Technical solutions for multi carrier integrated systems under the LEC concept: A review

Date of document – July/2021 (M9)

D2.2: Technical solutions for multi carrier integrated systems under the LEC concept: A review
WP2, Task 2.2

Authors: Gabriele Comodi (UNIVPM), Mosè Rossi (UNIVPM), Lingkang Jin (UNIVPM), Andrea Monforti Ferrario (UNIVPM), Francesco Ferracuti (UNIVPM), Alessia Arteconi (UNIVPM), Marialaura Di Somma (ENEA), Amedeo Buonanno (ENEA), Martina Caliano (ENEA), Valeria Palladino (ENEA), Victoria Rebillas-Loredo (IREC), Cristina Corchero García (IREC), Jesus Fraile Ardanuy (UPM), Álvaro Gutiérrez (UPM), Giuseppe Conti (UPM), David Jiménez Bermejo (UPM), Daniel Fernández-Muñoz (UPM), Juan Ignacio Perez Dias (UPM), Andres Cortes (TECNALIA), Maider Santos-Mugica, (TECNALIA), Edoardo Garcia (TECNALIA), Chrysanthos Charalambous (UCY/FOSS), Loizos Loizou (UCY/FOSS), Christina Papadimitriou (UCY/FOSS), Manuel Pio (EDP), Rafael Oliveira (EDP), Andrei Morch, (SINTEF), Signe Marie Oland (SINTEF), Alison O'Connell (EPRI), Alessio Coccia (EPRI), Francisco Cunha Gomes (NAVY), Ata Khavari (DERlab).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 957779.

Technical references

Project Acronym	eNeuron
Project Title	greEN Energy hUbs for local integRated energy cOmmunities optimizatioN
Project Coordinator	Marialaura Di Somma Department of Energy Technologies and Renewable Sources - Smart Grid and Energy Networks Lab, ENEA marialaura.disomma@enea.it
Technical Coordinator	Christina Papadimitriou FOSS Research Centre for Sustainable Energy, University of Cyprus papadimitriou.n.christina@ucy.ac.cy
Project Duration	November 2020 – October 2024 (48 months)

Deliverable No.	D2.2
Dissemination level [1]	PU
Work Package	WP 2 - Limitations and shortcomings for optimal use of local resources
Task	T 2.2 - Status for deployment of integrated local multi-vector energy systems and corresponding enabling technologies and solutions
Lead beneficiary	9 (UNIVPM)
Contributing beneficiary(ies)	ENEA, IREC, UPM, TECNALIA, UCY/FOSS, EDP, SINTEF, EPRI, NAVY
Due date of deliverable	31 July 2021
Actual submission date	9 August 2021

* PU = Public
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for members of the consortium (including the Commission Services)

v	Date	Beneficiary	Author/Reviewer
00	16/07/2021	UNIVPM	All Consortium
01	21/07/2021	ENEA	Amedeo Buonanno
02	23/07/2021	DERLAB	Ata Khavari
03	02/08/2021	ENEA	Marialaura Di Somma
04	03/08/2021	UCY/FOSS	Christina Papadimitriou
05	06/08/2021	UNIVPM	Gabriele Comodi, Mosè Rossi, Lingkang Jin, Andrea Monforti Ferrario, Francesco Ferracuti, Alessia Arteconi

Disclaimer of Warranties

The contents of this publication are the sole responsibility of the eNeuron Consortium (2020-2024) and do not necessarily reflect the opinion of the European Union.

“This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No 957779”.

This document has been prepared by eNeuron project partners as an account of work carried out within the framework of the EC-GA contract no 957779.

Neither Project Coordinator, nor any signatory party of eNeuron Project Consortium Agreement, nor any person acting on behalf of any of them:

- makes any warranty or representation whatsoever, express or implied,
    - with respect to the use of any information, apparatus, method, process, or similar item disclosed in this document, including merchantability and fitness for a particular purpose, or
    - that such use does not infringe on or interfere with privately owned rights, including any party's intellectual property, or
    - that this document is suitable to any particular user's circumstance; or
- assumes responsibility for any damages or other liability whatsoever (including any consequential damages, even if Project Coordinator or any representative of a signatory party of the eNeuron Project Consortium Agreement, has been advised of the possibility of such damages) resulting from your selection or use of this document or any information, apparatus, method, process, or similar item disclosed in this document.

Executive summary

This deliverable is the second one in the series of three reports that are planned to be developed in the activity "Limitations and shortcomings for optimal use of local resources" in the H2020 project eNeuron.

After the completion of a previous deliverable of the eNeuron project regarding the critical analysis of the European policy and regulatory framework on the local multi-vector energy systems, the present one provides an overview of technological solution enabling the eNeuron concept. The introduction section presents the “micro energy hub” and the “energy hub” which are at the basis of the eNeuron concept. The introduction also presents the management systems which enable the opportunity to carry out control strategies at all levels. Section 2 presents a comprehensive review of the connecting technologies, that are the technologies enabling interaction between different energy carriers/networks. Connecting technologies are presented for both micro-energy hub and energy hub level in order to consider the differences in terms of size, efficiency and capital/O&M costs. The main goal of the eNeuron project is to develop innovative tools for the optimal design and operation of local energy communities (LECs), integrating distributed energy resources and multiple energy carriers at different scales. For this reason, Section 3 presents a critical review of the existing planning tools; this section providing recommendations for the enhancement of eTransport (Integrate) that is centered at the core of eNeuron tool. Finally, Section 4 presents an overview of the four pilots in which the eNeuron tools will be tested. In particular, it reports: a brief description of each demo site; a presentation on how the eNeuron tool will be tested in the real environment of each demo; a table and a scheme summarizing the energy carriers involved and the connecting technologies enabling cross sector interactions in each pilot.

Table of Contents

Abbreviations and acronyms

Acronym	Meaning	Acronym	Meaning
AC	Alternate Current	**IoT**	Internet of Things
AI	Artificial Intelligence	**LEC**	Local Energy Community
ALK	Alkaline	**LTFC**	Low Temperature Fuel Cells
API REST	Application Programming Interface Representational State Transfer	**MCEC**	Molten Carbon
AV	Autonomous Vehicles	**MCFC**	Molten Carbonate Fuel Cells
BMS	Building Management System	**MEA**	Membrane Electrode Assembly
BEMS	Building Energy Management System	**MED**	Multi Effect Distillation
BEV	Battery Electric Vehicle	**mEH**	micro-Energy Hub
BMS	Building Management System	**MGT**	Micro Gas Turbine
CAPEX	Capital Expenses	**MILP**	Mixed-Integer Linear Programming
CC	Combined Cycle	**MPC**	Model Predictive Control
CC	Carbon Capture	**MSF**	Multi-Stage Flash
CCHP	Combined Cooling Heat and Power	**NG**	Natural Gas
CCS	Carbon Capture and Storage	**O&M**	Operating and Maintenance
CCTV	Closed Circuit Television	**OPEX**	Operating Expenses
CHP	Combined Heat and Power	**PBI**	Polybenzimidazole
COP	Coefficient Of Performance	**PEM**	Proton Exchange Membrane
C-V2X	Cellular Vehicle-to-Everything	**PID**	Proportional, Integral, Derivative
DC	Direct Current	**PLC**	Programmable Logic Controller
DCS	Distributed Control System	**PSA**	Pressure Swing Absorption
DH	District Heating	**PV**	Photovoltaic
DR	Demand Response	**PWM**	Pulse-Width Modulation
DSM	Demand Side Management	**RES**	Renewable Energy Sources
DSO	Distributed System Operator	**RL**	Reinforcement Learning
DSRC	Short-Range Communications	**RO**	Reverse Osmosis
EER	Energy Efficiency Ratio	**SAM**	Shared Autonomous Mobility
EH	Energy Hub	**SCADA**	Supervisory Control And Data Acquisition
EHS	Electrochemical Hydrogen Separation	**SIM**	Subscriber Identify Module
EMS	Energy Management System	**SME**	Small or Medium Enterprise
EV	Electric Vehicles	**SOEC**	Solid Oxide Electrolyzer
EVSE	Electric Vehicle Supply Equipment	**SOFC**	Solid Oxide Fuel Cells
FC	Fuel Cell	**SQL**	Structured Query Language
FTP	File Transfer Protocol	**ST**	Steam Turbine
GAMS	General Algebraic Modelling System	**TCP**	Transmission Control Protocol
GHG	Green House Gas	**TRL**	Technology Readiness Level
GPRS	General Packet Radio Service	**TSA**	Temperature Swing Absorption
GT	Gas Turbine	**UPS**	Uninterruptible Power System
GUI	Graphical User Interface	**V2G**	Vehicle-to-Grid
HST	Hydrogen Separation Technology	**V2I**	Vehicle-to-Infrastructure
HTFC	High Temperature Fuel Cell	**WoC**	Web-of-Cell

HVAC	Heating, Ventilation and Air conditioning		
ICE	Internal Combustion Engine		

1 Introduction

This deliverable is the second one in the series of three reports that are planned to be developed in the activity "Limitations and shortcomings for optimal use of local resources" in the H2020 project eNeuron. The main objective of this activity is to scope the study based on the Pan-European decarbonisation targets and consequent regulatory acts, trends and roadmaps, e.g., European Technology & Innovation Platform - Smart Networks for Energy Transition (ETIP-SNET) "Vision 2050". The study further identifies and benchmarks the indicative status for the deployment of integrated local multi-vector energy systems (including batteries and electric vehicles - EVs) and corresponding supporting mechanisms, tools and technologies in the Member States. The next step will identify the present (technical) limitations, shortcomings, and obstacles to innovation, which may prevent the intended transformation of the European energy landscape towards local multi-vector energy systems with a high level of decarbonisation.

