMRs) and Micro Reactors	-k€150	-k€143	-k€137	-k€130	-k€124
District Heating (4th Generation)	-k€36	-k€34	-k€33	-k€31	-k€30
District Heating and Cooling (5th Generation)	-k€11	-k€10	-k€10	-k€9	-k€9

Table 47: Dynamic opex in a large community, year 41–45.

DYNAMIC OPEX PER TECHNOLOGY	46	47	48	49	50
Biogas Production (Anaerobic Digestion)	-k€102	-k€97	-k€92	-k€88	-k€84
Bio-Oil Production (Pyrolysis)	-k€237	-k€226	-k€216	-k€206	-k€196
Green Hydrogen Production (Electrolysis)	-k€108	-k€103	-k€98	-k€93	-k€89
Aquathermal Energy Systems	-k€11	-k€10	-k€10	-k€9	-k€9
Sewage Thermal Energy Systems	-k€26	-k€25	-k€24	-k€23	-k€22
Residual Heat Recovery Systems	-k€12	-k€11	-k€11	-k€10	-k€10
Geothermal Energy Systems (ATES/BTES)	-k€8	-k€8	-k€7	-k€7	-k€7
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€21	-k€20	-k€19	-k€18	-k€17
Solar Panels (PV)	-k€8	-k€8	-k€8	-k€7	-k€7
Solar Panels (PT)	-k€17	-k€16	-k€15	-k€15	-k€14
Solar Panels (PVT)	-k€21	-k€20	-k€19	-k€18	-k€17
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€71	-k€68	-k€65	-k€62	-k€59
Wind Energy Systems (Onshore)	-k€12	-k€11	-k€11	-k€10	-k€10
Small and Medium Wind Turbines (SMWT)	-k€32	-k€30	-k€29	-k€27	-k€26
Micro Hydropower	-k€24	-k€23	-k€22	-k€21	-k€20
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€68	-k€65	-k€62	-k€59	-k€56
Small Modular Reactors (SMRs) and Micro Reactors	-k€118	-k€113	-k€108	-k€103	-k€98
District Heating (4th Generation)	-k€28	-k€27	-k€26	-k€25	-k€24
District Heating and Cooling (5th Generation)	-k€8	-k€8	-k€8	-k€7	-k€7

Table 48: Dynamic opex in a large community, year 46–50.

C Total DCF over 50 Years

C.1 Small-sized Communities (100 MWh, 20–30 dwellings)

TOTAL DCF PER TECHNOLOGY	1	2	3	4	5
Biogas Production (Anaerobic Digestion)	-€23.714	-€22.616	-€21.569	-€20.571	-€19.618
Bio-Oil Production (Pyrolysis)	-€48.000	-€45.778	-€43.658	-€41.637	-€39.710
Green Hydrogen Production (Electrolysis)	-€12.803	-€12.210	-€11.645	-€11.106	-€10.592
Aquathermal Energy Systems	€3.818	€3.641	€3.473	€3.312	€3.159
Sewage Thermal Energy Systems	€5.333	€5.086	€4.851	€4.626	€4.412
Residual Heat Recovery Systems	€6.000	€5.722	€5.457	€5.205	€4.964
Geothermal Energy Systems (ATES/BTES)	€6.000	€5.722	€5.457	€5.205	€4.964
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€8.000	€7.630	€7.276	€6.940	€6.618
Solar Panels (PV)	€28.235	€26.928	€25.681	€24.492	€23.359
Solar Panels (PT)	€9.176	€8.752	€8.346	€7.960	€7.592
Solar Panels (PVT)	€12.088	€11.529	€10.995	€10.486	€10.000
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€3.000	-€2.861	-€2.729	-€2.602	-€2.482
Wind Energy Systems (Onshore)	€27.500	€26.227	€25.013	€23.855	€22.750
Small and Medium Wind Turbines (SMWT)	€24.000	€22.889	€21.829	€20.819	€19.855
Micro Hydropower	€20.667	€19.710	€18.797	€17.927	€17.097
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€7.143	€6.812	€6.497	€6.196	€5.909
Small Modular Reactors (SMRs) and Micro Reactors	€2.000	€1.907	€1.819	€1.735	€1.655
District Heating (4th Generation)	€6.000	€5.722	€5.457	€5.205	€4.964
District Heating and Cooling (5th Generation)	€9.143	€8.720	€8.316	€7.931	€7.564

Table 49: Total DCF in a small community, year 1–5.

TOTAL DCF PER TECHNOLOGY	6	7	8	9	10
Biogas Production (Anaerobic Digestion)	-€18.710	-€17.844	-€17.018	-€16.230	-€15.479
Bio-Oil Production (Pyrolysis)	-€37.871	-€36.118	-€34.446	-€32.851	-€31.330
Green Hydrogen Production (Electrolysis)	-€10.101	-€9.634	-€9.188	-€8.762	-€8.357
Aquathermal Energy Systems	€3.012	€2.873	€2.740	€2.613	€2.492
Sewage Thermal Energy Systems	€4.208	€4.013	€3.827	€3.650	€3.481
Residual Heat Recovery Systems	€4.734	€4.515	€4.306	€4.106	€3.916
Geothermal Energy Systems (ATES/BTES)	€4.734	€4.515	€4.306	€4.106	€3.916
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€6.312	€6.020	€5.741	€5.475	€5.222
Solar Panels (PV)	€22.277	€21.246	€20.262	€19.324	€18.429
Solar Panels (PT)	€7.240	€6.905	€6.585	€6.280	€5.990
Solar Panels (PVT)	€9.537	€9.096	€8.675	€8.273	€7.890
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€2.367	-€2.257	-€2.153	-€2.053	-€1.958
Wind Energy Systems (Onshore)	€21.697	€20.693	€19.735	€18.821	€17.950
Small and Medium Wind Turbines (SMWT)	€18.936	€18.059	€17.223	€16.426	€15.665
Micro Hydropower	€16.306	€15.551	€14.831	€14.144	€13.489
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€5.636	€5.375	€5.126	€4.889	€4.662
Small Modular Reactors (SMRs) and Micro Reactors	€1.578	€1.505	€1.435	€1.369	€1.305
District Heating (4th Generation)	€4.734	€4.515	€4.306	€4.106	€3.916
District Heating and Cooling (5th Generation)	€7.214	€6.880	€6.561	€6.257	€5.968

Table 50: Total DCF in a small community, year 6–10.

TOTAL DCF PER TECHNOLOGY	11	12	13	14	15
Biogas Production (Anaerobic Digestion)	-€14.762	-€14.079	-€13.427	-€12.805	-€12.212
Bio-Oil Production (Pyrolysis)	-€29.880	-€28.496	-€27.177	-€25.919	-€24.719
Green Hydrogen Production (Electrolysis)	-€7.970	-€7.601	-€7.249	-€6.913	-€6.593
Aquathermal Energy Systems	€2.377	€2.267	€2.162	€2.062	€1.966
Sewage Thermal Energy Systems	€3.320	€3.166	€3.020	€2.880	€2.747
Residual Heat Recovery Systems	€3.735	€3.562	€3.397	€3.240	€3.090
Geothermal Energy Systems (ATES/BTES)	€3.735	€3.562	€3.397	€3.240	€3.090
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€4.980	€4.749	€4.530	€4.320	€4.120
Solar Panels (PV)	€17.576	€16.763	€15.987	€15.246	€14.541
Solar Panels (PT)	€5.712	€5.448	€5.196	€4.955	€4.726
Solar Panels (PVT)	€7.525	€7.176	€6.844	€6.527	€6.225
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€1.867	-€1.781	-€1.699	-€1.620	-€1.545
Wind Energy Systems (Onshore)	€17.119	€16.326	€15.570	€14.849	€14.162
Small and Medium Wind Turbines (SMWT)	€14.940	€14.248	€13.589	€12.959	€12.359
Micro Hydropower	€12.865	€12.269	€11.701	€11.160	€10.643
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€4.446	€4.241	€4.044	€3.857	€3.678
Small Modular Reactors (SMRs) and Micro Reactors	€1.245	€1.187	€1.132	€1.080	€1.030
District Heating (4th Generation)	€3.735	€3.562	€3.397	€3.240	€3.090
District Heating and Cooling (5th Generation)	€5.691	€5.428	€5.177	€4.937	€4.708

Table 51: Total DCF in a small community, year 11–15.

TOTAL DCF PER TECHNOLOGY	16	17	18	19	20
Biogas Production (Anaerobic Digestion)	-€11.647	-€11.108	-€10.593	-€10.103	-€9.635
Bio-Oil Production (Pyrolysis)	-€23.575	-€22.483	-€21.442	-€20.450	-€19.503
Green Hydrogen Production (Electrolysis)	-€6.288	-€5.997	-€5.719	-€5.455	-€5.202
Aquathermal Energy Systems	€1.875	€1.788	€1.706	€1.627	€1.551
Sewage Thermal Energy Systems	€2.619	€2.498	€2.382	€2.272	€2.167
Residual Heat Recovery Systems	€2.947	€2.810	€2.680	€2.556	€2.438
Geothermal Energy Systems (ATES/BTES)	€2.947	€2.810	€2.680	€2.556	€2.438
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€3.929	€3.747	€3.574	€3.408	€3.250
Solar Panels (PV)	€13.867	€13.225	€12.613	€12.029	€11.472
Solar Panels (PT)	€4.507	€4.298	€4.099	€3.909	€3.728
Solar Panels (PVT)	€5.937	€5.662	€5.400	€5.150	€4.912
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€1.473	-€1.405	-€1.340	-€1.278	-€1.219
Wind Energy Systems (Onshore)	€13.506	€12.881	€12.285	€11.716	€11.173
Small and Medium Wind Turbines (SMWT)	€11.787	€11.242	€10.721	€10.225	€9.751
Micro Hydropower	€10.150	€9.680	€9.232	€8.805	€8.397
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€3.508	€3.346	€3.191	€3.043	€2.902
Small Modular Reactors (SMRs) and Micro Reactors	€982	€937	€893	€852	€813
District Heating (4th Generation)	€2.947	€2.810	€2.680	€2.556	€2.438
District Heating and Cooling (5th Generation)	€4.490	€4.283	€4.084	€3.895	€3.715

Table 52: Total DCF in a small community, year 16–20.

TOTAL DCF PER TECHNOLOGY	21	22	23	24	25
Biogas Production (Anaerobic Digestion)	-€9.189	-€8.764	-€8.358	-€7.971	-€7.602
Bio-Oil Production (Pyrolysis)	-€18.600	-€17.739	-€16.918	-€16.134	-€15.387
Green Hydrogen Production (Electrolysis)	-€4.961	-€4.731	-€4.512	-€4.304	-€4.104
Aquathermal Energy Systems	€1.480	€1.411	€1.346	€1.283	€1.224
Sewage Thermal Energy Systems	€2.067	€1.971	€1.880	€1.793	€1.710
Residual Heat Recovery Systems	€2.325	€2.217	€2.115	€2.017	€1.923
Geothermal Energy Systems (ATES/BTES)	€2.325	€2.217	€2.115	€2.017	€1.923
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€3.100	€2.956	€2.820	€2.689	€2.565
Solar Panels (PV)	€10.941	€10.435	€9.952	€9.491	€9.051
Solar Panels (PT)	€3.556	€3.391	€3.234	€3.085	€2.942
Solar Panels (PVT)	€4.684	€4.467	€4.260	€4.063	€3.875
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€1.162	-€1.109	-€1.057	-€1.008	-€962
Wind Energy Systems (Onshore)	€10.656	€10.163	€9.692	€9.244	€8.816
Small and Medium Wind Turbines (SMWT)	€9.300	€8.869	€8.459	€8.067	€7.694
Micro Hydropower	€8.008	€7.638	€7.284	€6.947	€6.625
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€2.768	€2.640	€2.517	€2.401	€2.290
Small Modular Reactors (SMRs) and Micro Reactors	€775	€739	€705	€672	€641
District Heating (4th Generation)	€2.325	€2.217	€2.115	€2.017	€1.923
District Heating and Cooling (5th Generation)	€3.543	€3.379	€3.222	€3.073	€2.931

Table 53: Total DCF in a small community, year 21–25.

TOTAL DCF PER TECHNOLOGY	26	27	28	29	30
Biogas Production (Anaerobic Digestion)	-€7.250	-€6.914	-€6.594	-€6.289	-€5.998
Bio-Oil Production (Pyrolysis)	-€14.675	-€13.996	-€13.348	-€12.730	-€12.140
Green Hydrogen Production (Electrolysis)	-€3.914	-€3.733	-€3.560	-€3.395	-€3.238
Aquathermal Energy Systems	€1.167	€1.113	€1.062	€1.013	€966
Sewage Thermal Energy Systems	€1.631	€1.555	€1.483	€1.414	€1.349
Residual Heat Recovery Systems	€1.834	€1.749	€1.668	€1.591	€1.518
Geothermal Energy Systems (ATES/BTES)	€1.834	€1.749	€1.668	€1.591	€1.518
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€2.446	€2.333	€2.225	€2.122	€2.023
Solar Panels (PV)	€8.632	€8.233	€7.852	€7.488	€7.141
Solar Panels (PT)	€2.806	€2.676	€2.552	€2.434	€2.321
Solar Panels (PVT)	€3.696	€3.525	€3.361	€3.206	€3.057
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€917	-€875	-€834	-€796	-€759
Wind Energy Systems (Onshore)	€8.408	€8.018	€7.647	€7.293	€6.955
Small and Medium Wind Turbines (SMWT)	€7.337	€6.998	€6.674	€6.365	€6.070
Micro Hydropower	€6.318	€6.026	€5.747	€5.481	€5.227
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€2.184	€2.083	€1.986	€1.894	€1.807
Small Modular Reactors (SMRs) and Micro Reactors	€611	€583	€556	€530	€506
District Heating (4th Generation)	€1.834	€1.749	€1.668	€1.591	€1.518
District Heating and Cooling (5th Generation)	€2.795	€2.666	€2.542	€2.425	€2.312

Table 54: Total DCF in a small community, year 26–30.

TOTAL DCF PER TECHNOLOGY	31	32	33	34	35
Biogas Production (Anaerobic Digestion)	-€5.720	-€5.455	-€5.203	-€4.962	-€4.732
Bio-Oil Production (Pyrolysis)	-€11.578	-€11.042	-€10.531	-€10.044	-€9.579
Green Hydrogen Production (Electrolysis)	-€3.088	-€2.945	-€2.809	-€2.679	-€2.555
Aquathermal Energy Systems	€921	€878	€838	€799	€762
Sewage Thermal Energy Systems	€1.286	€1.227	€1.170	€1.116	€1.064
Residual Heat Recovery Systems	€1.447	€1.380	€1.316	€1.255	€1.197
Geothermal Energy Systems (ATES/BTES)	€1.447	€1.380	€1.316	€1.255	€1.197
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€1.930	€1.840	€1.755	€1.674	€1.596
Solar Panels (PV)	€6.811	€6.495	€6.195	€5.908	€5.634
Solar Panels (PT)	€2.214	€2.111	€2.013	€1.920	€1.831
Solar Panels (PVT)	€2.916	€2.781	€2.652	€2.529	€2.412
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€724	-€690	-€658	-€628	-€599
Wind Energy Systems (Onshore)	€6.633	€6.326	€6.033	€5.754	€5.488
Small and Medium Wind Turbines (SMWT)	€5.789	€5.521	€5.266	€5.022	€4.789
Micro Hydropower	€4.985	€4.754	€4.534	€4.324	€4.124
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€1.723	€1.643	€1.567	€1.495	€1.425
Small Modular Reactors (SMRs) and Micro Reactors	€482	€460	€439	€418	€399
District Heating (4th Generation)	€1.447	€1.380	€1.316	€1.255	€1.197
District Heating and Cooling (5th Generation)	€2.205	€2.103	€2.006	€1.913	€1.824

Table 55: Total DCF in a small community, year 31–35.