The results will be presented in three different technical reports:
D2.1 Local multi-vector energy systems within the European political and regulatory landscape: scope and key priorities for the present study
D2.2 Technical solutions for multi-carrier integrated systems under the LEC concept: A review (the present document)
D2.3 Limitations and shortcomings for optimal use of local resources

Potential implications of the identified gaps, limitations and shortcomings will be qualitatively evaluated, and the results will be used as an input to the specification of the pilots.

1.1 eNeuron in a nutshell

The main goal of the eNeuron (greEN Energy hUbs for local integRated energy cOmmunities optimizatioN) project is to develop innovative tools for the optimal design and operation of local energy communities (LECs), integrating distributed energy resources and multiple energy carriers at different scales.

This goal will be achieved by having in mind all the potential benefits achievable for the different actors involved and by promoting the Energy Hub concept as a conceptual model for controlling and managing multi-carrier energy systems in order to optimize their architecture and operation. To ensure both the short- and the long-term sustainability of this new energy paradigm and thus support an effective implementation and deployment, economic and environmental aspects will be considered in the optimisation tools through a multi-objective approach.

eNeuron’s proposed tools enable tangible sustainability and energy security benefits for all the stakeholders in the LEC. Local prosumers (households, commercial and industrial actors) stand to benefit through the reduction of energy costs while leveraging local, low carbon energy. Developers and solution providers will find new opportunities for technologies as part of an integrated, replicable operational business model. Distribution System Operators (DSOs) benefit from avoiding grid congestion and deferring network investments. Policymakers benefit from increasingly sustainable and secure energy supply systems.

eNeuron is a high Technology Readiness Level (TRL) project in line with the Work Programme by developing innovative approaches and methodologies to optimally plan and operate integrated LECs through the optimal selection and use of multiple energy carriers and by considering both short- and long-run priorities. Through optimally coordinating all energy carriers, cost-effective and low-carbon solutions will be provided to foster the deployment and implementation of this new energy paradigm at the European level.

1.2 Structure of the document

This deliverable starts with a summary chapter and a list of abbreviations, followed by an introduction where both the concept proposed by eNeuron project is presented, with particular focus on energy hub as the main architectural and operational solution for coupling multiple energy carriers at different scales in Local Energy Communities. Section 2 focuses on technologies enabling the coupling of multiple energy carriers both at micro energy and energy hub level. Section 3 presents an overview of the main existing tools available for planning and operating energy systems in Local Energy Communities and provides hints for the development of the eTransport optimization tool which will be used as a basis for the eNeuron optimal design tool for LECs. Section 4 presents an overview of the pilots. Finally, Section 5 reports the conclusions of the report.

1.3 eNeuron Concept: overview

eNeuron project proposes the **Energy Hub (EH)** as the main architectural and operational solution for coupling multiple energy carriers at different scales to identify the potential benefits achievable for the community and its stakeholders.
An **EH** is considered an abstract unit where multiple energy carriers can be converted, conditioned, stored and consumed. It represents an interface between the local community and external energy infrastructures and/or loads. EHs exchange energy at their interfaces, e.g., electricity and natural gas networks, for achieving an optimal balance within the EHs themselves from both technical and economical points of view. Within the hub, energy is converted and conditioned by technologies such as storage, Combined Heat and Power (CHP), transformers, power-electronic devices, compressors, heat exchangers, etc.
The EH concept is not limited to a certain size of the system: the concept enables the integration of an arbitrary number of energy carriers and products providing significant flexibility in system modelling architecture and operation. Due to this high flexibility, various real facilities can be modelled as EHs. In the **eNeuron** project, the LEC will form the Energy Hub at a higher level while **micro-Energy Hub concept (mEH)** is offered to capture the different levels of application, as explained later. The Energy Hub definition is thus seen as a conceptual model for controlling and managing multi-energy carrier systems across multiple scales, in order to optimize their architecture and operation. For ensuring short- and long- run sustainability of this energy paradigm, economic, reliability and environmental aspects are the basis for EH design optimisation in the proposed toolset.
Inherent flexibility potentials of EHs allows introducing the concept of mEH representing the prosumer (industrial, commercial or residential) within the community. Under this assumption, each mEH will represent an integrated energy system consisting of multi-energy generation, conversion and storage technologies to satisfy its own energy needs. In the eNeuron LEC, mEHs cooperate by sharing all energy carriers, with the aim to satisfy the energy needs of the entire local community

represented by the EH. Community generation, and community storage systems are also involved through dedicated community energy management systems. The EH promotes local balancing as well as strategic exchanges with electrical external grids through coordination of exchange. In this way, the energy hub will always have interactions with larger systems, sustaining access to the largest pool of external resources possible, while leaving open the possibility of local resource optimization and provision of services to other hubs or the bulk system. The system as a whole will allow synergies between different sectors such as electricity, heat, cooling and transport (electric and hydrogen) as well as between different technologies. The interactions among mEHs within the LEC and with the larger system under eNeuron concept are shown in Figure 1.

Micro-energy hubs can exchange energy locally. The connection to the larger system will allow covering the residual demand and selling excess or procuring shortfalls of energy as well as providing system services to the grid operators. The defining characteristics of the mEH and EH in eNeuron project are shown in Figure 2.

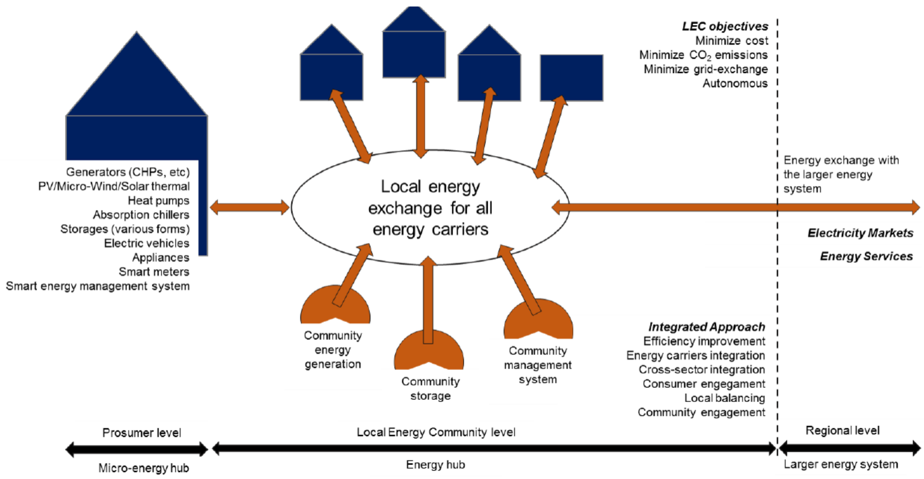


Figure 1 – eNeuron concept

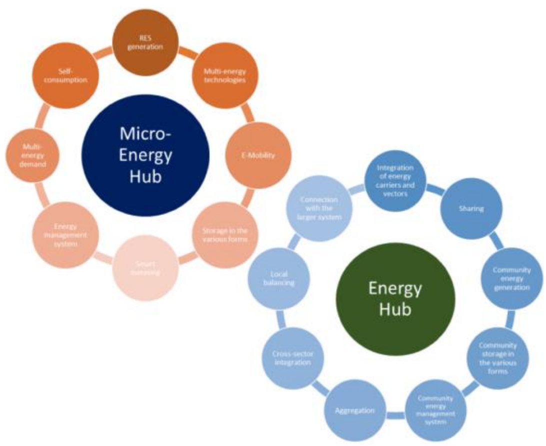


Figure 2 – Micro-Energy Hub (mEH) and Energy Hub (EH) definitions

1.4 "Micro energy hub" and "Energy hub"

This section describes the most common Micro-Energy Hub and Energy Hub configurations in real contexts, namely:

Micro-Energy Hub	Energy Hub
• Apartment/house • Condominium • Office buildings • Industries • Campuses	• Districts • City • Energy islands

The information is organized in tables with the same format:

- Short description
- Technologies involved
- Energy carriers involved
- Energy networks which could be involved
- Level of deployment
- Techno-economic barriers
- References

1.4.1 Micro energy hub

Apartment/ detached house
Short Description
The apartment mEH introduces several benefits including: electric consumption monitoring in real-time; organizing electrical billing; identifying energy efficiency measures or energy waste; determining the cost/benefit ratio of measures or corrective actions aimed at reducing energy consumption. At the residential level, the active users can participate to the demand/response programs that monitor their energy production and consumption. The demand/response program objectives address the reduction of peak electricity demand and injection from and into the national grid, increasing thus the self-consumption of the renewable sources. The optimal management of the large appliances, like washing machine, dishwasher, dryer, and so on, can be implemented in order to demonstrate the load shifting and peak shaving potentials of the selected users. The interaction through the dedicated app could allow the users to acquire greater awareness of their consumption and interact with other players (such as the local DSO, Aggergators, local energy communities or other peers), thus empowering final consumers/prosumers for participation in flexibility programs. For example, each time the information system detects the occurrence of the predetermined event (for example, reaching a voltage threshold), a notification will be sent to the users, in order to request the increase/reduction of consumption (by switching on/off a large appliance)

Technologies involved

- Heat pumps
- Hybrid heat pumps
- Natural gas Boilers
- Electric boilers
- Batteries
- PV
- EV charging stations (wall box)

Energy carriers involved

- Electricity
- Hot water
- Chilled water
- Natural gas

Energy networks which could be involved

- Electricity
- Natural gas

Level of deployment

High, most of market driven

Techno-economic barriers

- Need of interoperable sensors,controls and of a pervasive use of BEMS (Building Energy Management System) that are not widely deployed so far at apartment level
- Need of a business model to engage final users
- Lack of tools and UI to engage poorly skilled final users (e.g. elderly people)

References

G. Tonellato, A. Heidari, J. Pereira, L. Carnieletto, F. Flourentzou, M. De Carli, D. Khovalyg, Optimal design and operation of a building energy hub: A comparison of exergy-based and energy-based optimization in Swiss and Italian case studies, Energy Conversion and Management, Volume 242, 2021, Article 114316, https://doi.org/10.1016/j.enconman.2021.114316

A. Najafi-Ghalelou, K. Zare, S. Nojavan, Risk-based scheduling of smart apartment building under market price uncertainty using robust optimization approach, Sustainable Cities and Society, Volume 48, 2019, Article 101549, https://doi.org/10.1016/j.scs.2019.101549

D. Setlhaolo, S. Sichilalu, J. Zhang, Residential load management in an energy hub with heat pump water heater, Applied Energy, Volume 208, 2017, Pages 551-560, https://doi.org/10.1016/j.apenergy.2017.09.099

Condominium

Short Description

The residential sector is among the highest energy consumers in Europe mainly due to high distribution losses, low efficiency equipment and no loads management. The main energy carriers that provide energy to condominiums are electricity and natural gas that are purchased by the national grid and network, respectively as well as district heating and cooling. The goal is to have an energy efficient residential sector according to an objective function that can be annual cost, energy, and emissions minimization: to do this, the demand-side management program has led to important improvements in terms of loads control so far since the end-users are active part providing energy when needed, especially during the peak hours. The improvement of the technologies involved in this sector can lead to the reduction of both the energy consumption and price: for instance, the use of hybrid heat pumps, Combined Cooling, Heat and Power (CCHP) units (e.g., internal combustion engines, micro-turbines and fuel cells), natural gas or electric boilers coupled with PV panels and storage systems, such as batteries and thermal energy storage, have an important role to achieve the desired goal

Technologies involved

- Heat pumps
- Hybrid heat pumps
- Natural gas Boilers
- Electric boilers
- Batteries
- Thermal energy storage
- PV
- EV charging stations
- Centralized heating/cooling
- Micro-CHP

Energy carriers involved

- Electricity
- Hot water
- Chilled water
- Natural gas

Energy networks which could be involved

- Electricity
- Natural gas
- District heating/cooling

Level of deployment

High

Potential barriers

- Governance in the decision of energy management
- Need of interoperable sensors, controls and of a pervasive use of BEMS (Building Energy Management System) that are not widely deployed so far at condominium level
- Need of a business model to engage final users (e.g. Collective self-consumption)
- Lack of tools and UI to engage poorly skilled final users (e.g. elderly people)

References

B. Fina, H. Auer, W. Friedl, Profitability of active retrofitting of multi-apartment buildings: Building-attached/integrated photovoltaics with special consideration of different heating systems, Energy and Buildings, Vol. 190, 2019, Pages 86-102, https://doi.org/10.1016/j.enbuild.2019.02.034

A. Rahimzadeh, T. Victor Christiaanse, R. Evins, Optimal storage systems for residential energy systems in British Columbia, Sustainable Energy Technologies and Assessments, Volume 45, 2021, Article 101108, https://doi.org/10.1016/j.seta.2021.101108

A.T.D. Perera, D. Mauree, J-L. Scartezzini, The energy hub concept applied to a case study of mixed residential and administrative buildings in Switzerland, Energy Procedia, Vol. 122, 2017, Pages 181-186, https://doi.org/10.1016/j.egypro.2017.07.342

Office buildings

Short Description

This sector is involved in the definition of an optimal energy management strategy; as it was stated for the condominiums, the main two important energy carriers that provide energy are electricity and natural gas that are purchased by the national grid and network, respectively. The deployment of the distributed generation undoubtedly leads the office buildings to improve their use of energy as it occurs for the residential sector. Different technologies can be involved for this purpose: most of them have been already mentioned before such as CCHP units (e.g., internal combustion engines, micro-turbines and fuel cells) coupled with PV panels. However, the key role in the optimal energy management is performed through BEMSs that consider several parameters for improving the energy efficiency of the office buildings. These systems are fundamental for performing an optimal scheduling of the demand-side management programs in smart cities. In particular, thermal (e.g., heating, ventilation, and air conditioning) and lighting loads are the most involved in this sector, both functions of the weather conditions. These loads present variations that occur in a quite large time frame with respect to the residential ones, constituting one of the strengths on participating to demand-side management programs. Due to the quite large time frame on which the loads vary, BEMSs are suitable in this sector because they increase the office building efficiency when appropriate information related to both the system conditions and the external factors can be accurately forecasted

Technologies involved

- Heat pumps
- Hybrid heat pumps
- Natural gas Boilers

- Electric boilers
- Batteries
- Thermal energy storage
- PV
- EV charging stations
- Centralized heating/cooling
- Micro-CHP

Energy carriers involved

- Electricity
- Hot water
- Chilled water
- Natural gas

Energy networks which could be involved

- Electricity
- Natural gas

Level of deployment

High

Potential barriers

- Governance in the decision of energy management
  - Building owned by one company (bank, company headquarter)
  - Building with several offices of different companies (comparable to a condominium)
- Need of interoperable sensors, controls and of a pervasive use of BEMS (Building Energy Management System) that are not widely deployed so far in office building hosting several companies
- Need of a business model to engage final users (e.g. Collective self-consumption)

References

M. Ghorab, Energy hubs optimization for smart energy network system to minimize economic and environmental impact at Canadian community, Applied Thermal Engineering, Vol. 151, 2019, Pages 214-230, https://doi.org/10.1016/j.applthermaleng.2019.01.107

M. Roustai, M. Rayati, A. Sheikhi, A. Ranjbar, A scenario-based optimization of Smart Energy Hub operation in a stochastic environment using conditional-value-at-risk, Sustainable Cities and Society, Volume 39, 2018, Pages 309-316, https://doi.org/10.1016/j.scs.2018.01.045

Industries

Short Description

The industrial sector is the highest energy consumer in most of the countries worldwide. The main interventions that lead to an energy efficiency improvement in this sector are energy audits and waste heat recovery. A detailed overview of the consumption of each industry process in which energy efficiency interventions, in terms of technical/technological improvement, policy making, internal training, and overall system management, must be done. The integration of renewables/CCHP units coupled with the demand-side management program, driven by energy management systems/tools, boosted the efficiency improvement of industries in the recent years mainly because the loads involved in this sector are more predictable than the ones related to the other sectors previously discussed. Together with the renewables/CCHP units coupled with the demand-side management program, the demand response can increase the benefits of the industrial sector since different energies are involved. Finally, it can be stated that the use of a proper Energy Management System (EMS) is anyway required for performing energy efficiency improvements in the industrial sector; indeed, the combination with smart grids and the integration with distributed energy resources can be achieved in an energy hub context

Technologies involved

- Heat pumps
- Hybrid heat pumps
- Natural gas Boilers
- Electric boilers
- Batteries
- Thermal energy storage
- PV
- EV charging stations
- Centralized heating/cooling
- CHP
- Steam boilers

Energy carriers involved

- Electricity
- Hot water
- Chilled water
- Steam
- Natural gas

Energy networks which could be involved

- Electricity
- Natural gas

Level of deployment

- High in large companies
- Poor-medium in SMEs (Small or Medium Enterprises)
- Highly driven by energy efficiency and cost reduction

Potential barriers

- Size (small companies do not have an energy manager)
- Energy price (different cost of electricity and natural gas according to the size of the industries can influence the type of energy carrier involved)

References

V. Halmschlager, R. Hofmann, Assessing the potential of combined production and energy management in Industrial Energy Hubs – Analysis of a chipboard production plant, Energy, Vol. 226, 2021, Article 120415, https://doi.org/10.1016/j.energy.2021.120415

S. Taqvi, A. Almansoori, A. Elkamel, Optimal renewable energy integration into the process industry using multi-energy hub approach with economic and environmental considerations: Refinery-wide case study, Computer & Chemical Engineering, Volume 151, 2021, Article 107345, https://doi.org/10.1016/j.compchemeng.2021.107345

Campuses

Short Description

Campuses can be considered as micro energy hubs due to the presence of different loads like electric, thermal and water. In particular, the load curves can be divided into two groups, namely weekday and weekend ones, since both assume a similar

Technologies involved

• Heat pumps	• Thermal energy storage
• Hybrid heat pumps	• PV
• Natural gas Boilers	• EV charging stations
• Electric boilers	• Centralized heating/cooling
• Batteries	• CHP

Energy carriers involved

- Electricity
- Hot water
- Chilled water
- Natural gas

Energy networks which could be involved

- Electricity
- Natural gas

Level of deployment

Medium: not all universities are organized in campuses; and not all campuses are multi energy systems