TOTAL DCF PER TECHNOLOGY	36	37	38	39	40
Biogas Production (Anaerobic Digestion)	-€4.513	-€4.304	-€4.105	-€3.915	-€3.734
Bio-Oil Production (Pyrolysis)	-€9.135	-€8.712	-€8.309	-€7.924	-€7.557
Green Hydrogen Production (Electrolysis)	-€2.437	-€2.324	-€2.216	-€2.114	-€2.016
Aquathermal Energy Systems	€727	€693	€661	€630	€601
Sewage Thermal Energy Systems	€1.015	€968	€923	€880	€840
Residual Heat Recovery Systems	€1.142	€1.089	€1.039	€991	€945
Geothermal Energy Systems (ATES/BTES)	€1.142	€1.089	€1.039	€991	€945
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€1.523	€1.452	€1.385	€1.321	€1.260
Solar Panels (PV)	€5.374	€5.125	€4.888	€4.661	€4.445
Solar Panels (PT)	€1.746	€1.666	€1.588	€1.515	€1.445
Solar Panels (PVT)	€2.301	€2.194	€2.092	€1.996	€1.903
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€571	-€545	-€519	-€495	-€472
Wind Energy Systems (Onshore)	€5.234	€4.991	€4.760	€4.540	€4.330
Small and Medium Wind Turbines (SMWT)	€4.568	€4.356	€4.154	€3.962	€3.779
Micro Hydropower	€3.933	€3.751	€3.577	€3.412	€3.254
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€1.359	€1.296	€1.236	€1.179	€1.125
Small Modular Reactors (SMRs) and Micro Reactors	€381	€363	€346	€330	€315
District Heating (4th Generation)	€1.142	€1.089	€1.039	€991	€945
District Heating and Cooling (5th Generation)	€1.740	€1.659	€1.583	€1.509	€1.439

Table 56: Total DCF in a small community, year 36–40.

TOTAL DCF PER TECHNOLOGY	41	42	43	44	45
Biogas Production (Anaerobic Digestion)	-€3.561	-€3.396	-€3.239	-€3.089	-€2.946
Bio-Oil Production (Pyrolysis)	-€7.207	-€6.874	-€6.556	-€6.252	-€5.963
Green Hydrogen Production (Electrolysis)	-€1.922	-€1.833	-€1.749	-€1.668	-€1.590
Aquathermal Energy Systems	€573	€547	€521	€497	€474
Sewage Thermal Energy Systems	€801	€764	€728	€695	€663
Residual Heat Recovery Systems	€901	€859	€819	€782	€745
Geothermal Energy Systems (ATES/BTES)	€901	€859	€819	€782	€745
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€1.201	€1.146	€1.093	€1.042	€994
Solar Panels (PV)	€4.240	€4.043	€3.856	€3.678	€3.507
Solar Panels (PT)	€1.378	€1.314	€1.253	€1.195	€1.140
Solar Panels (PVT)	€1.815	€1.731	€1.651	€1.574	€1.502
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€450	-€430	-€410	-€391	-€373
Wind Energy Systems (Onshore)	€4.129	€3.938	€3.756	€3.582	€3.416
Small and Medium Wind Turbines (SMWT)	€3.604	€3.437	€3.278	€3.126	€2.981
Micro Hydropower	€3.103	€2.960	€2.823	€2.692	€2.567
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€1.073	€1.023	€976	€930	€887
Small Modular Reactors (SMRs) and Micro Reactors	€300	€286	€273	€261	€248
District Heating (4th Generation)	€901	€859	€819	€782	€745
District Heating and Cooling (5th Generation)	€1.373	€1.309	€1.249	€1.191	€1.136

Table 57: Total DCF in a small community, year 41–45.

TOTAL DCF PER TECHNOLOGY	46	47	48	49	50
Biogas Production (Anaerobic Digestion)	-€2.809	-€2.679	-€2.555	-€2.437	-€2.324
Bio-Oil Production (Pyrolysis)	-€5.687	-€5.423	-€5.172	-€4.933	-€4.704
Green Hydrogen Production (Electrolysis)	-€1.517	-€1.447	-€1.380	-€1.316	-€1.255
Aquathermal Energy Systems	€452	€431	€411	€392	€374
Sewage Thermal Energy Systems	€632	€603	€575	€548	€523
Residual Heat Recovery Systems	€711	€678	€647	€617	€588
Geothermal Energy Systems (ATES/BTES)	€711	€678	€647	€617	€588
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€948	€904	€862	€822	€784
Solar Panels (PV)	€3.345	€3.190	€3.042	€2.902	€2.767
Solar Panels (PT)	€1.087	€1.037	€989	€943	€899
Solar Panels (PVT)	€1.432	€1.366	€1.303	€1.242	€1.185
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-€355	-€339	-€323	-€308	-€294
Wind Energy Systems (Onshore)	€3.258	€3.107	€2.963	€2.826	€2.695
Small and Medium Wind Turbines (SMWT)	€2.843	€2.712	€2.586	€2.466	€2.352
Micro Hydropower	€2.448	€2.335	€2.227	€2.124	€2.025
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€846	€807	€770	€734	€700
Small Modular Reactors (SMRs) and Micro Reactors	€237	€226	€216	€206	€196
District Heating (4th Generation)	€711	€678	€647	€617	€588
District Heating and Cooling (5th Generation)	€1.083	€1.033	€985	€940	€896

Table 58: Total DCF in a small community, year 46–50.

C.2 Medium-sized Communities (1 GWh, 200–300 dwellings)

TOTAL DCF PER TECHNOLOGY	1	2	3	4	5
Biogas Production (Anaerobic Digestion)	-€80.000	-€76.296	-€72.764	-€69.395	-€66.183
Bio-Oil Production (Pyrolysis)	-€255.000	-€243.194	-€231.935	-€221.198	-€210.957
Green Hydrogen Production (Electrolysis)	-€6.818	-€6.503	-€6.201	-€5.914	-€5.641
Aquathermal Energy Systems	€80.227	€76.513	€72.971	€69.592	€66.371
Sewage Thermal Energy Systems	€78.333	€74.707	€71.248	€67.950	€64.804
Residual Heat Recovery Systems	€90.000	€85.833	€81.860	€78.070	€74.455
Geothermal Energy Systems (ATES/BTES)	€93.333	€89.012	€84.891	€80.961	€77.213
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€92.222	€87.953	€83.881	€79.997	€76.294
Solar Panels (PV)	€288.235	€274.891	€262.165	€250.027	€238.452
Solar Panels (PT)	€99.412	€94.809	€90.420	€86.234	€82.242
Solar Panels (PVT)	€135.588	€129.311	€123.324	€117.615	€112.170
Solar Panels (PC)					
Concentrated Solar Power (CSP)	€20.000	€19.074	€18.191	€17.349	€16.546
Wind Energy Systems (Onshore)	€283.333	€270.216	€257.706	€245.775	€234.397
Small and Medium Wind Turbines (SMWT)	€258.333	€246.373	€234.967	€224.089	€213.715
Micro Hydropower	€250.000	€238.426	€227.388	€216.860	€206.821
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€171.429	€163.492	€155.923	€148.704	€141.820
Small Modular Reactors (SMRs) and Micro Reactors	€120.000	€114.444	€109.146	€104.093	€99.274
District Heating (4th Generation)	€80.000	€76.296	€72.764	€69.395	€66.183
District Heating and Cooling (5th Generation)	€103.929	€99.117	€94.528	€90.152	€85.978

Table 59: Total DCF in a medium community, year 1–5.

TOTAL DCF PER TECHNOLOGY	6	7	8	9	10
Biogas Production (Anaerobic Digestion)	-€63.119	-€60.196	-€57.410	-€54.752	-€52.217
Bio-Oil Production (Pyrolysis)	-€201.191	-€191.876	-€182.993	-€174.521	-€166.441
Green Hydrogen Production (Electrolysis)	-€5.379	-€5.130	-€4.893	-€4.666	-€4.450
Aquathermal Energy Systems	€63.298	€60.367	€57.573	€54.907	€52.365
Sewage Thermal Energy Systems	€61.804	€58.942	€56.214	€53.611	€51.129
Residual Heat Recovery Systems	€71.008	€67.721	€64.586	€61.596	€58.744
Geothermal Energy Systems (ATES/BTES)	€73.638	€70.229	€66.978	€63.877	€60.920
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€72.762	€69.393	€66.180	€63.117	€60.194
Solar Panels (PV)	€227.413	€216.884	€206.843	€197.267	€188.134
Solar Panels (PT)	€78.434	€74.803	€71.340	€68.037	€64.887
Solar Panels (PVT)	€106.977	€102.024	€97.301	€92.796	€88.500
Solar Panels (PC)					
Concentrated Solar Power (CSP)	€15.780	€15.049	€14.352	€13.688	€13.054
Wind Energy Systems (Onshore)	€223.545	€213.196	€203.326	€193.912	€184.935
Small and Medium Wind Turbines (SMWT)	€203.820	€194.384	€185.385	€176.802	€168.617
Micro Hydropower	€197.246	€188.114	€179.405	€171.099	€163.178
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€135.254	€128.992	€123.021	€117.325	€111.893
Small Modular Reactors (SMRs) and Micro Reactors	€94.678	€90.295	€86.114	€82.128	€78.325
District Heating (4th Generation)	€63.119	€60.196	€57.410	€54.752	€52.217
District Heating and Cooling (5th Generation)	€81.998	€78.202	€74.581	€71.128	€67.835

Table 60: Total DCF in a medium community, year 6–10.

TOTAL DCF PER TECHNOLOGY	11	12	13	14	15
Biogas Production (Anaerobic Digestion)	-€49.799	-€47.494	-€45.295	-€43.198	-€41.198
Bio-Oil Production (Pyrolysis)	-€158.736	-€151.387	-€144.378	-€137.694	-€131.319
Green Hydrogen Production (Electrolysis)	-€4.244	-€4.048	-€3.860	-€3.682	-€3.511
Aquathermal Energy Systems	€49.941	€47.629	€45.424	€43.321	€41.315
Sewage Thermal Energy Systems	€48.762	€46.504	€44.351	€42.298	€40.340
Residual Heat Recovery Systems	€56.024	€53.431	€50.957	€48.598	€46.348
Geothermal Energy Systems (ATES/BTES)	€58.099	€55.410	€52.844	€50.398	€48.065
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€57.408	€54.750	€52.215	€49.798	€47.492
Solar Panels (PV)	€179.425	€171.118	€163.196	€155.640	€148.435
Solar Panels (PT)	€61.883	€59.018	€56.286	€53.680	€51.195
Solar Panels (PVT)	€84.403	€80.495	€76.769	€73.215	€69.825
Solar Panels (PC)					
Concentrated Solar Power (CSP)	€12.450	€11.873	€11.324	€10.800	€10.300
Wind Energy Systems (Onshore)	€176.373	€168.208	€160.420	€152.993	€145.910
Small and Medium Wind Turbines (SMWT)	€160.811	€153.366	€146.266	€139.494	€133.036
Micro Hydropower	€155.623	€148.419	€141.547	€134.994	€128.744
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€106.713	€101.773	€97.061	€92.567	€88.282
Small Modular Reactors (SMRs) and Micro Reactors	€74.699	€71.241	€67.943	€64.797	€61.797
District Heating (4th Generation)	€49.799	€47.494	€45.295	€43.198	€41.198
District Heating and Cooling (5th Generation)	€64.695	€61.700	€58.843	€56.119	€53.521

Table 61: Total DCF in a medium community, year 11–15.

TOTAL DCF PER TECHNOLOGY	16	17	18	19	20
Biogas Production (Anaerobic Digestion)	-€39.291	-€37.472	-€35.737	-€34.083	-€32.505
Bio-Oil Production (Pyrolysis)	-€125.240	-€119.442	-€113.912	-€108.638	-€103.609
Green Hydrogen Production (Electrolysis)	-€3.349	-€3.194	-€3.046	-€2.905	-€2.770
Aquathermal Energy Systems	€39.403	€37.578	€35.839	€34.179	€32.597
Sewage Thermal Energy Systems	€38.472	€36.691	€34.993	€33.373	€31.827
Residual Heat Recovery Systems	€44.202	€42.156	€40.204	€38.343	€36.568
Geothermal Energy Systems (ATES/BTES)	€45.839	€43.717	€41.693	€39.763	€37.922
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€45.294	€43.197	€41.197	€39.290	€37.471
Solar Panels (PV)	€141.563	€135.009	€128.759	€122.798	€117.112
Solar Panels (PT)	€48.825	€46.564	€44.409	€42.353	€40.392
Solar Panels (PVT)	€66.592	€63.509	€60.569	€57.765	€55.091
Solar Panels (PC)					
Concentrated Solar Power (CSP)	€9.823	€9.368	€8.934	€8.521	€8.126
Wind Energy Systems (Onshore)	€139.155	€132.713	€126.569	€120.709	€115.121
Small and Medium Wind Turbines (SMWT)	€126.877	€121.003	€115.401	€110.058	€104.963
Micro Hydropower	€122.784	€117.100	€111.678	€106.508	€101.577
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€84.195	€80.297	€76.579	€73.034	€69.653
Small Modular Reactors (SMRs) and Micro Reactors	€58.936	€56.208	€53.606	€51.124	€48.757
District Heating (4th Generation)	€39.291	€37.472	€35.737	€34.083	€32.505
District Heating and Cooling (5th Generation)	€51.043	€48.680	€46.426	€44.277	€42.227

Table 62: Total DCF in a medium community, year 16–20.

TOTAL DCF PER TECHNOLOGY	21	22	23	24	25
Biogas Production (Anaerobic Digestion)	-€31.000	-€29.565	-€28.196	-€26.891	-€25.646
Bio-Oil Production (Pyrolysis)	-€98.812	-€94.237	-€89.875	-€85.714	-€81.745
Green Hydrogen Production (Electrolysis)	-€2.642	-€2.520	-€2.403	-€2.292	-€2.186
Aquathermal Energy Systems	€31.088	€29.649	€28.276	€26.967	€25.718
Sewage Thermal Energy Systems	€30.354	€28.949	€27.609	€26.330	€25.111
Residual Heat Recovery Systems	€34.875	€33.260	€31.720	€30.252	€28.851
Geothermal Energy Systems (ATES/BTES)	€36.166	€34.492	€32.895	€31.372	€29.920
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€35.736	€34.081	€32.504	€30.999	€29.564
Solar Panels (PV)	€111.691	€106.520	€101.588	€96.885	€92.400
Solar Panels (PT)	€38.522	€36.738	€35.038	€33.415	€31.868
Solar Panels (PVT)	€52.540	€50.108	€47.788	€45.576	€43.466
Solar Panels (PC)					
Concentrated Solar Power (CSP)	€7.750	€7.391	€7.049	€6.723	€6.411
Wind Energy Systems (Onshore)	€109.791	€104.708	€99.861	€95.237	€90.828
Small and Medium Wind Turbines (SMWT)	€100.104	€95.469	€91.049	€86.834	€82.814
Micro Hydropower	€96.874	€92.390	€88.112	€84.033	€80.143
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€66.428	€63.353	€60.420	€57.623	€54.955
Small Modular Reactors (SMRs) and Micro Reactors	€46.500	€44.347	€42.294	€40.336	€38.468
District Heating (4th Generation)	€31.000	€29.565	€28.196	€26.891	€25.646
District Heating and Cooling (5th Generation)	€40.272	€38.408	€36.630	€34.934	€33.316

Table 63: Total DCF in a medium community, year 21–25.

TOTAL DCF PER TECHNOLOGY	26	27	28	29	30
Biogas Production (Anaerobic Digestion)	-€24.458	-€23.326	-€22.246	-€21.216	-€20.234
Bio-Oil Production (Pyrolysis)	-€77.961	-€74.352	-€70.909	-€67.627	-€64.496
Green Hydrogen Production (Electrolysis)	-€2.085	-€1.988	-€1.896	-€1.808	-€1.724
Aquathermal Energy Systems	€24.528	€23.392	€22.309	€21.276	€20.291
Sewage Thermal Energy Systems	€23.949	€22.840	€21.783	€20.774	€19.812
Residual Heat Recovery Systems	€27.516	€26.242	€25.027	€23.868	€22.763
Geothermal Energy Systems (ATES/BTES)	€28.535	€27.214	€25.954	€24.752	€23.606
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€28.195	€26.890	€25.645	€24.458	€23.325
Solar Panels (PV)	€88.122	€84.042	€80.151	€76.441	€72.902
Solar Panels (PT)	€30.393	€28.986	€27.644	€26.364	€25.144
Solar Panels (PVT)	€41.453	€39.534	€37.704	€35.958	€34.294
Solar Panels (PC)					
Concentrated Solar Power (CSP)	€6.115	€5.831	€5.562	€5.304	€5.058
Wind Energy Systems (Onshore)	€86.623	€82.613	€78.788	€75.141	€71.662
Small and Medium Wind Turbines (SMWT)	€78.980	€75.324	€71.836	€68.511	€65.339
Micro Hydropower	€76.432	€72.894	€69.519	€66.301	€63.231
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€52.411	€49.984	€47.670	€45.463	€43.358
Small Modular Reactors (SMRs) and Micro Reactors	€36.687	€34.989	€33.369	€31.824	€30.351
District Heating (4th Generation)	€24.458	€23.326	€22.246	€21.216	€20.234
District Heating and Cooling (5th Generation)	€31.774	€30.303	€28.900	€27.562	€26.286

Table 64: Total DCF in a medium community, year 26–30.

TOTAL DCF PER TECHNOLOGY	31	32	33	34	35
Biogas Production (Anaerobic Digestion)	-€19.297	-€18.404	-€17.552	-€16.739	-€15.964
Bio-Oil Production (Pyrolysis)	-€61.510	-€58.662	-€55.946	-€53.356	-€50.886
Green Hydrogen Production (Electrolysis)	-€1.645	-€1.569	-€1.496	-€1.427	-€1.361
Aquathermal Energy Systems	€19.352	€18.456	€17.602	€16.787	€16.010
Sewage Thermal Energy Systems	€18.895	€18.020	€17.186	€16.390	€15.632
Residual Heat Recovery Systems	€21.709	€20.704	€19.746	€18.832	€17.960
Geothermal Energy Systems (ATES/BTES)	€22.513	€21.471	€20.477	€19.529	€18.625
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€22.245	€21.215	€20.233	€19.297	€18.403
Solar Panels (PV)	€69.527	€66.308	€63.238	€60.310	€57.518
Solar Panels (PT)	€23.980	€22.869	€21.811	€20.801	€19.838
Solar Panels (PVT)	€32.706	€31.192	€29.748	€28.370	€27.057
Solar Panels (PC)					
Concentrated Solar Power (CSP)	€4.824	€4.601	€4.388	€4.185	€3.991
Wind Energy Systems (Onshore)	€68.344	€65.180	€62.163	€59.285	€56.540
Small and Medium Wind Turbines (SMWT)	€62.314	€59.429	€56.678	€54.054	€51.551
Micro Hydropower	€60.304	€57.512	€54.849	€52.310	€49.888
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€41.351	€39.437	€37.611	€35.870	€34.209
Small Modular Reactors (SMRs) and Micro Reactors	€28.946	€27.606	€26.328	€25.109	€23.946
District Heating (4th Generation)	€19.297	€18.404	€17.552	€16.739	€15.964
District Heating and Cooling (5th Generation)	€25.069	€23.909	€22.802	€21.746	€20.739

Table 65: Total DCF in a medium community, year 31–35.

TOTAL DCF PER TECHNOLOGY	36	37	38	39	40
Biogas Production (Anaerobic Digestion)	-€15.225	-€14.520	-€13.848	-€13.207	-€12.595
Bio-Oil Production (Pyrolysis)	-€48.530	-€46.283	-€44.141	-€42.097	-€40.148
Green Hydrogen Production (Electrolysis)	-€1.298	-€1.238	-€1.180	-€1.126	-€1.073
Aquathermal Energy Systems	€15.268	€14.562	€13.887	€13.244	€12.631
Sewage Thermal Energy Systems	€14.908	€14.218	€13.560	€12.932	€12.333
Residual Heat Recovery Systems	€17.128	€16.335	€15.579	€14.858	€14.170
Geothermal Energy Systems (ATES/BTES)	€17.763	€16.940	€16.156	€15.408	€14.695
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€17.551	€16.739	€15.964	€15.225	€14.520
Solar Panels (PV)	€54.855	€52.316	€49.894	€47.584	€45.381
Solar Panels (PT)	€18.919	€18.044	€17.208	€16.412	€15.652
Solar Panels (PVT)	€25.804	€24.610	€23.470	€22.384	€21.348
Solar Panels (PC)					
Concentrated Solar Power (CSP)	€3.806	€3.630	€3.462	€3.302	€3.149
Wind Energy Systems (Onshore)	€53.922	€51.426	€49.045	€46.775	€44.609
Small and Medium Wind Turbines (SMWT)	€49.165	€46.888	€44.718	€42.647	€40.673
Micro Hydropower	€47.579	€45.376	€43.275	€41.272	€39.361
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€32.625	€31.115	€29.674	€28.301	€26.990
Small Modular Reactors (SMRs) and Micro Reactors	€22.838	€21.780	€20.772	€19.810	€18.893
District Heating (4th Generation)	€15.225	€14.520	€13.848	€13.207	€12.595
District Heating and Cooling (5th Generation)	€19.779	€18.863	€17.990	€17.157	€16.363

Table 66: Total DCF in a medium community, year 36–40.

TOTAL DCF PER TECHNOLOGY	41	42	43	44	45
Biogas Production (Anaerobic Digestion)	-€12.012	-€11.456	-€10.926	-€10.420	-€9.938
Bio-Oil Production (Pyrolysis)	-€38.289	-€36.517	-€34.826	-€33.214	-€31.676
Green Hydrogen Production (Electrolysis)	-€1.024	-€976	-€931	-€888	-€847
Aquathermal Energy Systems	€12.046	€11.489	€10.957	€10.450	€9.966
Sewage Thermal Energy Systems	€11.762	€11.218	€10.698	€10.203	€9.731
Residual Heat Recovery Systems	€13.514	€12.888	€12.292	€11.723	€11.180
Geothermal Energy Systems (ATES/BTES)	€14.014	€13.366	€12.747	€12.157	€11.594
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€13.848	€13.207	€12.595	€12.012	€11.456
Solar Panels (PV)	€43.280	€41.276	€39.365	€37.543	€35.805
Solar Panels (PT)	€14.927	€14.236	€13.577	€12.948	€12.349
Solar Panels (PVT)	€20.359	€19.417	€18.518	€17.660	€16.843
Solar Panels (PC)					
Concentrated Solar Power (CSP)	€3.003	€2.864	€2.731	€2.605	€2.484
Wind Energy Systems (Onshore)	€42.544	€40.574	€38.696	€36.904	€35.196
Small and Medium Wind Turbines (SMWT)	€38.790	€36.994	€35.281	€33.648	€32.090
Micro Hydropower	€37.539	€35.801	€34.143	€32.563	€31.055
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€25.741	€24.549	€23.413	€22.329	€21.295
Small Modular Reactors (SMRs) and Micro Reactors	€18.019	€17.184	€16.389	€15.630	€14.906
District Heating (4th Generation)	€12.012	€11.456	€10.926	€10.420	€9.938
District Heating and Cooling (5th Generation)	€15.605	€14.883	€14.194	€13.537	€12.910

Table 67: Total DCF in a medium community, year 41–45.

TOTAL DCF PER TECHNOLOGY	46	47	48	49	50
Biogas Production (Anaerobic Digestion)	-€9.478	-€9.039	-€8.620	-€8.221	-€7.841
Bio-Oil Production (Pyrolysis)	-€30.210	-€28.811	-€27.477	-€26.205	-€24.992
Green Hydrogen Production (Electrolysis)	-€808	-€770	-€735	-€701	-€668
Aquathermal Energy Systems	€9.504	€9.064	€8.645	€8.245	€7.863
Sewage Thermal Energy Systems	€9.280	€8.850	€8.441	€8.050	€7.677
Residual Heat Recovery Systems	€10.662	€10.169	€9.698	€9.249	€8.821
Geothermal Energy Systems (ATES/BTES)	€11.057	€10.545	€10.057	€9.591	€9.147
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	€10.926	€10.420	€9.937	€9.477	€9.038
Solar Panels (PV)	€34.147	€32.566	€31.058	€29.621	€28.249
Solar Panels (PT)	€11.777	€11.232	€10.712	€10.216	€9.743
Solar Panels (PVT)	€16.063	€15.319	€14.610	€13.934	€13.289
Solar Panels (PC)					
Concentrated Solar Power (CSP)	€2.369	€2.260	€2.155	€2.055	€1.960
Wind Energy Systems (Onshore)	€33.566	€32.012	€30.530	€29.117	€27.769
Small and Medium Wind Turbines (SMWT)	€30.605	€29.188	€27.836	€26.548	€25.319
Micro Hydropower	€29.617	€28.246	€26.938	€25.691	€24.502
Ocean Power					
Organic Rankine Cycle (ORC) Systems	€20.309	€19.369	€18.472	€17.617	€16.801
Small Modular Reactors (SMRs) and Micro Reactors	€14.216	€13.558	€12.930	€12.332	€11.761
District Heating (4th Generation)	€9.478	€9.039	€8.620	€8.221	€7.841
District Heating and Cooling (5th Generation)	€12.312	€11.742	€11.199	€10.680	€10.186

Table 68: Total DCF in a medium community, year 46–50.

C.3 Large-sized Communities (10 GWh, 2000–3000 dwellings)

TOTAL DCF PER TECHNOLOGY	1	2	3	4	5
Biogas Production (Anaerobic Digestion)	k€287	k€274	k€261	k€249	k€238
Bio-Oil Production (Pyrolysis)	-k€856	-k€816	-k€778	-k€742	-k€708
Green Hydrogen Production (Electrolysis)	k€760	k€725	k€691	k€659	k€629
Aquathermal Energy Systems	k€1054	k€1005	k€958	k€914	k€872
Sewage Thermal Energy Systems	k€922	k€880	k€839	k€800	k€763
Residual Heat Recovery Systems	k€1044	k€996	k€950	k€906	k€864
Geothermal Energy Systems (ATES/BTES)	k€1078	k€1028	k€980	k€935	k€892
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€967	k€922	k€879	k€839	k€800
Solar Panels (PV)	k€2791	k€2661	k€2538	k€2421	k€2309
Solar Panels (PT)	k€1003	k€957	k€913	k€870	k€830
Solar Panels (PVT)	k€1397	k€1332	k€1271	k€1212	k€1156
Solar Panels (PC)					
Concentrated Solar Power (CSP)	k€544	k€519	k€495	k€472	k€450
Wind Energy Systems (Onshore)	k€2761	k€2633	k€2511	k€2395	k€2284
Small and Medium Wind Turbines (SMWT)	k€2594	k€2474	k€2360	k€2251	k€2146
Micro Hydropower	k€2661	k€2538	k€2420	k€2308	k€2201
Ocean Power					
Organic Rankine Cycle (ORC) Systems	k€2290	k€2184	k€2083	k€1986	k€1894
Small Modular Reactors (SMRs) and Micro Reactors	k€1861	k€1775	k€1693	k€1614	k€1540
District Heating (4th Generation)	k€904	k€863	k€823	k€785	k€748
District Heating and Cooling (5th Generation)	k€1073	k€1023	k€976	k€931	k€888

Table 69: Total DCF in a large community, year 1–5.

TOTAL DCF PER TECHNOLOGY	6	7	8	9	10
Biogas Production (Anaerobic Digestion)	k€227	k€216	k€206	k€197	k€188
Bio-Oil Production (Pyrolysis)	-k€675	-k€644	-k€614	-k€586	-k€558
Green Hydrogen Production (Electrolysis)	k€600	k€572	k€545	k€520	k€496
Aquathermal Energy Systems	k€831	k€793	k€756	k€721	k€688
Sewage Thermal Energy Systems	k€728	k€694	k€662	k€631	k€602
Residual Heat Recovery Systems	k€824	k€786	k€750	k€715	k€682
Geothermal Energy Systems (ATES/BTES)	k€850	k€811	k€773	k€738	k€703
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€763	k€727	k€694	k€662	k€631
Solar Panels (PV)	k€2202	k€2100	k€2003	k€1910	k€1821
Solar Panels (PT)	k€792	k€755	k€720	k€687	k€655
Solar Panels (PVT)	k€1102	k€1051	k€1003	k€956	k€912
Solar Panels (PC)					
Concentrated Solar Power (CSP)	k€430	k€410	k€391	k€373	k€355
Wind Energy Systems (Onshore)	k€2178	k€2078	k€1981	k€1890	k€1802
Small and Medium Wind Turbines (SMWT)	k€2047	k€1952	k€1862	k€1776	k€1693
Micro Hydropower	k€2100	k€2002	k€1910	k€1821	k€1737
Ocean Power					
Organic Rankine Cycle (ORC) Systems	k€1807	k€1723	k€1643	k€1567	k€1495
Small Modular Reactors (SMRs) and Micro Reactors	k€1468	k€1400	k€1336	k€1274	k€1215
District Heating (4th Generation)	k€714	k€681	k€649	k€619	k€590
District Heating and Cooling (5th Generation)	k€847	k€807	k€770	k€734	k€700

Table 70: Total DCF in a large community, year 6–10.