Potential barriers
• Cost for retrofitting/refurbishment
References
V. Kourgiozou, *A*. Commin, M. Dowson, D. Rovas, D. Mumovic, Scalable pathways to net zero carbon in the UK higher education sector: A systematic review of smart energy systems in university campuses, Renewable and Sustainable Energy Reviews, Vol. 147, 2021, Article 111234, https://doi.org/10.1016/j.rser.2021.111234 L. Al-Ghussain, A. Darwish Ahmad, A.M. Abubaker, M.A. Mohamed, An integrated photovoltaic/wind/biomass and hybrid energy storage systems towards 100% renewable energy microgrids in university campuses, Sustainable Energy Technologies and Assessments, Volume 46, 2021, Article 101273, https://doi.org/10.1016/j.seta.2021.101273 H. Liu, Smart campus student management system based on 5G network and Internet of Things, Microprocessors and Microsystems, In press, 2020, Article 103428, https://doi.org/10.1016/j.micpro.2020.103428

1.4.2 Energy hub

District

Short Description

In recent years, the increasing population of metropolitan areas has drastically boosted the demand of energy. One of the more promising concepts for tackling the increase of the demand is the district energy network. District energy systems consist of a group of buildings with a shared facility that produce the required energy, such as electricity or heating or cooling, at a district level, through the available local energy/waste resources. District energy systems provide benefits for:

- **the environment**, because they have overall better efficiency, and provide the opportunity to recover waste thermal energy from cogeneration or waste-to-energy power plants
- **communities**, because they will exploit local energy sources generating job opportunities
- **building owners and tenants**, since they will reduce the overall cost of heating and cooling

Technologies involved

- Heat pumps
- Hybrid heat pumps
- Natural gas Boilers
- Electric boilers
- Batteries
- Thermal energy storage
- PV
- EV charging stations
- Centralized heating/cooling
- CHP
- Adsorption/Adsorption chiller

Energy carriers involved

- Electricity
- Natural gas
- Hot water/chilled water

Energy networks which could be involved

- Electricity
- Natural gas
- District heating and cooling
- EV infrastructure

Main characteristics

Districts could be future energy hubs.
The design of more complex cogeneration and tri-generation systems at a local level are expected in the upcoming future (Figure 3). They cannot supply only the electricity demand, but also, in combination with thermal energy storage systems, the heating or cooling ones of a district more efficiently (heat recovery systems, etc.)

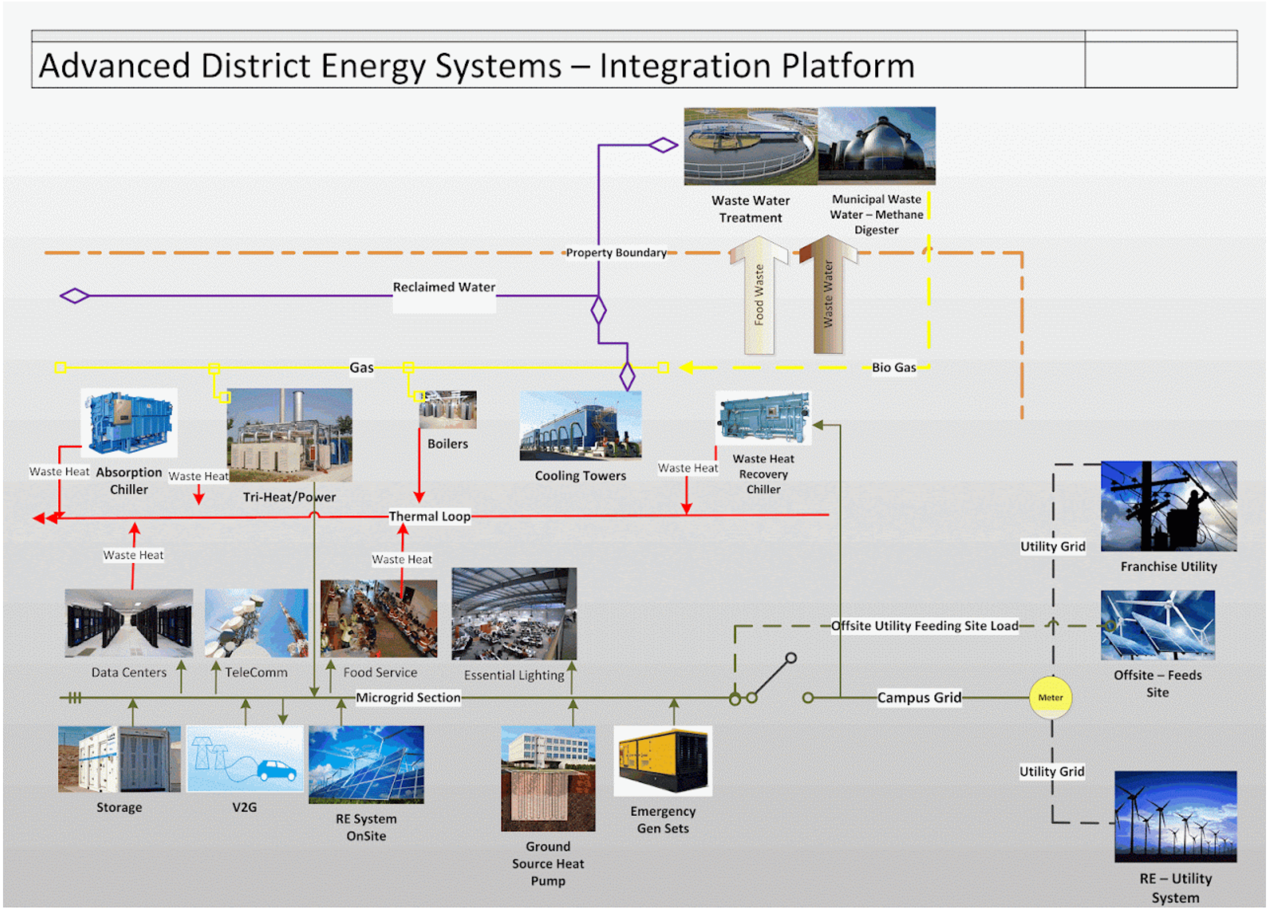


Figure 3 - Example of advanced district energy systems [Green, Clean, & Mean]

Level of deployment

Poor: districts are not yet organized as a coordinated multi-energy system.
From the economic point of view, the business model is well established in USA and Europe. In the Middle East, the business model is not appealing to the investors due to the low energy prices. In Asia, the system is still in the development stage. In Australia, the policy and regulations for selling energy in the district energy system is still not in place

Potential barriers

The transformation of districts in Energy Hubs could face some potential barriers mainly related to governance assets and business models of multi carrier integrated systems rather than to technical aspects. Indeed, in the optimal planning, management and operation of multi carrier integrated systems, it must be taken into account that different subjects come into play sometimes with conflicting interests. In the following, non-exhaustive, list some barriers are reported with a very short comment:

- Governance: who is the subject managing the district, setting goals for long-term design optimisation of multi-carrier local integrated energy systems? once defined the optimal configurations of the LEC as a whole (types, quantities and sizes of all technologies) who is going to cover the investment costs?

- Ownerships of energy networks: at the present time most of energy networks are managed by different players (e.g. natural gas DSO, electric network DSO, district heating/cooling utilities) often with conflicting interests. How these players could be profitably involved in an Energy hub scheme? How these network could be optimally coordinated?
- Cost of infrastructure and connecting technologies: multi carrier integrated systems often require new infrastructure, or retrofitting of existing one and for installation of connecting technologies enabling synergies among different energy networks. Investment costs could be very high.
- Need for data/communication and management infrastructure: the need to collect and manage data from different actors (DSO, utilities, final prosumers/users…) could raise issues about GDPR, data ownership… Moreover, not all the final users have smart meters installed in different networks (natural gas, electricity, thermal/cooling energy, …) and their replacement
- Lack of fundings and /or proper business models: as highlighted in previous points multi-carrier local integrated energy systems require a high initial investment with a long time for payback. A proper business model would be useful for providing a framework for subjects willing to invest in infrastructure deployment in the medium-long term.
- Social acceptance and citizen skills:final users/prosumers play a pivotal role in energy hub paradigm. Potential barriers could be related to social acceptance of new technologies by final users; to the engagement of poorly skilled final users; to issues related to privacy and data ownership.
- Regulatory framework

References

B. Rismanchi, District energy network (DEN), current global status and future development, Renewable and Sustainable Energy Reviews, Volume 75, 2017, Pages 571-579, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2016.11.025

A. Revesz, Phil Jones, C. Dunham, G. Davies, C. Marques, Rodrigo Matabuena, Jim Scott, Graeme Maidment, Developing novel 5th generation district energy networks, Energy, Volume 201, 2020, 117389, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2020.117389

Green, Clean, & Mean, Key strategies, District level energy services. Available at: https://sites.google.com/a/lbl.gov/green-clean-mean/key-strategies/district-level-energy-services