TOTAL DCF PER TECHNOLOGY	11	12	13	14	15
Biogas Production (Anaerobic Digestion)	k€179	k€171	k€163	k€155	k€148
Bio-Oil Production (Pyrolysis)	-k€533	-k€508	-k€484	-k€462	-k€441
Green Hydrogen Production (Electrolysis)	k€473	k€451	k€430	k€410	k€391
Aquathermal Energy Systems	k€656	k€625	k€597	k€569	k€543
Sewage Thermal Energy Systems	k€574	k€547	k€522	k€498	k€475
Residual Heat Recovery Systems	k€650	k€620	k€591	k€564	k€538
Geothermal Energy Systems (ATES/BTES)	k€671	k€640	k€610	k€582	k€555
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€602	k€574	k€547	k€522	k€498
Solar Panels (PV)	k€1737	k€1657	k€1580	k€1507	k€1437
Solar Panels (PT)	k€625	k€596	k€568	k€542	k€517
Solar Panels (PVT)	k€870	k€829	k€791	k€754	k€719
Solar Panels (PC)					
Concentrated Solar Power (CSP)	k€339	k€323	k€308	k€294	k€280
Wind Energy Systems (Onshore)	k€1719	k€1639	k€1563	k€1491	k€1422
Small and Medium Wind Turbines (SMWT)	k€1615	k€1540	k€1469	k€1401	k€1336
Micro Hydropower	k€1657	k€1580	k€1507	k€1437	k€1370
Ocean Power					
Organic Rankine Cycle (ORC) Systems	k€1425	k€1359	k€1296	k€1236	k€1179
Small Modular Reactors (SMRs) and Micro Reactors	k€1159	k€1105	k€1054	k€1005	k€958
District Heating (4th Generation)	k€563	k€537	k€512	k€488	k€466
District Heating and Cooling (5th Generation)	k€668	k€637	k€608	k€579	k€553

Table 71: Total DCF in a large community, year 11–15.

TOTAL DCF PER TECHNOLOGY	16	17	18	19	20
Biogas Production (Anaerobic Digestion)	k€141	k€135	k€128	k€122	k€117
Bio-Oil Production (Pyrolysis)	-k€420	-k€401	-k€382	-k€364	-k€348
Green Hydrogen Production (Electrolysis)	k€373	k€356	k€339	k€324	k€309
Aquathermal Energy Systems	k€517	k€493	k€471	k€449	k€428
Sewage Thermal Energy Systems	k€453	k€432	k€412	k€393	k€375
Residual Heat Recovery Systems	k€513	k€489	k€467	k€445	k€424
Geothermal Energy Systems (ATES/BTES)	k€529	k€505	k€481	k€459	k€438
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€475	k€453	k€432	k€412	k€393
Solar Panels (PV)	k€1371	k€1307	k€1247	k€1189	k€1134
Solar Panels (PT)	k€493	k€470	k€448	k€427	k€408
Solar Panels (PVT)	k€686	k€654	k€624	k€595	k€568
Solar Panels (PC)					
Concentrated Solar Power (CSP)	k€267	k€255	k€243	k€232	k€221
Wind Energy Systems (Onshore)	k€1356	k€1293	k€1233	k€1176	k€1122
Small and Medium Wind Turbines (SMWT)	k€1274	k€1215	k€1159	k€1105	k€1054
Micro Hydropower	k€1307	k€1246	k€1189	k€1134	k€1081
Ocean Power					
Organic Rankine Cycle (ORC) Systems	k€1125	k€1072	k€1023	k€975	k€930
Small Modular Reactors (SMRs) and Micro Reactors	k€914	k€872	k€831	k€793	k€756
District Heating (4th Generation)	k€444	k€424	k€404	k€385	k€367
District Heating and Cooling (5th Generation)	k€527	k€503	k€479	k€457	k€436

Table 72: Total DCF in a large community, year 16–20.

TOTAL DCF PER TECHNOLOGY	21	22	23	24	25
Biogas Production (Anaerobic Digestion)	k€111	k€106	k€101	k€97	k€92
Bio-Oil Production (Pyrolysis)	-k€332	-k€316	-k€302	-k€288	-k€274
Green Hydrogen Production (Electrolysis)	k€294	k€281	k€268	k€255	k€244
Aquathermal Energy Systems	k€408	k€389	k€371	k€354	k€338
Sewage Thermal Energy Systems	k€357	k€341	k€325	k€310	k€296
Residual Heat Recovery Systems	k€405	k€386	k€368	k€351	k€335
Geothermal Energy Systems (ATES/BTES)	k€418	k€398	k€380	k€362	k€346
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€375	k€357	k€341	k€325	k€310
Solar Panels (PV)	k€1081	k€1031	k€984	k€938	k€895
Solar Panels (PT)	k€389	k€371	k€354	k€337	k€322
Solar Panels (PVT)	k€541	k€516	k€492	k€470	k€448
Solar Panels (PC)					
Concentrated Solar Power (CSP)	k€211	k€201	k€192	k€183	k€175
Wind Energy Systems (Onshore)	k€1070	k€1020	k€973	k€928	k€885
Small and Medium Wind Turbines (SMWT)	k€1005	k€959	k€914	k€872	k€832
Micro Hydropower	k€1031	k€983	k€938	k€894	k€853
Ocean Power					
Organic Rankine Cycle (ORC) Systems	k€887	k€846	k€807	k€770	k€734
Small Modular Reactors (SMRs) and Micro Reactors	k€721	k€688	k€656	k€626	k€597
District Heating (4th Generation)	k€350	k€334	k€319	k€304	k€290
District Heating and Cooling (5th Generation)	k€416	k€397	k€378	k€361	k€344

Table 73: Total DCF in a large community, year 21–25.

TOTAL DCF PER TECHNOLOGY	26	27	28	29	30
Biogas Production (Anaerobic Digestion)	k€88	k€84	k€80	k€76	k€73
Bio-Oil Production (Pyrolysis)	-k€262	-k€249	-k€238	-k€227	-k€216
Green Hydrogen Production (Electrolysis)	k€232	k€222	k€211	k€202	k€192
Aquathermal Energy Systems	k€322	k€307	k€293	k€279	k€266
Sewage Thermal Energy Systems	k€282	k€269	k€256	k€245	k€233
Residual Heat Recovery Systems	k€319	k€305	k€290	k€277	k€264
Geothermal Energy Systems (ATES/BTES)	k€330	k€314	k€300	k€286	k€273
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€296	k€282	k€269	k€256	k€244
Solar Panels (PV)	k€853	k€814	k€776	k€740	k€706
Solar Panels (PT)	k€307	k€293	k€279	k€266	k€254
Solar Panels (PVT)	k€427	k€407	k€389	k€371	k€353
Solar Panels (PC)					
Concentrated Solar Power (CSP)	k€166	k€159	k€151	k€144	k€138
Wind Energy Systems (Onshore)	k€844	k€805	k€768	k€732	k€698
Small and Medium Wind Turbines (SMWT)	k€793	k€756	k€721	k€688	k€656
Micro Hydropower	k€814	k€776	k€740	k€706	k€673
Ocean Power					
Organic Rankine Cycle (ORC) Systems	k€700	k€668	k€637	k€607	k€579
Small Modular Reactors (SMRs) and Micro Reactors	k€569	k€543	k€518	k€494	k€471
District Heating (4th Generation)	k€277	k€264	k€252	k€240	k€229
District Heating and Cooling (5th Generation)	k€328	k€313	k€298	k€285	k€271

Table 74: Total DCF in a large community, year 26–30.

TOTAL DCF PER TECHNOLOGY	31	32	33	34	35
Biogas Production (Anaerobic Digestion)	k€69	k€66	k€63	k€60	k€57
Bio-Oil Production (Pyrolysis)	-k€206	-k€197	-k€188	-k€179	-k€171
Green Hydrogen Production (Electrolysis)	k€183	k€175	k€167	k€159	k€152
Aquathermal Energy Systems	k€254	k€242	k€231	k€220	k€210
Sewage Thermal Energy Systems	k€222	k€212	k€202	k€193	k€184
Residual Heat Recovery Systems	k€252	k€240	k€229	k€219	k€208
Geothermal Energy Systems (ATES/BTES)	k€260	k€248	k€236	k€226	k€215
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€233	k€222	k€212	k€202	k€193
Solar Panels (PV)	k€673	k€642	k€612	k€584	k€557
Solar Panels (PT)	k€242	k€231	k€220	k€210	k€200
Solar Panels (PVT)	k€337	k€321	k€307	k€292	k€279
Solar Panels (PC)					
Concentrated Solar Power (CSP)	k€131	k€125	k€119	k€114	k€109
Wind Energy Systems (Onshore)	k€666	k€635	k€606	k€578	k€551
Small and Medium Wind Turbines (SMWT)	k€626	k€597	k€569	k€543	k€518
Micro Hydropower	k€642	k€612	k€584	k€557	k€531
Ocean Power					
Organic Rankine Cycle (ORC) Systems	k€552	k€527	k€502	k€479	k€457
Small Modular Reactors (SMRs) and Micro Reactors	k€449	k€428	k€408	k€389	k€371
District Heating (4th Generation)	k€218	k€208	k€198	k€189	k€180
District Heating and Cooling (5th Generation)	k€259	k€247	k€235	k€225	k€214

Table 75: Total DCF in a large community, year 31–35.

TOTAL DCF PER TECHNOLOGY	36	37	38	39	40
Biogas Production (Anaerobic Digestion)	k€55	k€52	k€50	k€47	k€45
Bio-Oil Production (Pyrolysis)	-k€163	-k€155	-k€148	-k€141	-k€135
Green Hydrogen Production (Electrolysis)	k€145	k€138	k€132	k€125	k€120
Aquathermal Energy Systems	k€201	k€191	k€182	k€174	k€166
Sewage Thermal Energy Systems	k€176	k€167	k€160	k€152	k€145
Residual Heat Recovery Systems	k€199	k€190	k€181	k€172	k€164
Geothermal Energy Systems (ATES/BTES)	k€205	k€196	k€187	k€178	k€170
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€184	k€175	k€167	k€160	k€152
Solar Panels (PV)	k€531	k€506	k€483	k€461	k€439
Solar Panels (PT)	k€191	k€182	k€174	k€166	k€158
Solar Panels (PVT)	k€266	k€254	k€242	k€231	k€220
Solar Panels (PC)					
Concentrated Solar Power (CSP)	k€104	k€99	k€94	k€90	k€86
Wind Energy Systems (Onshore)	k€525	k€501	k€478	k€456	k€435
Small and Medium Wind Turbines (SMWT)	k€494	k€471	k€449	k€428	k€408
Micro Hydropower	k€506	k€483	k€461	k€439	k€419
Ocean Power					
Organic Rankine Cycle (ORC) Systems	k€436	k€416	k€396	k€378	k€360
Small Modular Reactors (SMRs) and Micro Reactors	k€354	k€338	k€322	k€307	k€293
District Heating (4th Generation)	k€172	k€164	k€157	k€149	k€142
District Heating and Cooling (5th Generation)	k€204	k€195	k€186	k€177	k€169

Table 76: Total DCF in a large community, year 36–40.

TOTAL DCF PER TECHNOLOGY	41	42	43	44	45
Biogas Production (Anaerobic Digestion)	k€43	k€41	k€39	k€37	k€36
Bio-Oil Production (Pyrolysis)	-k€128	-k€123	-k€117	-k€111	-k€106
Green Hydrogen Production (Electrolysis)	k€114	k€109	k€104	k€99	k€94
Aquathermal Energy Systems	k€158	k€151	k€144	k€137	k€131
Sewage Thermal Energy Systems	k€138	k€132	k€126	k€120	k€115
Residual Heat Recovery Systems	k€157	k€150	k€143	k€136	k€130
Geothermal Energy Systems (ATES/BTES)	k€162	k€154	k€147	k€140	k€134
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€145	k€138	k€132	k€126	k€120
Solar Panels (PV)	k€419	k€400	k€381	k€363	k€347
Solar Panels (PT)	k€151	k€144	k€137	k€131	k€125
Solar Panels (PVT)	k€210	k€200	k€191	k€182	k€174
Solar Panels (PC)					
Concentrated Solar Power (CSP)	k€82	k€78	k€74	k€71	k€68
Wind Energy Systems (Onshore)	k€415	k€395	k€377	k€360	k€343
Small and Medium Wind Turbines (SMWT)	k€390	k€372	k€354	k€338	k€322
Micro Hydropower	k€400	k€381	k€363	k€347	k€331
Ocean Power					
Organic Rankine Cycle (ORC) Systems	k€344	k€328	k€313	k€298	k€284
Small Modular Reactors (SMRs) and Micro Reactors	k€279	k€267	k€254	k€242	k€231
District Heating (4th Generation)	k€136	k€130	k€124	k€118	k€112
District Heating and Cooling (5th Generation)	k€161	k€154	k€147	k€140	k€133

Table 77: Total DCF in a large community, year 41–45.

TOTAL DCF PER TECHNOLOGY	46	47	48	49	50
Biogas Production (Anaerobic Digestion)	k€34	k€32	k€31	k€30	k€28
Bio-Oil Production (Pyrolysis)	-k€101	-k€97	-k€92	-k€88	-k€84
Green Hydrogen Production (Electrolysis)	k€90	k€86	k€82	k€78	k€74
Aquathermal Energy Systems	k€125	k€119	k€114	k€108	k€103
Sewage Thermal Energy Systems	k€109	k€104	k€99	k€95	k€90
Residual Heat Recovery Systems	k€124	k€118	k€113	k€107	k€102
Geothermal Energy Systems (ATES/BTES)	k€128	k€122	k€116	k€111	k€106
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€115	k€109	k€104	k€99	k€95
Solar Panels (PV)	k€331	k€315	k€301	k€287	k€273
Solar Panels (PT)	k€119	k€113	k€108	k€103	k€98
Solar Panels (PVT)	k€166	k€158	k€151	k€144	k€137
Solar Panels (PC)					
Concentrated Solar Power (CSP)	k€64	k€62	k€59	k€56	k€53
Wind Energy Systems (Onshore)	k€327	k€312	k€298	k€284	k€271
Small and Medium Wind Turbines (SMWT)	k€307	k€293	k€280	k€267	k€254
Micro Hydropower	k€315	k€301	k€287	k€273	k€261
Ocean Power					
Organic Rankine Cycle (ORC) Systems	k€271	k€259	k€247	k€235	k€224
Small Modular Reactors (SMRs) and Micro Reactors	k€220	k€210	k€201	k€191	k€182
District Heating (4th Generation)	k€107	k€102	k€97	k€93	k€89
District Heating and Cooling (5th Generation)	k€127	k€121	k€116	k€110	k€105

Table 78: Total DCF in a large community, year 46–50.