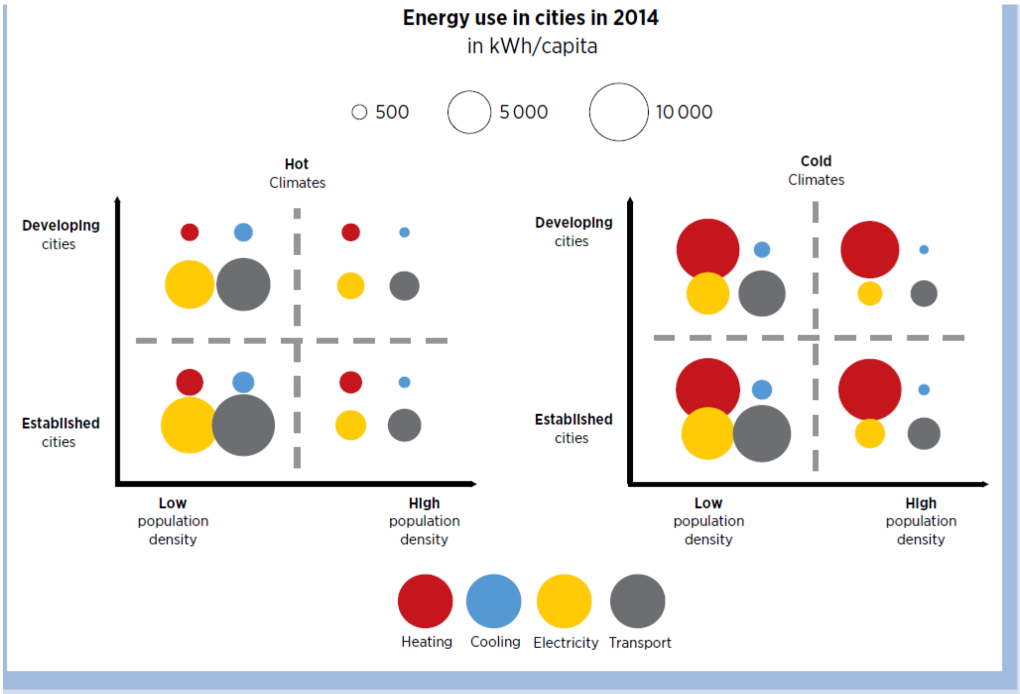
City

Short Description

Today, urban areas account for more than half world’s population, as well as 65% of the global energy demand (Figure 4), and 70% of energy-related carbon dioxide (CO_2) emissions.

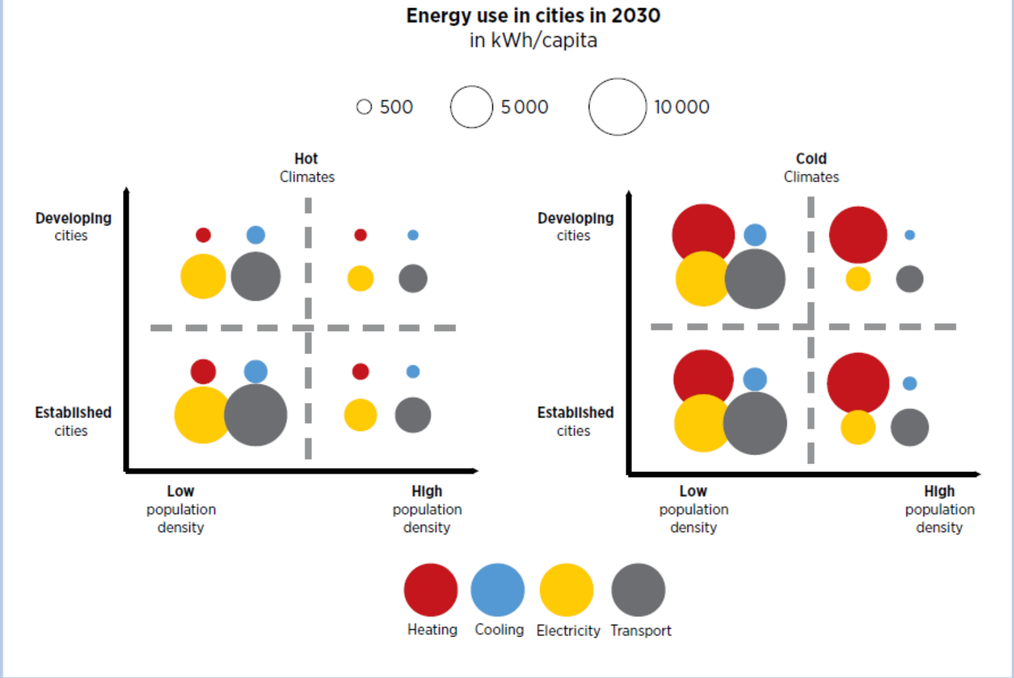
Cities, therefore, need to take action to meet the rising needs of their populations while maintaining a healthy and sustainable living environment. This fast urbanization needs new and innovative solutions to meet development and climate objectives. Transforming the urban energy system is not a question of simply replacing one form of energy with another, but of rethinking the entire energy system with all the related interactions and uses. The potential of renewables varies greatly depending on each city's characteristics (e.g., population density, growth prospects and demand profiles in cold versus hot climates) as shown by Figure 5.

The other priority areas in which action must be taken are buildings and transport (the two largest energy consumers in cities). Decentralized renewable energy production (i.e., solar thermal collectors, solar PV panels, biomass boilers, and modern cook-stoves using bio-energy - mainly in developing countries) could be one feasible solution, but the improvement of energy efficiency could provide the greatest potential. As with buildings, electrification in transport can drive the uptake of renewable energy but biofuels and hydrogen (although still in early stages of deployment) will also play significant roles in the sector



Note: to distinguish city types, the city database was split into upper and lower groups (lowest/highest 50% of values) based on population growth 2014-2030, population density in 2014, and heating degree days in 2014. Heating degree days are a metric used to measure the demand for heating relative to a reference/base temperature (typically outdoor temperature). Electricity use excludes energy use for heating and cooling.

Figure 4 - Energy use in cities in 2014 in kWh/capita [IRENA (2016)]



Based on IRENA estimates

Note: to distinguish city types the city database was split into top and bottom (lowest/highest 50% of values) based on population growth 2014-2030, population density in 2014, and heating degree days in 2014. Hence, developing cities are those cities with population growth >2.1% per year in 2014-2030, mostly located in emerging economies. Established cities population growth <2.1% per year in 2014-2030. High population density is defined as >65 capita/hectare, low population density as <65 capita/hectare. Hot climates are defined as annual heating degree days > 1231, cold climates are defined as cooling degree days > 1231.

Figure 5 - The potential for renewable energy options for transport and in buildings in different city types [IRENA (2016)]

Technologies involved

- Heat pumps
- Hybrid heat pumps
- Natural gas Boilers
- Biomass Boilers
- Electric boilers
- Batteries
- Thermal energy storage
- PV
- Solar thermal systems
- EV charging stations
- Centralized heating/cooling
- CHP

Energy carriers involved

- Electricity
- Natural gas
- Hot water/chilled water
- Water (non-energy carrier)
- Hydrogen

Energy networks which could be involved

- Electricity
- Natural gas

• District heating and cooling • EV infrastructure • Water (non-energy network)
Main characteristics
Cities could be future energy hub (of districts) as already mentioned in the description
Level of deployment
Very low
Potential barriers
References
IRENA, Renewable energy in cities. https://irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Renewable_Energy_in_Cities_2016.pdf

Energy Island
Short Description
The fast growth of the energy production from Renewable Energy Sources (RES) offers new and economically attractive opportunities for decarbonizing local energy systems. Energy islands can be defined as self-managed and self-operated local energy systems (i.e., isolated villages, small cities, urban districts, rural areas with weak or non-existing grid connections, physical islands). From an electricity network perspective, energy islands present technological and financial challenges for integrating higher levels of renewables, but there are also opportunities to optimize the electricity system operation in synergy with other energy carriers to increase the hosting capacity for renewables, not just for electricity but also for heating/cooling, transport and/or industry in a sector coupling approach. This multi-carrier energy approach enables the high penetration of RES keeping the entire energy system safe. **Artificial energy island** Artificial energy islands are becoming an interesting topic for the proper energy management of self-independent communities using renewable sources; in this regard, different examples have been realized so far. In Denmark, two energy islands (one artificial) will be constructed in order to exploit the local wind resource. The energy islands will serve as hubs that can create better connections between energy generated from offshore wind and the energy systems in the region around the two seas (North Sea and Baltic Sea). This allows electricity from an area with vast wind resources to be more easily routed to areas that need it the most, while also ensuring that the energy generated from the turbines is used as efficiently as possible in terms of demand for electricity.

Technologies involved
• Heat pumps • Hybrid heat pumps • Natural gas Boilers • Electric boilers • Batteries • Thermal energy storage • PV • EV charging stations • Centralized heating/cooling • CHP
Energy carriers involved
• Electricity • Natural gas • Hot water/chilled water • Water (non-energy carrier)
Energy networks which could be involved
• Electricity • Natural gas • District heating and cooling • EV infrastructure • Water (non-energy network) • Hydrogen
Level of deployment
• High for geographical energy islands • Poor for energy island (also due to the topology of the energy island itself)
Potential barrier energy islands
The potential barriers to the transformation of energy islands in Energy Hubs are the same described for districts: • Governance • Ownerships of energy networks • Cost for new infrastructure • Cost for retrofitting existing infrastructure • Absence of business models • Social acceptance • Citizen skills • Cost for smart meters • Need for data/communication and management infrastructure • Cost for enabling technologies
References

European Commission, CORDIS EU research results. Available at: https://cordis.europa.eu/programme/id/H2020_LC-SC3-ES-3-2018-2020

L. Herenčić, M. Melnjak, T. Capuder, I. Andročec, I. Rajšl, Techno-economic and environmental assessment of energy vectors in decarbonization of energy islands, Energy Conversion and Management, Volume 236, 2021, 114064, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2021.114064

G. Krajacic, R. Martins, A. Busuttila, N. Duic, M. da Grac-a Carvalho, Hydrogen as an energy vector in the islands' energy supply, International Journal of Hydrogen Energy, Volume 33, 2018, Pages 1091-1103, https://doi.org/10.1016/j.ijhydene.2007.12.025

Duurzaam Ameland. https://duurzaamameland.nl/projecten/

Danish Energy Agency. https://ens.dk/en/our-responsibilities/wind-power/energy-islands/denmarks-energy-islands

RED Eléctrica de Espana. https://www.ree.es/en/activities/unique-projects/soria-chira-pumped-storage-hydropower-plant

1.5 Management system

Digital energy means the possibility of using digital technologies to control energy exchange. The digitalization of energy is a process that is radically transforming the energy sector offering products and services to allow everyone to become independent active customers and to be responsible for the use of energy and surpassing the concept of energy manager/distributor. Energy and micro-energy hubs aim to accelerate the energy transition towards decentralized and bidirectional management systems, by employing distributed architectures, and hardware and software systems for monitoring and operating the various energy systems at different levels.