D Dynamic payback tables (NPV) over 50 years

D.1 Small-sized Communities (100 MWh, 20–30 dwellings)

DYNAMIC PAYBACK	1	2	3	4	5
Biogas Production (Anaerobic Digestion)	-k€738	-k€761	-k€782	-k€803	-k€822
Bio-Oil Production (Pyrolysis)	-k€1048	-k€1094	-k€1137	-k€1179	-k€1219
Green Hydrogen Production (Electrolysis)	-k€770	-k€783	-k€794	-k€805	-k€816
Aquathermal Energy Systems	-k€269	-k€265	-k€262	-k€258	-k€255
Sewage Thermal Energy Systems	-k€217	-k€212	-k€207	-k€202	-k€198
Residual Heat Recovery Systems	-k€294	-k€288	-k€283	-k€278	-k€273
Geothermal Energy Systems (ATES/BTES)	-k€194	-k€188	-k€183	-k€178	-k€173
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€125	-k€118	-k€110	-k€103	-k€97
Solar Panels (PV)	-k€89	-k€62	-k€37	-k€12	k€11
Solar Panels (PT)	-k€132	-k€123	-k€115	-k€107	-k€99
Solar Panels (PVT)	-k€164	-k€153	-k€142	-k€131	-k€121
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€503	-k€506	-k€509	-k€511	-k€514
Wind Energy Systems (Onshore)	-k€73	-k€46	-k€21	k€3	k€25
Small and Medium Wind Turbines (SMWT)	-k€176	-k€153	-k€131	-k€110	-k€91
Micro Hydropower	-k€213	-k€193	-k€174	-k€156	-k€139
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€564	-k€557	-k€551	-k€545	-k€539
Small Modular Reactors (SMRs) and Micro Reactors	-k€398	-k€396	-k€394	-k€393	-k€391
District Heating (4th Generation)	-k€234	-k€228	-k€223	-k€218	-k€213
District Heating and Cooling (5th Generation)	-k€134	-k€125	-k€117	-k€109	-k€101

Table 79: Dynamic payback (NPV) in a small community, year 1–5.

DYNAMIC PAYBACK	6	7	8	9	10
Biogas Production (Anaerobic Digestion)	-k€841	-k€859	-k€876	-k€892	-k€908
Bio-Oil Production (Pyrolysis)	-k€1257	-k€1293	-k€1327	-k€1360	-k€1391
Green Hydrogen Production (Electrolysis)	-k€826	-k€836	-k€845	-k€854	-k€862
Aquathermal Energy Systems	-k€252	-k€249	-k€247	-k€244	-k€242
Sewage Thermal Energy Systems	-k€194	-k€190	-k€186	-k€182	-k€179
Residual Heat Recovery Systems	-k€268	-k€263	-k€259	-k€255	-k€251
Geothermal Energy Systems (ATES/BTES)	-k€168	-k€163	-k€159	-k€155	-k€151
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€91	-k€85	-k€79	-k€73	-k€68
Solar Panels (PV)	k€33	k€55	k€75	k€94	k€113
Solar Panels (PT)	-k€92	-k€85	-k€79	-k€72	-k€66
Solar Panels (PVT)	-k€112	-k€103	-k€94	-k€86	-k€78
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€516	-k€518	-k€520	-k€523	-k€524
Wind Energy Systems (Onshore)	k€47	k€68	k€87	k€106	k€124
Small and Medium Wind Turbines (SMWT)	-k€72	-k€54	-k€36	-k€20	-k€4
Micro Hydropower	-k€123	-k€107	-k€92	-k€78	-k€65
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€533	-k€528	-k€523	-k€518	-k€513
Small Modular Reactors (SMRs) and Micro Reactors	-k€389	-k€388	-k€386	-k€385	-k€384
District Heating (4th Generation)	-k€208	-k€203	-k€199	-k€195	-k€191
District Heating and Cooling (5th Generation)	-k€94	-k€87	-k€81	-k€74	-k€68

Table 80: Dynamic payback (NPV) in a small community, year 6–10.

DYNAMIC PAYBACK	11	12	13	14	15
Biogas Production (Anaerobic Digestion)	-k€922	-k€936	-k€950	-k€963	-k€975
Bio-Oil Production (Pyrolysis)	-k€1421	-k€1450	-k€1477	-k€1503	-k€1528
Green Hydrogen Production (Electrolysis)	-k€870	-k€878	-k€885	-k€892	-k€898
Aquathermal Energy Systems	-k€239	-k€237	-k€235	-k€233	-k€231
Sewage Thermal Energy Systems	-k€175	-k€172	-k€169	-k€166	-k€164
Residual Heat Recovery Systems	-k€247	-k€244	-k€240	-k€237	-k€234
Geothermal Energy Systems (ATES/BTES)	-k€147	-k€144	-k€140	-k€137	-k€134
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€63	-k€58	-k€54	-k€50	-k€45
Solar Panels (PV)	k€130	k€147	k€163	k€178	k€193
Solar Panels (PT)	-k€61	-k€55	-k€50	-k€45	-k€40
Solar Panels (PVT)	-k€70	-k€63	-k€56	-k€50	-k€44
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€526	-k€528	-k€530	-k€531	-k€533
Wind Energy Systems (Onshore)	k€141	k€158	k€173	k€188	k€202
Small and Medium Wind Turbines (SMWT)	k€11	k€25	k€38	k€51	k€64
Micro Hydropower	-k€52	-k€40	-k€28	-k€17	-k€6
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€509	-k€504	-k€500	-k€497	-k€493
Small Modular Reactors (SMRs) and Micro Reactors	-k€382	-k€381	-k€380	-k€379	-k€378
District Heating (4th Generation)	-k€187	-k€184	-k€180	-k€177	-k€174
District Heating and Cooling (5th Generation)	-k€63	-k€57	-k€52	-k€47	-k€42

Table 81: Dynamic payback (NPV) in a small community, year 11–15.

DYNAMIC PAYBACK	16	17	18	19	20
Biogas Production (Anaerobic Digestion)	-k€987	-k€998	-k€1008	-k€1018	-k€1028
Bio-Oil Production (Pyrolysis)	-k€1551	-k€1574	-k€1595	-k€1616	-k€1635
Green Hydrogen Production (Electrolysis)	-k€905	-k€911	-k€916	-k€922	-k€927
Aquathermal Energy Systems	-k€229	-k€227	-k€225	-k€224	-k€222
Sewage Thermal Energy Systems	-k€161	-k€158	-k€156	-k€154	-k€152
Residual Heat Recovery Systems	-k€231	-k€228	-k€226	-k€223	-k€221
Geothermal Energy Systems (ATES/BTES)	-k€131	-k€128	-k€126	-k€123	-k€121
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€41	-k€38	-k€34	-k€31	-k€27
Solar Panels (PV)	k€207	k€220	k€232	k€244	k€256
Solar Panels (PT)	-k€36	-k€32	-k€27	-k€23	-k€20
Solar Panels (PVT)	-k€38	-k€32	-k€27	-k€21	-k€17
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€534	-k€536	-k€537	-k€538	-k€540
Wind Energy Systems (Onshore)	k€216	k€229	k€241	k€253	k€264
Small and Medium Wind Turbines (SMWT)	k€76	k€87	k€98	k€108	k€118
Micro Hydropower	k€4	k€14	k€23	k€32	k€40
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€489	-k€486	-k€483	-k€480	-k€477
Small Modular Reactors (SMRs) and Micro Reactors	-k€377	-k€376	-k€375	-k€374	-k€374
District Heating (4th Generation)	-k€171	-k€168	-k€166	-k€163	-k€161
District Heating and Cooling (5th Generation)	-k€38	-k€34	-k€30	-k€26	-k€22

Table 82: Dynamic payback (NPV) in a small community, year 16–20.

DYNAMIC PAYBACK	21	22	23	24	25
Biogas Production (Anaerobic Digestion)	-k€1037	-k€1046	-k€1054	-k€1062	-k€1070
Bio-Oil Production (Pyrolysis)	-k€1654	-k€1671	-k€1688	-k€1704	-k€1720
Green Hydrogen Production (Electrolysis)	-k€932	-k€937	-k€941	-k€945	-k€950
Aquathermal Energy Systems	-k€221	-k€219	-k€218	-k€217	-k€215
Sewage Thermal Energy Systems	-k€150	-k€148	-k€146	-k€144	-k€142
Residual Heat Recovery Systems	-k€218	-k€216	-k€214	-k€212	-k€210
Geothermal Energy Systems (ATES/BTES)	-k€118	-k€116	-k€114	-k€112	-k€110
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€24	-k€21	-k€19	-k€16	-k€13
Solar Panels (PV)	k€267	k€277	k€287	k€297	k€306
Solar Panels (PT)	-k€16	-k€13	-k€10	-k€7	-k€4
Solar Panels (PVT)	-k€12	-k€7	-k€3	k€1	k€5
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€541	-k€542	-k€543	-k€544	-k€545
Wind Energy Systems (Onshore)	k€274	k€285	k€294	k€304	k€312
Small and Medium Wind Turbines (SMWT)	k€127	k€136	k€144	k€152	k€160
Micro Hydropower	k€48	k€56	k€63	k€70	k€77
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€474	-k€472	-k€469	-k€467	-k€464
Small Modular Reactors (SMRs) and Micro Reactors	-k€373	-k€372	-k€371	-k€371	-k€370
District Heating (4th Generation)	-k€158	-k€156	-k€154	-k€152	-k€150
District Heating and Cooling (5th Generation)	-k€18	-k€15	-k€12	-k€9	-k€6

Table 83: Dynamic payback (NPV) in a small community, year 21–25.

DYNAMIC PAYBACK	26	27	28	29	30
Biogas Production (Anaerobic Digestion)	-k€1077	-k€1084	-k€1091	-k€1097	-k€1103
Bio-Oil Production (Pyrolysis)	-k€1734	-k€1748	-k€1762	-k€1775	-k€1787
Green Hydrogen Production (Electrolysis)	-k€953	-k€957	-k€961	-k€964	-k€967
Aquathermal Energy Systems	-k€214	-k€213	-k€212	-k€211	-k€210
Sewage Thermal Energy Systems	-k€141	-k€139	-k€138	-k€136	-k€135
Residual Heat Recovery Systems	-k€208	-k€206	-k€205	-k€203	-k€202
Geothermal Energy Systems (ATES/BTES)	-k€108	-k€106	-k€105	-k€103	-k€102
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€11	-k€9	-k€6	-k€4	-k€2
Solar Panels (PV)	k€314	k€323	k€330	k€338	k€345
Solar Panels (PT)	-k€1	k€2	k€4	k€7	k€9
Solar Panels (PVT)	k€9	k€12	k€15	k€19	k€22
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€546	-k€547	-k€548	-k€548	-k€549
Wind Energy Systems (Onshore)	k€321	k€329	k€336	k€344	k€351
Small and Medium Wind Turbines (SMWT)	k€167	k€174	k€181	k€187	k€193
Micro Hydropower	k€83	k€89	k€95	k€100	k€105
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€462	-k€460	-k€458	-k€456	-k€454
Small Modular Reactors (SMRs) and Micro Reactors	-k€369	-k€369	-k€368	-k€368	-k€367
District Heating (4th Generation)	-k€148	-k€146	-k€145	-k€143	-k€142
District Heating and Cooling (5th Generation)	-k€3	k€0	k€2	k€5	k€7

Table 84: Dynamic payback (NPV) in a small community, year 26–30.

DYNAMIC PAYBACK	31	32	33	34	35
Biogas Production (Anaerobic Digestion)	-k€1109	-k€1114	-k€1119	-k€1124	-k€1129
Bio-Oil Production (Pyrolysis)	-k€1798	-k€1809	-k€1820	-k€1830	-k€1839
Green Hydrogen Production (Electrolysis)	-k€971	-k€973	-k€976	-k€979	-k€981
Aquathermal Energy Systems	-k€209	-k€208	-k€208	-k€207	-k€206
Sewage Thermal Energy Systems	-k€134	-k€132	-k€131	-k€130	-k€129
Residual Heat Recovery Systems	-k€200	-k€199	-k€198	-k€196	-k€195
Geothermal Energy Systems (ATES/BTES)	-k€100	-k€99	-k€98	-k€96	-k€95
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€0	k€2	k€3	k€5	k€7
Solar Panels (PV)	k€352	k€358	k€365	k€371	k€376
Solar Panels (PT)	k€11	k€14	k€16	k€17	k€19
Solar Panels (PVT)	k€25	k€27	k€30	k€33	k€35
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€550	-k€551	-k€551	-k€552	-k€552
Wind Energy Systems (Onshore)	k€357	k€364	k€370	k€375	k€381
Small and Medium Wind Turbines (SMWT)	k€199	k€205	k€210	k€215	k€220
Micro Hydropower	k€110	k€115	k€120	k€124	k€128
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€453	-k€451	-k€449	-k€448	-k€447
Small Modular Reactors (SMRs) and Micro Reactors	-k€367	-k€366	-k€366	-k€365	-k€365
District Heating (4th Generation)	-k€140	-k€139	-k€138	-k€136	-k€135
District Heating and Cooling (5th Generation)	k€9	k€11	k€13	k€15	k€17

Table 85: Dynamic payback (NPV) in a small community, year 31–35.

DYNAMIC PAYBACK	36	37	38	39	40
Biogas Production (Anaerobic Digestion)	-k€1134	-k€1138	-k€1142	-k€1146	-k€1150
Bio-Oil Production (Pyrolysis)	-k€1849	-k€1857	-k€1866	-k€1874	-k€1881
Green Hydrogen Production (Electrolysis)	-k€984	-k€986	-k€988	-k€991	-k€993
Aquathermal Energy Systems	-k€205	-k€205	-k€204	-k€203	-k€203
Sewage Thermal Energy Systems	-k€128	-k€127	-k€126	-k€125	-k€124
Residual Heat Recovery Systems	-k€194	-k€193	-k€192	-k€191	-k€190
Geothermal Energy Systems (ATES/BTES)	-k€94	-k€93	-k€92	-k€91	-k€90
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€8	k€10	k€11	k€12	k€14
Solar Panels (PV)	k€382	k€387	k€392	k€396	k€401
Solar Panels (PT)	k€21	k€23	k€24	k€26	k€27
Solar Panels (PVT)	k€37	k€39	k€42	k€44	k€45
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€553	-k€554	-k€554	-k€555	-k€555
Wind Energy Systems (Onshore)	k€386	k€391	k€396	k€400	k€405
Small and Medium Wind Turbines (SMWT)	k€224	k€229	k€233	k€237	k€241
Micro Hydropower	k€132	k€136	k€139	k€143	k€146
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€445	-k€444	-k€443	-k€441	-k€440
Small Modular Reactors (SMRs) and Micro Reactors	-k€365	-k€364	-k€364	-k€364	-k€363
District Heating (4th Generation)	-k€134	-k€133	-k€132	-k€131	-k€130
District Heating and Cooling (5th Generation)	k€19	k€20	k€22	k€24	k€25

Table 86: Dynamic payback (NPV) in a small community, year 36–40.

DYNAMIC PAYBACK	41	42	43	44	45
Biogas Production (Anaerobic Digestion)	-k€1153	-k€1157	-k€1160	-k€1163	-k€1166
Bio-Oil Production (Pyrolysis)	-k€1888	-k€1895	-k€1902	-k€1908	-k€1914
Green Hydrogen Production (Electrolysis)	-k€995	-k€996	-k€998	-k€1000	-k€1001
Aquathermal Energy Systems	-k€202	-k€202	-k€201	-k€200	-k€200
Sewage Thermal Energy Systems	-k€124	-k€123	-k€122	-k€121	-k€121
Residual Heat Recovery Systems	-k€189	-k€188	-k€187	-k€186	-k€186
Geothermal Energy Systems (ATES/BTES)	-k€89	-k€88	-k€87	-k€86	-k€86
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€15	k€16	k€17	k€18	k€19
Solar Panels (PV)	k€405	k€409	k€413	k€416	k€420
Solar Panels (PT)	k€29	k€30	k€31	k€32	k€34
Solar Panels (PVT)	k€47	k€49	k€51	k€52	k€54
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€556	-k€556	-k€556	-k€557	-k€557
Wind Energy Systems (Onshore)	k€409	k€413	k€417	k€420	k€424
Small and Medium Wind Turbines (SMWT)	k€244	k€248	k€251	k€254	k€257
Micro Hydropower	k€149	k€152	k€155	k€158	k€160
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€439	-k€438	-k€437	-k€436	-k€435
Small Modular Reactors (SMRs) and Micro Reactors	-k€363	-k€363	-k€362	-k€362	-k€362
District Heating (4th Generation)	-k€129	-k€128	-k€127	-k€126	-k€126
District Heating and Cooling (5th Generation)	k€26	k€28	k€29	k€30	k€31

Table 87: Dynamic payback (NPV) in a small community, year 41–45.

DYNAMIC PAYBACK	46	47	48	49	50
Biogas Production (Anaerobic Digestion)	-k€1169	-k€1171	-k€1174	-k€1176	-k€1179
Bio-Oil Production (Pyrolysis)	-k€1920	-k€1925	-k€1930	-k€1935	-k€1940
Green Hydrogen Production (Electrolysis)	-k€1003	-k€1004	-k€1006	-k€1007	-k€1008
Aquathermal Energy Systems	-k€200	-k€199	-k€199	-k€198	-k€198
Sewage Thermal Energy Systems	-k€120	-k€119	-k€119	-k€118	-k€118
Residual Heat Recovery Systems	-k€185	-k€184	-k€184	-k€183	-k€183
Geothermal Energy Systems (ATES/BTES)	-k€85	-k€84	-k€84	-k€83	-k€83
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€20	k€21	k€22	k€23	k€23
Solar Panels (PV)	k€423	k€427	k€430	k€432	k€435
Solar Panels (PT)	k€35	k€36	k€37	k€38	k€39
Solar Panels (PVT)	k€55	k€57	k€58	k€59	k€60
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€557	-k€558	-k€558	-k€558	-k€559
Wind Energy Systems (Onshore)	k€427	k€430	k€433	k€436	k€438
Small and Medium Wind Turbines (SMWT)	k€260	k€263	k€265	k€268	k€270
Micro Hydropower	k€163	k€165	k€167	k€169	k€171
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€435	-k€434	-k€433	-k€432	-k€432
Small Modular Reactors (SMRs) and Micro Reactors	-k€362	-k€361	-k€361	-k€361	-k€361
District Heating (4th Generation)	-k€125	-k€124	-k€124	-k€123	-k€123
District Heating and Cooling (5th Generation)	k€32	k€33	k€34	k€35	k€36

Table 88: Dynamic payback (NPV) in a small community, year 46–50.

D.2 Medium-sized Communities (1 GWh, 200–300 dwellings)

DYNAMIC PAYBACK	1	2	3	4	5
Biogas Production (Anaerobic Digestion)	-k€5080	-k€5156	-k€5229	-k€5298	-k€5365
Bio-Oil Production (Pyrolysis)	-k€7755	-k€7998	-k€8230	-k€8451	-k€8662
Green Hydrogen Production (Electrolysis)	-k€6067	-k€6074	-k€6080	-k€6086	-k€6092
Aquathermal Energy Systems	-k€1511	-k€1434	-k€1361	-k€1292	-k€1225
Sewage Thermal Energy Systems	-k€1588	-k€1514	-k€1442	-k€1374	-k€1310
Residual Heat Recovery Systems	-k€1910	-k€1824	-k€1742	-k€1664	-k€1590
Geothermal Energy Systems (ATES/BTES)	-k€1240	-k€1151	-k€1066	-k€985	-k€908
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€1019	-k€931	-k€847	-k€767	-k€691
Solar Panels (PV)	-k€653	-k€378	-k€116	k€134	k€373
Solar Panels (PT)	-k€1077	-k€982	-k€892	-k€806	-k€723
Solar Panels (PVT)	-k€1335	-k€1206	-k€1082	-k€965	-k€853
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€3980	-k€3961	-k€3943	-k€3925	-k€3909
Wind Energy Systems (Onshore)	-k€550	-k€280	-k€22	k€224	k€458
Small and Medium Wind Turbines (SMWT)	-k€1408	-k€1162	-k€927	-k€703	-k€489
Micro Hydropower	-k€1417	-k€1178	-k€951	-k€734	-k€527
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€4114	-k€3951	-k€3795	-k€3646	-k€3504
Small Modular Reactors (SMRs) and Micro Reactors	-k€2880	-k€2766	-k€2656	-k€2552	-k€2453
District Heating (4th Generation)	-k€1920	-k€1844	-k€1771	-k€1702	-k€1635
District Heating and Cooling (5th Generation)	-k€968	-k€868	-k€774	-k€684	-k€598

Table 89: Dynamic payback (NPV) in a medium community, year 1–5.

DYNAMIC PAYBACK	6	7	8	9	10
Biogas Production (Anaerobic Digestion)	-k€5428	-k€5488	-k€5545	-k€5600	-k€5652
Bio-Oil Production (Pyrolysis)	-k€8863	-k€9055	-k€9238	-k€9413	-k€9579
Green Hydrogen Production (Electrolysis)	-k€6097	-k€6102	-k€6107	-k€6112	-k€6116
Aquathermal Energy Systems	-k€1162	-k€1102	-k€1044	-k€989	-k€937
Sewage Thermal Energy Systems	-k€1248	-k€1189	-k€1133	-k€1079	-k€1028
Residual Heat Recovery Systems	-k€1519	-k€1451	-k€1386	-k€1325	-k€1266
Geothermal Energy Systems (ATES/BTES)	-k€834	-k€764	-k€697	-k€633	-k€572
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€618	-k€549	-k€482	-k€419	-k€359
Solar Panels (PV)	k€600	k€817	k€1024	k€1221	k€1409
Solar Panels (PT)	-k€645	-k€570	-k€499	-k€431	-k€366
Solar Panels (PVT)	-k€746	-k€644	-k€546	-k€453	-k€365
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€3893	-k€3878	-k€3864	-k€3850	-k€3837
Wind Energy Systems (Onshore)	k€682	k€895	k€1098	k€1292	k€1477
Small and Medium Wind Turbines (SMWT)	-k€285	-k€91	k€94	k€271	k€440
Micro Hydropower	-k€330	-k€142	k€38	k€209	k€372
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€3369	-k€3240	-k€3117	-k€3000	-k€2888
Small Modular Reactors (SMRs) and Micro Reactors	-k€2358	-k€2268	-k€2182	-k€2100	-k€2022
District Heating (4th Generation)	-k€1572	-k€1512	-k€1455	-k€1400	-k€1348
District Heating and Cooling (5th Generation)	-k€516	-k€438	-k€363	-k€292	-k€224

Table 90: Dynamic payback (NPV) in a medium community, year 6–10.

DYNAMIC PAYBACK	11	12	13	14	15
Biogas Production (Anaerobic Digestion)	-k€5702	-k€5750	-k€5795	-k€5838	-k€5879
Bio-Oil Production (Pyrolysis)	-k€9738	-k€9889	-k€10034	-k€10172	-k€10303
Green Hydrogen Production (Electrolysis)	-k€6120	-k€6124	-k€6128	-k€6132	-k€6136
Aquathermal Energy Systems	-k€887	-k€839	-k€794	-k€750	-k€709
Sewage Thermal Energy Systems	-k€979	-k€933	-k€888	-k€846	-k€806
Residual Heat Recovery Systems	-k€1210	-k€1157	-k€1106	-k€1057	-k€1011
Geothermal Energy Systems (ATES/BTES)	-k€514	-k€459	-k€406	-k€356	-k€307
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€302	-k€247	-k€195	-k€145	-k€97
Solar Panels (PV)	k€1589	k€1760	k€1923	k€2079	k€2227
Solar Panels (PT)	-k€304	-k€245	-k€189	-k€135	-k€84
Solar Panels (PVT)	-k€281	-k€200	-k€123	-k€50	k€20
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€3824	-k€3813	-k€3801	-k€3790	-k€3780
Wind Energy Systems (Onshore)	k€1653	k€1822	k€1982	k€2135	k€2281
Small and Medium Wind Turbines (SMWT)	k€601	k€754	k€900	k€1040	k€1173
Micro Hydropower	k€527	k€676	k€817	k€952	k€1081
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€2781	-k€2679	-k€2582	-k€2490	-k€2401
Small Modular Reactors (SMRs) and Micro Reactors	-k€1947	-k€1876	-k€1808	-k€1743	-k€1681
District Heating (4th Generation)	-k€1298	-k€1250	-k€1205	-k€1162	-k€1121
District Heating and Cooling (5th Generation)	-k€159	-k€98	-k€39	k€17	k€71

Table 91: Dynamic payback (NPV) in a medium community, year 11–15.

DYNAMIC PAYBACK	16	17	18	19	20
Biogas Production (Anaerobic Digestion)	-k€5919	-k€5956	-k€5992	-k€6026	-k€6058
Bio-Oil Production (Pyrolysis)	-k€10428	-k€10548	-k€10661	-k€10770	-k€10874
Green Hydrogen Production (Electrolysis)	-k€6139	-k€6142	-k€6145	-k€6148	-k€6151
Aquathermal Energy Systems	-k€670	-k€632	-k€596	-k€562	-k€529
Sewage Thermal Energy Systems	-k€767	-k€731	-k€696	-k€662	-k€630
Residual Heat Recovery Systems	-k€967	-k€924	-k€884	-k€846	-k€809
Geothermal Energy Systems (ATES/BTES)	-k€262	-k€218	-k€176	-k€136	-k€99
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€52	-k€9	k€32	k€72	k€109
Solar Panels (PV)	k€2369	k€2504	k€2632	k€2755	k€2872
Solar Panels (PT)	-k€35	k€12	k€56	k€98	k€139
Solar Panels (PVT)	k€86	k€150	k€210	k€268	k€323
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€3770	-k€3761	-k€3752	-k€3744	-k€3735
Wind Energy Systems (Onshore)	k€2420	k€2553	k€2679	k€2800	k€2915
Small and Medium Wind Turbines (SMWT)	k€1300	k€1421	k€1536	k€1646	k€1751
Micro Hydropower	k€1204	k€1321	k€1433	k€1539	k€1641
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€2317	-k€2237	-k€2160	-k€2087	-k€2018
Small Modular Reactors (SMRs) and Micro Reactors	-k€1622	-k€1566	-k€1512	-k€1461	-k€1412
District Heating (4th Generation)	-k€1081	-k€1044	-k€1008	-k€974	-k€942
District Heating and Cooling (5th Generation)	k€122	k€171	k€217	k€261	k€304

Table 92: Dynamic payback (NPV) in a medium community, year 16–20.

DYNAMIC PAYBACK	21	22	23	24	25
Biogas Production (Anaerobic Digestion)	-k€6089	-k€6119	-k€6147	-k€6174	-k€6200
Bio-Oil Production (Pyrolysis)	-k€10972	-k€11067	-k€11157	-k€11242	-k€11324
Green Hydrogen Production (Electrolysis)	-k€6153	-k€6156	-k€6158	-k€6161	-k€6163
Aquathermal Energy Systems	-k€498	-k€469	-k€440	-k€414	-k€388
Sewage Thermal Energy Systems	-k€600	-k€571	-k€543	-k€517	-k€492
Residual Heat Recovery Systems	-k€774	-k€741	-k€709	-k€679	-k€650
Geothermal Energy Systems (ATES/BTES)	-k€62	-k€28	k€5	k€36	k€66
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€145	k€179	k€211	k€242	k€272
Solar Panels (PV)	k€2984	k€3090	k€3192	k€3289	k€3381
Solar Panels (PT)	k€177	k€214	k€249	k€282	k€314
Solar Panels (PVT)	k€376	k€426	k€474	k€519	k€563
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€3728	-k€3720	-k€3713	-k€3706	-k€3700
Wind Energy Systems (Onshore)	k€3025	k€3130	k€3230	k€3325	k€3416
Small and Medium Wind Turbines (SMWT)	k€1851	k€1947	k€2038	k€2125	k€2207
Micro Hydropower	k€1738	k€1830	k€1918	k€2002	k€2082
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€1951	-k€1888	-k€1828	-k€1770	-k€1715
Small Modular Reactors (SMRs) and Micro Reactors	-k€1366	-k€1322	-k€1279	-k€1239	-k€1200
District Heating (4th Generation)	-k€911	-k€881	-k€853	-k€826	-k€800
District Heating and Cooling (5th Generation)	k€344	k€382	k€419	k€454	k€487

Table 93: Dynamic payback (NPV) in a medium community, year 21–25.

DYNAMIC PAYBACK	26	27	28	29	30
Biogas Production (Anaerobic Digestion)	-k€6224	-k€6247	-k€6270	-k€6291	-k€6311
Bio-Oil Production (Pyrolysis)	-k€11402	-k€11476	-k€11547	-k€11615	-k€11679
Green Hydrogen Production (Electrolysis)	-k€6165	-k€6167	-k€6169	-k€6171	-k€6172
Aquathermal Energy Systems	-k€363	-k€340	-k€318	-k€296	-k€276
Sewage Thermal Energy Systems	-k€468	-k€445	-k€423	-k€403	-k€383
Residual Heat Recovery Systems	-k€623	-k€597	-k€572	-k€548	-k€525
Geothermal Energy Systems (ATES/BTES)	k€95	k€122	k€148	k€173	k€196
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€300	k€327	k€353	k€377	k€400
Solar Panels (PV)	k€3469	k€3553	k€3634	k€3710	k€3783
Solar Panels (PT)	k€345	k€374	k€401	k€428	k€453
Solar Panels (PVT)	k€604	k€644	k€681	k€717	k€752
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€3694	-k€3688	-k€3683	-k€3677	-k€3672
Wind Energy Systems (Onshore)	k€3502	k€3585	k€3664	k€3739	k€3810
Small and Medium Wind Turbines (SMWT)	k€2286	k€2362	k€2434	k€2502	k€2567
Micro Hydropower	k€2159	k€2232	k€2301	k€2368	k€2431
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€1663	-k€1613	-k€1565	-k€1519	-k€1476
Small Modular Reactors (SMRs) and Micro Reactors	-k€1164	-k€1129	-k€1095	-k€1064	-k€1033
District Heating (4th Generation)	-k€776	-k€753	-k€730	-k€709	-k€689
District Heating and Cooling (5th Generation)	k€519	k€549	k€578	k€606	k€632

Table 94: Dynamic payback (NPV) in a medium community, year 26–30.