Even if energy management at the micro-level could be considered state-of-the-art since many real cases of application and implementation of energy management systems already exist in the industrial and consumer sectors, there are some open challenging points that will be faced in the eNeuron project.

On the other hand, the application of commercial solutions related to EH is demanding since the coordination of several micro-energy hubs is difficult due to the constraints shown in national/international regulations, technology barrier, electrical/mechanical constraints of the assets, reliability, the experimentation of new business models and the cybersecurity issues.

1.5.1 Micro-energy hub management system

A mEH represents an integrated energy system consisting of multi-energy generation, conversion and storage technologies to satisfy its own energy needs. So, micro-energy hubs are an evolution of the traditional distribution network and mainly have the following advantages. From the energy supply aspect, mEHs can promote local RES generation and self-consumption of renewable resources and coordinate multi-energy demand through multi-energy technologies. Micro-energy hubs can cooperate by sharing all energy carriers, with the aim to satisfy the energy needs of the entire local community represented by the EH.

Micro-energy hubs are provided with energy management systems (software and hardware) that, locally, coordinate the operation of multiple carriers accelerating the development of multi-energy technology and improving the energy efficiency of mEHs.

Micro-energy hubs are composed of heterogeneous information and telecommunications technologies belonging to both industrial and consumer sectors as shown in Figure 6. The energy management system aims to monitor, optimize and control the micro-energy hub combining software (e.g., communication drivers, databases, control algorithms, etc.) and hardware components (sensors, actuation devices, etc.).

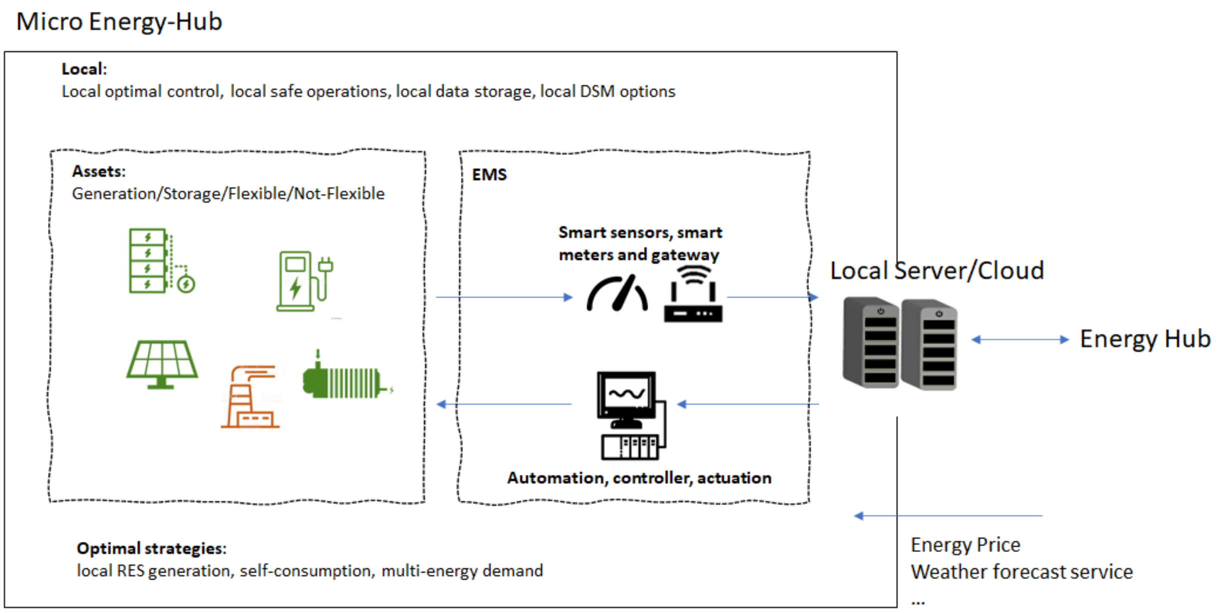


Figure 6 - Scheme of a mEH

Hardware/Software

The energy management systems include IoT devices to monitor the energy production and consumption (smart meters and gateway), automation systems such as Supervisory Control and Data Acquisition (SCADA) and Programmable Logic Controller (PLC)/Distributed Control System (DCS)/Embedded Personal Computer (PC) and actuators to control and monitor industrial plants. Local server can be included in the micro-energy hub to aggregate data for local data storage and allow the communication and coordination with other mEHs. For data collection at the district/city level, a remote acquisition infrastructure network is required, and in this case, the smart meters unidirectionally send the data to the receivers which communicate usually via General Packet Radio Service (GPRS) to File Transfer Protocol (FTP) server using a Subscriber Identify Module (SIM) card (one for each receiver) with active data service. In this way the meter data are collected by the FTP server.

The EMS could be provided with SCADA software and web applications (e.g., dashboards for analytics, reporting and maintenance), web services (e.g., weather forecast, energy price forecast), utility software (e.g., scripts for demand forecasting, algorithms for optimal management of energy assets also based on AI approach).

For what concern the data management and data logging, data collected from the field are normally stored in databases (SQL or noSQL), data lake or in files of different formats (.csv, .json, etc.).
Mainly the following two cases can be considered related to databases, data collection and communication protocols:

A) Industrial sector (industrial plants, building and facilities):

The assets are monitored and controlled by SCADA. Data are stored synchronously in SQL databases. The Facility Data Server communicates with all assets using the protocols such as Modbus TCP, Modbus RTU, CAN J1939, ProfiBus, ProfiNet, etc.

B) Consumer sector (building and facilities):

The assets can be monitored and controlled by local server or cloud solutions. Data are stored asynchronously mainly in NoSQL databases (e.g., MongoDB, Influx DB, etc.) and SQL databases such as Azure SQL, MySQL, SQL Server. The devices could communicate to the gateways normally using smart meters with the standards IEEE 802.15.4, Zigbee, Z-Wave, Bluetooth Low Energy, 868 MHz RF modules, wireless M-bus OMS (open metering system), others wireless M-bus R4 (proprietary protocol), etc.

Local server/cloud oversees connecting with the different data sources (being servers, gateways or SCADA platforms). It will deploy the required communication protocols to guarantee the input/output data flow to and from the controllers. It will also manage the local database where the data from different sources is aggregated in a common data structure shared by all the software modules. The database must be understood in a general way and can be built using SQL and NoSQL databases, files, local memory, OPC servers, etc.

For what concern office premises, BEMS is a system that allows to monitor and control the electrical equipment of a building, combining software (e.g., communication drivers, databases, control algorithms, etc.), and hardware components (sensors, actuation devices, etc.).
Even though sometimes the two terms are used interchangeably, Building Management System (BMS) and BEMS are different, the former monitoring and controlling all systems in a building, the latter focusing only on systems involving energy use. Hence, the BEMS monitors and controls energy-related building services such as Heating, Ventilation, and Air Conditioning (HVAC) and lighting excluding not energy-related systems such as fire, Closed Circuit Television (CCTV), etc.
The main functions of a BEMS can be grouped in four categories: monitoring, control, optimization and reporting. The BEMS monitors the sensor measurements and, using control algorithms, can modify the behavior of the facilities in the building in order to obtain the best performance regarding a particular objective. The BEMS allows to:

- improve energy efficiency
- provide better comfort for occupants
- review the performance of the building
- generate automatically alarms for failures or anomaly conditions
- identify planned and unplanned maintenance requirements
- log and archive data for energy management purpose

Control algorithms/strategies

The EMS is the system that permits the mEH to reach their objectives, and at the same time, it can improve the self-awareness of the consumers regarding the energy saving and environmental impact of their behavior.

The objective of the EMS is to manage local assets and optimize local objective functions by implementing low-level controllers that control the local assets considering the set-points received from the EMS and the actual conditions of the plant. Since mEHs give energy flexibility, they can also implement advanced Demand Side Management (DSM) strategies under the supervision and global set-points set by the energy hub (e.g., sharing available power among a group of EVs, etc.). Low-level control will have a key role to guarantee safety and security operation when the connection is lost between local devices and smart control. Low-level controls are based mainly on Pulse-Width Modulation (PWM), PID, rules-based (if-then rules), Fuzzy logic, and more advanced methodologies, i.e., optimization-based methodologies such as predictive controllers based on

Model Predictive Control (MPC) framework and Reinforcement Learning (RL) framework. The lasts two frameworks are introduced in the next section.

1.5.2 Energy hub management system

An energy hub is composed of heterogeneous micro-energy hubs belonging to industrial, commercial and residential sectors and its aim is to coordinate the different micro-energy hubs and manage the multiple carriers as shown in Figure 7.

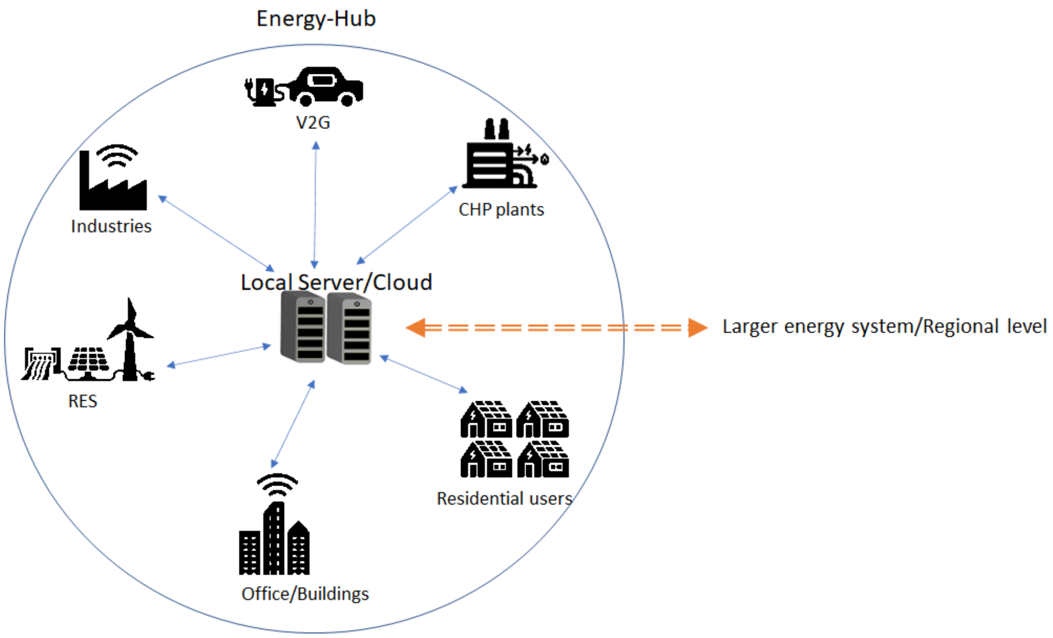


Figure 7 - Scheme of an EH (centralized solution)

Hardware/Software

The architecture of an EH must be defined including criteria for an open, scalable and replicable architecture that can be deployed in new and existing mEHs. The output is a high-level software solution installed in a server/cloud that collects data coming from the different mEHs, manages them into different actors (e.g., Flexibility Service Providers), allowing them to actively participate in the energy market. To allow the proper operation of the EH, the communication architecture is one of the key aspects of the energy hub that allows the data flow among the different devices and energy assets.

The communication among the different mEHs (i.e., the servers/clouds of LEC, EV charging station, RES, tertiary buildings, industrial plants mEHs) is carried out by Application Programming Interface Representational State Transfer (API REST), then the Internet-based Technologies are the key to create an energy hub. For what concerns the software, the energy hub is a web-based platform based on microservices and a list of possible software/frameworks (free and licensed) that could be used to develop and deploy the energy hub are:

- Web-Frameworks: .Net Core, Angular, React, Vue.js, etc.
- Database (SQL-NoSQL): SQL Server, MySQL, PostgreSQL, Oracle, MongoDB, InfluxDB, AzureSQL, etc.
- Event-based data ingestion: RabbitMQ, Kafka, etc.

- Deploy: Docker, Kubernetes, etc.
- AI and Analytics: Python scripts, Tableau, Power BI, etc.

The web-based architecture considered to manage the energy hub should provide the following high-level features:

- Different levels of authentication implemented to allow each different actor to access and visualize only the corresponding information and separately interact with the proper processes
- Storage of historical data of the monitored assets and access to specific data through the use of filters (data range, asset, geographical zone)
- Temporal aggregation of the data of the selected variables at different time resolutions for visualization purposes: 15 minutes, 30 minutes, hours, days, weeks, months, years
- Customizable import from csv and export to .csv/.xlsx
- Ability to connect via API Rest and sharing information on resources, data for registering a new flexibility resource, etc.
- Integrated map view for meters and micro-energy hubs, read out tours and data concentrators
- Dashboard view for system monitoring
- Pre-defined graphics to visualize readings and consumptions
- In-built task scheduler to automate procedures (e.g., import/export or analysis jobs)
- Energy reporting
- Energy management/control system to coordinate the whole mEHs

Energy management system

The energy management/control system must be capable of coordinating both the energy demand and consumption. For instance, residential and industrial sectors have different consumption patterns so that they can be controlled together, as well as using distributed energy resources to compensate the lack of each sector. Furthermore, the peak demand in those two sectors does not occur at the same time, thus the distributed generation from one sector can fulfill part of the peak demand in the other sector and vice versa.

The control strategy is a big issue to face when different mEHs are linked/connected, especially when the energy flow must be optimized according to the end-users' demand and each infrastructure/architecture. One of the most used is the centralized one (see Figure 7), which collects information of the controlled areas and solves optimization problems to find the best solution.

However, it is worth noting that the centralized control method is mainly applied to small-scale systems because it is not able to handle large-scale ones. This is due to the increase of the information that the centralized control strategy must deal with, which increases the computational time for reaching the best trade-off configuration of the EH. Indeed, many objectives such as technical, economic, reliability, and environmental parameters must be considered, constituting a multi-objective optimization problem. For this reason, the decentralized solution (see Figure 8), and distributed controllers can be used for controlling each mEH that constitutes an EH and each optimization result is shared with the others. Micro energy hubs can be also connected through a parallel/decentralized layout; in this way, the parallel layout lets the system operate also when failures occur.

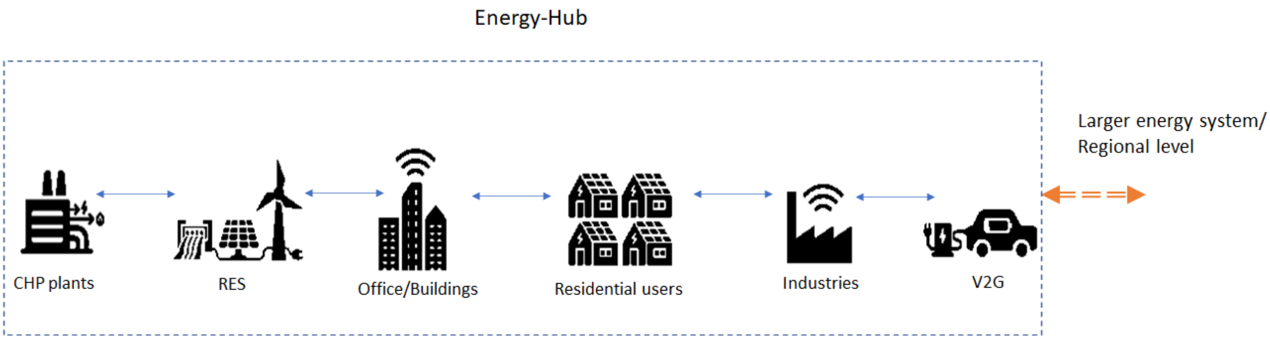


Figure 8 - Scheme of an energy hub (decentralized solution)

The decentralized EH is related to the Web-of-Cell (WoC) concept that is a decentralized energy architecture for energy management, and the control strategies are implemented in a decentralized manner based on local observations using local resources.

In conclusion, the EH improves the reliability of the system and, at the same time, both the economic and environmental advantages. Due to the high number of connections within and between the mEHs, the use of distributed control strategies instead of centralized ones can enhance and speed up the optimization procedure by finding the optimal condition locally and then making a trade-off considering the overall EH. This configuration is useful also in case of failures of a mEH since the optimization objective is anyway carried out due to the parallel layout of the system.

Control algorithms/strategies

The use of a control architecture leads to main pros regarding the production and the reliability of the energy system, the emissions reduction, and the share of renewables. However, all the control systems allow to find the optimal operation of a mEH, and an EH as well, in a short time frame; thus, a long-time frame optimization has become a big challenge in this research field. Indeed, for energy hub management, predictive controllers have required to optimal schedule/control/coordinate the mEHs. In this case, AI can be useful for the long-term prediction of energy consumption/production and load/demand forecast.

The high-level controllers are based on multi-objective optimization problem that can be defined in the MPC framework and RL framework. While the MPC is a classical approach in this context, RL is a cutting-edge and scalable solution to control complex systems that, recently, have been applied also to the energy management of buildings.

Reinforcement Learning

The Reinforcement Learning is a particular learning approach where the agent (the subsystem that performs actions) learns the policy (relation between states and actions to perform) based on a delayed reward system interacting with the environment representing other parts of the system that the agent cannot modify (Figure 9).