DYNAMIC PAYBACK	31	32	33	34	35
Biogas Production (Anaerobic Digestion)	-k€6330	-k€6349	-k€6366	-k€6383	-k€6399
Bio-Oil Production (Pyrolysis)	-k€11741	-k€11800	-k€11856	-k€11909	-k€11960
Green Hydrogen Production (Electrolysis)	-k€6174	-k€6176	-k€6177	-k€6178	-k€6180
Aquathermal Energy Systems	-k€257	-k€238	-k€221	-k€204	-k€188
Sewage Thermal Energy Systems	-k€364	-k€346	-k€329	-k€312	-k€297
Residual Heat Recovery Systems	-k€503	-k€483	-k€463	-k€444	-k€426
Geothermal Energy Systems (ATES/BTES)	k€219	k€240	k€261	k€280	k€299
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€423	k€444	k€464	k€483	k€502
Solar Panels (PV)	k€3852	k€3919	k€3982	k€4042	k€4100
Solar Panels (PT)	k€477	k€500	k€522	k€542	k€562
Solar Panels (PVT)	k€784	k€816	k€845	k€874	k€901
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€3667	-k€3663	-k€3658	-k€3654	-k€3650
Wind Energy Systems (Onshore)	k€3879	k€3944	k€4006	k€4065	k€4122
Small and Medium Wind Turbines (SMWT)	k€2630	k€2689	k€2746	k€2800	k€2851
Micro Hydropower	k€2491	k€2549	k€2603	k€2656	k€2706
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€1435	-k€1395	-k€1358	-k€1322	-k€1288
Small Modular Reactors (SMRs) and Micro Reactors	-k€1004	-k€977	-k€950	-k€925	-k€901
District Heating (4th Generation)	-k€670	-k€651	-k€634	-k€617	-k€601
District Heating and Cooling (5th Generation)	k€657	k€681	k€704	k€725	k€746

Table 95: Dynamic payback (NPV) in a medium community, year 31–35.

DYNAMIC PAYBACK	36	37	38	39	40
Biogas Production (Anaerobic Digestion)	-k€6414	-k€6429	-k€6443	-k€6456	-k€6469
Bio-Oil Production (Pyrolysis)	-k€12008	-k€12055	-k€12099	-k€12141	-k€12181
Green Hydrogen Production (Electrolysis)	-k€6181	-k€6182	-k€6184	-k€6185	-k€6186
Aquathermal Energy Systems	-k€173	-k€158	-k€144	-k€131	-k€118
Sewage Thermal Energy Systems	-k€282	-k€268	-k€254	-k€241	-k€229
Residual Heat Recovery Systems	-k€409	-k€393	-k€377	-k€362	-k€348
Geothermal Energy Systems (ATES/BTES)	k€317	k€334	k€350	k€365	k€380
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€519	k€536	k€552	k€567	k€582
Solar Panels (PV)	k€4155	k€4207	k€4257	k€4304	k€4350
Solar Panels (PT)	k€581	k€599	k€616	k€633	k€648
Solar Panels (PVT)	k€927	k€951	k€975	k€997	k€1018
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€3646	-k€3643	-k€3639	-k€3636	-k€3633
Wind Energy Systems (Onshore)	k€4176	k€4227	k€4276	k€4323	k€4368
Small and Medium Wind Turbines (SMWT)	k€2901	k€2947	k€2992	k€3035	k€3075
Micro Hydropower	k€2753	k€2799	k€2842	k€2883	k€2922
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€1255	-k€1224	-k€1194	-k€1166	-k€1139
Small Modular Reactors (SMRs) and Micro Reactors	-k€878	-k€857	-k€836	-k€816	-k€797
District Heating (4th Generation)	-k€586	-k€571	-k€557	-k€544	-k€531
District Heating and Cooling (5th Generation)	k€766	k€785	k€803	k€820	k€836

Table 96: Dynamic payback (NPV) in a medium community, year 36–40.

DYNAMIC PAYBACK	41	42	43	44	45
Biogas Production (Anaerobic Digestion)	-k€6481	-k€6492	-k€6503	-k€6513	-k€6523
Bio-Oil Production (Pyrolysis)	-k€12219	-k€12256	-k€12291	-k€12324	-k€12355
Green Hydrogen Production (Electrolysis)	-k€6187	-k€6188	-k€6189	-k€6190	-k€6190
Aquathermal Energy Systems	-k€106	-k€95	-k€84	-k€73	-k€63
Sewage Thermal Energy Systems	-k€217	-k€206	-k€195	-k€185	-k€175
Residual Heat Recovery Systems	-k€334	-k€321	-k€309	-k€297	-k€286
Geothermal Energy Systems (ATES/BTES)	k€394	k€407	k€420	k€432	k€444
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€596	k€609	k€621	k€633	k€645
Solar Panels (PV)	k€4393	k€4434	k€4474	k€4511	k€4547
Solar Panels (PT)	k€663	k€678	k€691	k€704	k€716
Solar Panels (PVT)	k€1039	k€1058	k€1077	k€1094	k€1111
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€3630	-k€3627	-k€3624	-k€3622	-k€3619
Wind Energy Systems (Onshore)	k€4410	k€4451	k€4490	k€4526	k€4562
Small and Medium Wind Turbines (SMWT)	k€3114	k€3151	k€3187	k€3220	k€3252
Micro Hydropower	k€2960	k€2996	k€3030	k€3063	k€3094
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€1113	-k€1089	-k€1065	-k€1043	-k€1022
Small Modular Reactors (SMRs) and Micro Reactors	-k€779	-k€762	-k€746	-k€730	-k€715
District Heating (4th Generation)	-k€519	-k€508	-k€497	-k€487	-k€477
District Heating and Cooling (5th Generation)	k€852	k€867	k€881	k€895	k€907

Table 97: Dynamic payback (NPV) in a medium community, year 41–45.

DYNAMIC PAYBACK	46	47	48	49	50
Biogas Production (Anaerobic Digestion)	-k€6533	-k€6542	-k€6550	-k€6559	-k€6566
Bio-Oil Production (Pyrolysis)	-k€12386	-k€12414	-k€12442	-k€12468	-k€12493
Green Hydrogen Production (Electrolysis)	-k€6191	-k€6192	-k€6193	-k€6193	-k€6194
Aquathermal Energy Systems	-k€54	-k€45	-k€36	-k€28	-k€20
Sewage Thermal Energy Systems	-k€166	-k€157	-k€149	-k€140	-k€133
Residual Heat Recovery Systems	-k€276	-k€265	-k€256	-k€247	-k€238
Geothermal Energy Systems (ATES/BTES)	k€455	k€465	k€475	k€485	k€494
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€656	k€666	k€676	k€686	k€695
Solar Panels (PV)	k€4581	k€4614	k€4645	k€4675	k€4703
Solar Panels (PT)	k€728	k€739	k€750	k€760	k€770
Solar Panels (PVT)	k€1127	k€1143	k€1157	k€1171	k€1184
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€3617	-k€3615	-k€3612	-k€3610	-k€3608
Wind Energy Systems (Onshore)	k€4595	k€4627	k€4658	k€4687	k€4715
Small and Medium Wind Turbines (SMWT)	k€3283	k€3312	k€3340	k€3366	k€3392
Micro Hydropower	k€3123	k€3151	k€3178	k€3204	k€3229
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€1001	-k€982	-k€963	-k€946	-k€929
Small Modular Reactors (SMRs) and Micro Reactors	-k€701	-k€687	-k€674	-k€662	-k€650
District Heating (4th Generation)	-k€467	-k€458	-k€450	-k€441	-k€434
District Heating and Cooling (5th Generation)	k€920	k€932	k€943	k€953	k€964

Table 98: Dynamic payback (NPV) in a medium community, year 46–50.

D.3 Large-sized Communities (10 GWh, 2000–3000 dwellings)

DYNAMIC PAYBACK	1	2	3	4	5
Biogas Production (Anaerobic Digestion)	-k€28284	-k€28010	-k€27749	-k€27500	-k€27262
Bio-Oil Production (Pyrolysis)	-k€50856	-k€51672	-k€52450	-k€53192	-k€53900
Green Hydrogen Production (Electrolysis)	-k€44695	-k€43970	-k€43279	-k€42620	-k€41991
Aquathermal Energy Systems	-k€3492	-k€2487	-k€1529	-k€615	k€257
Sewage Thermal Energy Systems	-k€10189	-k€9309	-k€8471	-k€7671	-k€6908
Residual Heat Recovery Systems	-k€8956	-k€7959	-k€7009	-k€6103	-k€5239
Geothermal Energy Systems (ATES/BTES)	-k€5589	-k€4561	-k€3581	-k€2646	-k€1754
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€7922	-k€7000	-k€6121	-k€5283	-k€4483
Solar Panels (PV)	-k€4268	-k€1607	k€931	k€3352	k€5660
Solar Panels (PT)	-k€8408	-k€7452	-k€6539	-k€5669	-k€4839
Solar Panels (PVT)	-k€10368	-k€9035	-k€7764	-k€6552	-k€5397
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€29456	-k€28936	-k€28441	-k€27969	-k€27518
Wind Energy Systems (Onshore)	-k€3906	-k€1272	k€1239	k€3634	k€5918
Small and Medium Wind Turbines (SMWT)	-k€10739	-k€8265	-k€5905	-k€3654	-k€1508
Micro Hydropower	-k€7339	-k€4801	-k€2381	-k€72	k€2129
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€26282	-k€24098	-k€22015	-k€20029	-k€18135
Small Modular Reactors (SMRs) and Micro Reactors	-k€18139	-k€16364	-k€14671	-k€13057	-k€11517
District Heating (4th Generation)	-k€15096	-k€14233	-k€13410	-k€12626	-k€11878
District Heating and Cooling (5th Generation)	-k€6070	-k€5047	-k€4071	-k€3140	-k€2252

Table 99: Dynamic payback (NPV) in a large community, year 1–5.

DYNAMIC PAYBACK	6	7	8	9	10
Biogas Production (Anaerobic Digestion)	-k€27035	-k€26819	-k€26613	-k€26416	-k€26229
Bio-Oil Production (Pyrolysis)	-k€54575	-k€55218	-k€55832	-k€56418	-k€56976
Green Hydrogen Production (Electrolysis)	-k€41391	-k€40820	-k€40274	-k€39754	-k€39258
Aquathermal Energy Systems	k€1088	k€1880	k€2637	k€3358	k€4045
Sewage Thermal Energy Systems	-k€6180	-k€5486	-k€4824	-k€4193	-k€3591
Residual Heat Recovery Systems	-k€4415	-k€3629	-k€2880	-k€2165	-k€1483
Geothermal Energy Systems (ATES/BTES)	-k€904	-k€93	k€681	k€1418	k€2122
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€3720	-k€2993	-k€2299	-k€1638	-k€1007
Solar Panels (PV)	k€7862	k€9962	k€11964	k€13874	k€15696
Solar Panels (PT)	-k€4047	-k€3292	-k€2572	-k€1886	-k€1231
Solar Panels (PVT)	-k€4294	-k€3243	-k€2240	-k€1284	-k€372
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€27089	-k€26679	-k€26289	-k€25916	-k€25561
Wind Energy Systems (Onshore)	k€8097	k€10175	k€12156	k€14046	k€15848
Small and Medium Wind Turbines (SMWT)	k€539	k€2491	k€4353	k€6129	k€7822
Micro Hydropower	k€4229	k€6231	k€8141	k€9962	k€11699
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€16329	-k€14606	-k€12963	-k€11396	-k€9901
Small Modular Reactors (SMRs) and Micro Reactors	-k€10049	-k€8648	-k€7313	-k€6039	-k€4824
District Heating (4th Generation)	-k€11164	-k€10483	-k€9834	-k€9215	-k€8625
District Heating and Cooling (5th Generation)	-k€1405	-k€598	k€172	k€906	k€1607

Table 100: Dynamic payback (NPV) in a large community, year 6–10.

DYNAMIC PAYBACK	11	12	13	14	15
Biogas Production (Anaerobic Digestion)	-k€26050	-k€25879	-k€25717	-k€25562	-k€25414
Bio-Oil Production (Pyrolysis)	-k€57509	-k€58017	-k€58501	-k€58963	-k€59404
Green Hydrogen Production (Electrolysis)	-k€38785	-k€38334	-k€37904	-k€37494	-k€37102
Aquathermal Energy Systems	k€4701	k€5327	k€5923	k€6492	k€7034
Sewage Thermal Energy Systems	-k€3017	-k€2470	-k€1947	-k€1449	-k€975
Residual Heat Recovery Systems	-k€833	-k€213	k€378	k€942	k€1480
Geothermal Energy Systems (ATES/BTES)	k€2793	k€3432	k€4043	k€4625	k€5180
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	-k€405	k€169	k€716	k€1238	k€1736
Solar Panels (PV)	k€17433	k€19089	k€20669	k€22176	k€23613
Solar Panels (PT)	-k€606	-k€11	k€557	k€1099	k€1616
Solar Panels (PVT)	k€497	k€1327	k€2118	k€2872	k€3592
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€25222	-k€24898	-k€24590	-k€24296	-k€24016
Wind Energy Systems (Onshore)	k€17567	k€19206	k€20769	k€22260	k€23682
Small and Medium Wind Turbines (SMWT)	k€9437	k€10977	k€12446	k€13847	k€15183
Micro Hydropower	k€13356	k€14935	k€16442	k€17879	k€19249
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€8476	-k€7116	-k€5820	-k€4584	-k€3404
Small Modular Reactors (SMRs) and Micro Reactors	-k€3666	-k€2561	-k€1507	-k€502	k€456
District Heating (4th Generation)	-k€8062	-k€7525	-k€7013	-k€6525	-k€6059
District Heating and Cooling (5th Generation)	k€2275	k€2912	k€3519	k€4099	k€4651

Table 101: Dynamic payback (NPV) in a large community, year 11–15.

DYNAMIC PAYBACK	16	17	18	19	20
Biogas Production (Anaerobic Digestion)	-k€25272	-k€25138	-k€25010	-k€24887	-k€24770
Bio-Oil Production (Pyrolysis)	-k€59824	-k€60225	-k€60607	-k€60971	-k€61319
Green Hydrogen Production (Electrolysis)	-k€36729	-k€36373	-k€36034	-k€35710	-k€35401
Aquathermal Energy Systems	k€7552	k€8045	k€8516	k€8965	k€9393
Sewage Thermal Energy Systems	-k€522	-k€90	k€322	k€715	k€1090
Residual Heat Recovery Systems	k€1993	k€2482	k€2949	k€3394	k€3818
Geothermal Energy Systems (ATES/BTES)	k€5709	k€6214	k€6695	k€7154	k€7592
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€2211	k€2664	k€3096	k€3507	k€3900
Solar Panels (PV)	k€24984	k€26291	k€27537	k€28726	k€29860
Solar Panels (PT)	k€2108	k€2578	k€3026	k€3454	k€3862
Solar Panels (PVT)	k€4278	k€4933	k€5557	k€6152	k€6720
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€23748	-k€23493	-k€23250	-k€23018	-k€22797
Wind Energy Systems (Onshore)	k€25038	k€26331	k€27565	k€28741	k€29863
Small and Medium Wind Turbines (SMWT)	k€16458	k€17673	k€18832	k€19937	k€20991
Micro Hydropower	k€20556	k€21803	k€22992	k€24125	k€25207
Ocean Power					
Organic Rankine Cycle (ORC) Systems	-k€2280	-k€1207	-k€185	k€791	k€1721
Small Modular Reactors (SMRs) and Micro Reactors	k€1370	k€2242	k€3074	k€3866	k€4623
District Heating (4th Generation)	-k€5615	-k€5191	-k€4787	-k€4402	-k€4034
District Heating and Cooling (5th Generation)	k€5178	k€5681	k€6160	k€6617	k€7053

Table 102: Dynamic payback (NPV) in a large community, year 16–20.

DYNAMIC PAYBACK	21	22	23	24	25
Biogas Production (Anaerobic Digestion)	-k€24659	-k€24553	-k€24452	-k€24355	-k€24263
Bio-Oil Production (Pyrolysis)	-k€61651	-k€61967	-k€62268	-k€62556	-k€62830
Green Hydrogen Production (Electrolysis)	-k€35107	-k€34826	-k€34558	-k€34303	-k€34059
Aquathermal Energy Systems	k€9801	k€10190	k€10562	k€10916	k€11254
Sewage Thermal Energy Systems	k€1447	k€1788	k€2113	k€2423	k€2719
Residual Heat Recovery Systems	k€4223	k€4609	k€4977	k€5328	k€5663
Geothermal Energy Systems (ATES/BTES)	k€8010	k€8408	k€8788	k€9150	k€9496
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€4275	k€4632	k€4973	k€5298	k€5607
Solar Panels (PV)	k€30941	k€31973	k€32956	k€33894	k€34789
Solar Panels (PT)	k€4250	k€4621	k€4975	k€5312	k€5633
Solar Panels (PVT)	k€7261	k€7777	k€8270	k€8739	k€9187
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€22586	-k€22385	-k€22193	-k€22010	-k€21835
Wind Energy Systems (Onshore)	k€30933	k€31953	k€32926	k€33855	k€34740
Small and Medium Wind Turbines (SMWT)	k€21997	k€22955	k€23870	k€24742	k€25574
Micro Hydropower	k€26238	k€27221	k€28159	k€29054	k€29907
Ocean Power					
Organic Rankine Cycle (ORC) Systems	k€2608	k€3455	k€4262	k€5031	k€5765
Small Modular Reactors (SMRs) and Micro Reactors	k€5344	k€6032	k€6687	k€7313	k€7910
District Heating (4th Generation)	-k€3684	-k€3349	-k€3031	-k€2727	-k€2437
District Heating and Cooling (5th Generation)	k€7469	k€7866	k€8244	k€8604	k€8948

Table 103: Dynamic payback (NPV) in a large community, year 21–25.

DYNAMIC PAYBACK	26	27	28	29	30
Biogas Production (Anaerobic Digestion)	-k€24175	-k€24091	-k€24011	-k€23935	-k€23863
Bio-Oil Production (Pyrolysis)	-k€63092	-k€63341	-k€63579	-k€63806	-k€64022
Green Hydrogen Production (Electrolysis)	-k€33827	-k€33605	-k€33394	-k€33192	-k€33000
Aquathermal Energy Systems	k€11576	k€11883	k€12176	k€12455	k€12722
Sewage Thermal Energy Systems	k€3001	k€3270	k€3526	k€3771	k€4004
Residual Heat Recovery Systems	k€5982	k€6287	k€6577	k€6854	k€7118
Geothermal Energy Systems (ATES/BTES)	k€9825	k€10140	k€10439	k€10725	k€10998
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€5903	k€6185	k€6454	k€6710	k€6955
Solar Panels (PV)	k€35642	k€36455	k€37231	k€37971	k€38677
Solar Panels (PT)	k€5940	k€6233	k€6512	k€6778	k€7032
Solar Panels (PVT)	k€9614	k€10022	k€10410	k€10781	k€11134
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€21669	-k€21510	-k€21359	-k€21214	-k€21077
Wind Energy Systems (Onshore)	k€35584	k€36389	k€37157	k€37889	k€38587
Small and Medium Wind Turbines (SMWT)	k€26367	k€27123	k€27845	k€28533	k€29189
Micro Hydropower	k€30720	k€31496	k€32236	k€32942	k€33615
Ocean Power					
Organic Rankine Cycle (ORC) Systems	k€6465	k€7133	k€7770	k€8377	k€8956
Small Modular Reactors (SMRs) and Micro Reactors	k€8479	k€9021	k€9539	k€10032	k€10503
District Heating (4th Generation)	-k€2160	-k€1896	-k€1645	-k€1405	-k€1176
District Heating and Cooling (5th Generation)	k€9276	k€9589	k€9888	k€10172	k€10444

Table 104: Dynamic payback (NPV) in a large community, year 26–30.

DYNAMIC PAYBACK	31	32	33	34	35
Biogas Production (Anaerobic Digestion)	-k€23793	-k€23727	-k€23664	-k€23604	-k€23547
Bio-Oil Production (Pyrolysis)	-k€64229	-k€64426	-k€64613	-k€64792	-k€64963
Green Hydrogen Production (Electrolysis)	-k€32817	-k€32642	-k€32475	-k€32316	-k€32165
Aquathermal Energy Systems	k€12976	k€13218	k€13449	k€13670	k€13880
Sewage Thermal Energy Systems	k€4226	k€4438	k€4641	k€4834	k€5018
Residual Heat Recovery Systems	k€7370	k€7610	k€7840	k€8058	k€8267
Geothermal Energy Systems (ATES/BTES)	k€11258	k€11506	k€11742	k€11968	k€12183
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€7188	k€7410	k€7622	k€7824	k€8017
Solar Panels (PV)	k€39350	k€39992	k€40604	k€41188	k€41745
Solar Panels (PT)	k€7274	k€7504	k€7724	k€7934	k€8135
Solar Panels (PVT)	k€11471	k€11793	k€12099	k€12391	k€12670
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€20945	-k€20820	-k€20701	-k€20587	-k€20478
Wind Energy Systems (Onshore)	k€39253	k€39888	k€40494	k€41072	k€41623
Small and Medium Wind Turbines (SMWT)	k€29815	k€30412	k€30981	k€31524	k€32041
Micro Hydropower	k€34257	k€34869	k€35453	k€36010	k€36541
Ocean Power					
Organic Rankine Cycle (ORC) Systems	k€9508	k€10035	k€10537	k€11016	k€11473
Small Modular Reactors (SMRs) and Micro Reactors	k€10952	k€11380	k€11789	k€12178	k€12549
District Heating (4th Generation)	-k€958	-k€750	-k€552	-k€362	-k€182
District Heating and Cooling (5th Generation)	k€10702	k€10949	k€11185	k€11409	k€11623

Table 105: Dynamic payback (NPV) in a large community, year 31–35.

DYNAMIC PAYBACK	36	37	38	39	40
Biogas Production (Anaerobic Digestion)	-k€23492	-k€23440	-k€23390	-k€23343	-k€23298
Bio-Oil Production (Pyrolysis)	-k€65126	-k€65281	-k€65429	-k€65570	-k€65705
Green Hydrogen Production (Electrolysis)	-k€32020	-k€31882	-k€31751	-k€31625	-k€31505
Aquathermal Energy Systems	k€14081	k€14272	k€14454	k€14628	k€14794
Sewage Thermal Energy Systems	k€5193	k€5361	k€5520	k€5673	k€5818
Residual Heat Recovery Systems	k€8465	k€8655	k€8836	k€9008	k€9173
Geothermal Energy Systems (ATES/BTES)	k€12388	k€12584	k€12770	k€12948	k€13118
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€8201	k€8377	k€8544	k€8704	k€8856
Solar Panels (PV)	k€42276	k€42783	k€43266	k€43727	k€44166
Solar Panels (PT)	k€8326	k€8508	k€8681	k€8847	k€9005
Solar Panels (PVT)	k€12936	k€13190	k€13432	k€13662	k€13882
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€20374	-k€20276	-k€20181	-k€20092	-k€20006
Wind Energy Systems (Onshore)	k€42148	k€42650	k€43128	k€43583	k€44018
Small and Medium Wind Turbines (SMWT)	k€32535	k€33006	k€33455	k€33884	k€34292
Micro Hydropower	k€37047	k€37530	k€37991	k€38430	k€38849
Ocean Power					
Organic Rankine Cycle (ORC) Systems	k€11909	k€12325	k€12721	k€13099	k€13459
Small Modular Reactors (SMRs) and Micro Reactors	k€12904	k€13241	k€13564	k€13871	k€14164
District Heating (4th Generation)	-k€10	k€154	k€311	k€460	k€603
District Heating and Cooling (5th Generation)	k€11828	k€12022	k€12208	k€12385	k€12554

Table 106: Dynamic payback (NPV) in a large community, year 36–40.

DYNAMIC PAYBACK	41	42	43	44	45
Biogas Production (Anaerobic Digestion)	-k€23254	-k€23213	-k€23174	-k€23137	-k€23101
Bio-Oil Production (Pyrolysis)	-k€65834	-k€65956	-k€66073	-k€66184	-k€66291
Green Hydrogen Production (Electrolysis)	-k€31391	-k€31283	-k€31179	-k€31080	-k€30985
Aquathermal Energy Systems	k€14952	k€15103	k€15247	k€15384	k€15515
Sewage Thermal Energy Systems	k€5956	k€6088	k€6214	k€6334	k€6449
Residual Heat Recovery Systems	k€9329	k€9479	k€9622	k€9758	k€9887
Geothermal Energy Systems (ATES/BTES)	k€13280	k€13434	k€13581	k€13721	k€13855
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€9001	k€9139	k€9271	k€9397	k€9517
Solar Panels (PV)	k€44585	k€44984	k€45366	k€45729	k€46076
Solar Panels (PT)	k€9156	k€9299	k€9436	k€9567	k€9692
Solar Panels (PVT)	k€14092	k€14292	k€14483	k€14665	k€14838
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€19924	-k€19846	-k€19772	-k€19701	-k€19633
Wind Energy Systems (Onshore)	k€44433	k€44828	k€45205	k€45565	k€45908
Small and Medium Wind Turbines (SMWT)	k€34682	k€35053	k€35407	k€35745	k€36068
Micro Hydropower	k€39249	k€39630	k€39993	k€40340	k€40670
Ocean Power					
Organic Rankine Cycle (ORC) Systems	k€13803	k€14131	k€14444	k€14742	k€15027
Small Modular Reactors (SMRs) and Micro Reactors	k€14443	k€14710	k€14964	k€15206	k€15438
District Heating (4th Generation)	k€738	k€868	k€991	k€1109	k€1222
District Heating and Cooling (5th Generation)	k€12715	k€12869	k€13015	k€13155	k€13289

Table 107: Dynamic payback (NPV) in a large community, year 41–45.

DYNAMIC PAYBACK	46	47	48	49	50
Biogas Production (Anaerobic Digestion)	-k€23067	-k€23034	-k€23003	-k€22974	-k€22946
Bio-Oil Production (Pyrolysis)	-k€66392	-k€66489	-k€66581	-k€66669	-k€66753
Green Hydrogen Production (Electrolysis)	-k€30895	-k€30810	-k€30728	-k€30650	-k€30575
Aquathermal Energy Systems	k€15640	k€15759	k€15872	k€15981	k€16084
Sewage Thermal Energy Systems	k€6558	k€6662	k€6762	k€6857	k€6947
Residual Heat Recovery Systems	k€10011	k€10129	k€10242	k€10349	k€10451
Geothermal Energy Systems (ATES/BTES)	k€13983	k€14105	k€14221	k€14332	k€14437
Absorption Cooling					
Air-to-Water Heat Pumps / Drycooler	k€9632	k€9741	k€9845	k€9945	k€10039
Solar Panels (PV)	k€46406	k€46722	k€47022	k€47309	k€47583
Solar Panels (PT)	k€9810	k€9924	k€10032	k€10135	k€10233
Solar Panels (PVT)	k€15004	k€15162	k€15312	k€15456	k€15593
Solar Panels (PC)					
Concentrated Solar Power (CSP)	-k€19569	-k€19507	-k€19449	-k€19393	-k€19339
Wind Energy Systems (Onshore)	k€46235	k€46547	k€46844	k€47128	k€47399
Small and Medium Wind Turbines (SMWT)	k€36375	k€36668	k€36948	k€37214	k€37469
Micro Hydropower	k€40986	k€41286	k€41573	k€41847	k€42107
Ocean Power					
Organic Rankine Cycle (ORC) Systems	k€15298	k€15557	k€15803	k€16039	k€16263
Small Modular Reactors (SMRs) and Micro Reactors	k€15658	k€15868	k€16069	k€16260	k€16442
District Heating (4th Generation)	k€1329	k€1431	k€1528	k€1621	k€1710
District Heating and Cooling (5th Generation)	k€13416	k€13537	k€13652	k€13763	k€13868

Table 108: Dynamic payback (NPV) in a large community, year 46–50.

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Executive Summary

This thesis explores how Utility Service Companies (USCOs) can accelerate the transition to a sustainable society by providing decentralized, integrated services in energy, water, mobility, and compute power. With the world facing increasing pressure to meet sustainability targets and decarbonize urban infrastructure, the traditional, centralized utility model is no longer sufficient. USCOs present a novel business approach that leverages technological innovation, economic scalability, and supportive legal frameworks to deliver reliable, local utility services that benefit communities and the environment.

At the core of this research is a comprehensive "table model," where three legs – environmental technology, financial viability, and political-legal feasibility – support a stable and socially rooted USCO concept. The study investigates a wide range of sustainable technologies across all utility domains, using multicriteria assessments, Technology Readiness Levels (TRLs), and detailed CAPEX/OPEX benchmarking. From solar PV and geothermal heat to greywater reuse and liquid-cooled data centers, the technological possibilities are not only available—they are rapidly maturing and increasingly cost-effective.

Economic modeling, both static and dynamic, demonstrates that many of the described technologies become significantly more viable when implemented at the community scale. Financing scenarios including debt, equity, and cooperative participation reveal strong potential for investment, especially when business models are structured to align user engagement with financial return. The concept of users as partial owners – such as through energy, water and mobility cooperatives – emerges as a powerful tool to lower the Weighted Average Cost of Capital (WACC) while building social buy-in.

Legally, the landscape is evolving. While regulatory fragmentation remains a barrier–particularly regarding decentralized energy sharing, greywater reuse, and infrastructure rights in public space–recent shifts such as the formation of the Vlaamse Nutsregulator (VNR) and the growing regulatory scope over district heating show promise. Municipal flexibility and pilot-friendly policies are beginning to bridge the gap between innovation and compliance.

In conclusion, USCOs represent a viable and scalable model to operationalize sustainability goals at the local level. By integrating environmentally friendly technologies with sound economics and progressive legal frameworks, USCOs can provide essential services more efficiently, more equitably, and more sustainably than traditional utility structures. This thesis offers both a strategic vision and a practical roadmap for making that future a reality.