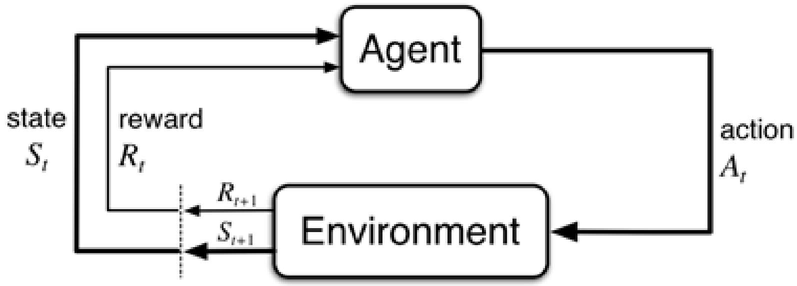


Figure 9 - The Agent-Environment interaction [Sutton 2018]

In order to tackle a problem using RL approaches, it is necessary to identify States, Actions and Rewards. The RL algorithms can be divided in *model-based* and *model-free* methods. In the model-based methods, the agent, based on the model of the environment (already known or learned from the experience), takes the decisions (e.g., dynamic programming, heuristic search, etc.). In the model-free methods, the agent learns directly how to behave (e.g., Monte Carlo methods, Temporal Difference, etc.). The RL methods have been applied to many areas of building energy management such as HVAC control, water heater, home management system providing energy savings of about 10% for HVAC applications, about 20% for water heater and greater than 20% for building energy management systems. The majority of RL applications to BEMS are mainly focused on improving the thermal performances and most publications only discuss energy efficiency and visual or thermal comfort not considering cost minimization.

In the smart home context (similar under several aspects to the smart building), the States generally consist of the time of day, temperature information (indoor and outdoor), current usage state of the various appliances/devices, electricity prices, grid load, information related to PV panels (e.g., solar irradiance), etc. The Actions available to the RL agents are usually the turning devices on or off. The Rewards are based on energy cost, thermal comfort or a combination of both. One of the most used algorithms is Q-learning but also new Deep Reinforcement Learning approaches are emerging since their effectiveness.

Even though RL algorithms can be directly applied to real scenarios, the initial exploratory phase with the evaluation of different policies, can lead to high energy cost (unacceptable in the real situations). For this reason, the majority of RL applications to building energy management is conducted in simulated environments and this leads to the necessity of data and simulators that are representative of real-world scenarios.

Usually, the training of RL agents starts in a simulation environment and, after, a further fine tuning can be done directly in the physical system.

Several studies in the literature examine the application of RL to energy communities, rather than single buildings. In these situations, multi-agent approaches (centralized, decentralized, cooperative, non-cooperative) are more suitable. In eNeuron LEC, the cooperative multi-agent approach could be suitable to consider the perspective of prosumers in peer-to-peer energy sharing within the community.

Model Predictive Control

Model Predictive Control is an advanced control strategy, trying to replace the standard PID controllers where its performance is not satisfactory. It is the highest impact advanced control

methodology in industrial control engineering. It cannot be considered a specific control strategy. It covers several control strategies which make an explicit use of a model of the process to predict its future behavior, minimizing an objective function to obtain the control inputs (Figure 10). MPC denotes the family of controllers that predicts the future dynamics of the process with an explicit model, involves optimization technique and follows the receding horizon idea.
Some of the most appreciated features are the optimal control, metavariables systems are treated in a straightforward way, system constraints are easily considered, it can be successfully implemented for simple or very complex processes; it can be handled by people with limited control knowledge, it does not have a fixed structure, modifications and new features are easily included.
The main drawback of MPC is related to the quality of the identified model. A model that does not represent the real process might heavily affect the control performance; stability is not often easily proven (finite horizon); the online computational effort is high but in process industry is weakly affected. Sampling time is in the order of seconds, or higher.

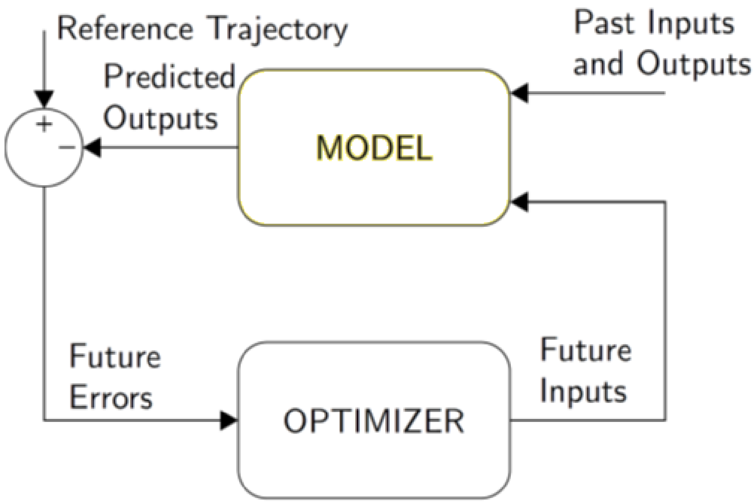


Figure 10 - Control scheme of MPC

MPC or receding horizon control has been widely used as high-level controller in microgrids with multiple types of RES and BEMS. In the context of microgrids, the standard MPC is extended to a Mixed-Integer Linear Programming (MILP) formulation for the optimal control of hybrid systems such as microgrids and RES.

References

D5.1. - Building Energy Management System (BEMS) definition, BRESAER Project, http://www.bresaer.eu/

K. Sayed, H.A. Gabbar, "Building Energy Management Systems (BEMS)," in Energy Conservation in Residential, Commercial, and Industrial Facilities, IEEE, 2018, Pages 15-81, https://doi.org/10.1002/9781119422099.ch2

R.S. Sutton, A.G. Barto. “Reinforcement Learning: An Introduction”, Cambridge, MA, USA, 2018

K. Mason, S. Grijalva, “A review of reinforcement learning for autonomous building energy management”, Computers & Electrical Engineering, Volume 78, 2019, Pages 300-312, ISSN 0045-7906, https://doi.org/10.1016/j.compeleceng.2019.07.019

S. Park, M. Choi, S. Lee, T. Lee, S. Kim, K. Cho, “Reinforcement Learning-Based BEMS Architecture for Energy Usage Optimization”, Sensors 2020, 20, 4918. https://doi.org/10.3390/s20174918

A.T.D. Perera, Parameswaran Kamalaruban, “Applications of reinforcement learning in energy systems”, Renewable and Sustainable Energy Reviews, Volume 137, 2021, 110618, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2020.110618

Z. Wang, T. Hong, “Reinforcement learning for building controls: The opportunities and challenges”, Applied Energy, Volume 269, 2020, 115036, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2020.115036

Yu, Liang, et al. "Deep Reinforcement Learning for Smart Building Energy Management: A Survey." arXiv preprint arXiv:2008.05074 (2020)

M. Mohammadi, Y. Noorollahi, B. Mohammadi-ivatloo, M. Hosseinzadeh, H. Yousefi, S. Torabzadeh Khorasani, “Optimal management of energy hubs and smart energy hubs – A review”, Renewable and Sustainable Energy Reviews, Volume 89, 2018, Pages 33-50, https://doi.org/10.1016/j.rser.2018.02.035

ELECTRA IRP, FP7-ENERGY project, http://www.electrairp.eu/

R. D'hulst et al., "Voltage and frequency control for future power systems: the ELECTRA IRP proposal," 2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST), 2015, pp. 245-250, doi: 10.1109/SEDST.2015.7315215

Bobinaite, Viktorija, et al. "Economically Efficient Design of market for System Services under the Web-of-cells Architecture." Energies 11.4 (2018): 729

J. Hu, Y. Shan, J.M. Guerrero, A. Ioinovici, K. Wing Chan, J. Rodriguez, “Model predictive control of microgrids – An overview”, Renewable and Sustainable Energy Reviews, Volume 136, 2021, 110422, ISSN 1364-0321, doi: 10.1016/j.rser.2020.110422

Bordons, Carlos, Félix Garcia-Torres, and Miguel A. Ridao. “Model predictive control of microgrids”. Vol. 358. Cham: Springer, 2020

G. Serale, M. Fiorentini, A. Capozzoli, D. Bernardini, A. Bemporad. “Model Predictive Control (MPC) for Enhancing Building and HVAC System Energy Efficiency: Problem Formulation, Applications and Opportunities”. Energies 2018, 11, 631. doi: 10.3390/en11030631

A. Abreu, R. Bourdais, H. Guéguen, Hierarchical Model Predictive Control for Building Energy Management of Hybrid Systems, IFAC-PapersOnLine, Volume 51, Issue 16, 2018, Pages 235-240, ISSN 2405-8963, doi 10.1016/j.ifacol.2018.08.040

W.C. Clarke, C. Manzie and M.J. Brear, "An economic MPC approach to microgrid control," 2016 Australian Control Conference (AuCC), 2016, pp. 276-281, doi: 10.1109/AUCC.2016.7868202

2 Technologies

This section focuses on technologies enabling local multi-carrier energy systems. The first sub-section presents the definition of connecting technologies and identifies the role of mEH and EH in the concept of sector coupling; then, the second and third sub-sections present the technologies available at mEH and EH level, respectively. The final sub-section focuses on two infrastructure enabling cross vector integration in energy hub: natural gas network to store hydrogen and electric vehicle infrastructure to connect electric and mobility network.

Micro energy-hub connecting technologies:	Energy-hub connecting technologies:
• Heat pumps • Hybrid heat pumps • Electric boilers • Electric chillers • Electric cooling technologies • Cogeneration and trigeneration • EV charging stations (wall-box)	• Heat pumps • Cogeneration and trigeneration • Electrolyzers • EV charging stations • Electric Planes, Electric Ferries, Hydrogen transport such as trains, vessels, and lorries • Desalination
Infrastructure • Natural gas network as H_2 storage • EV infrastructure	

The information for micro energy-hub and energy hub technologies is organized in tables with the same format:

- Short description
- Energy carriers involved
- Energy demand satisfied
- Energy networks involved
- Range size
- Market Maturity [1]
- Costs
- Techno-economic barriers
- Future perspectives
- References

Also the information for energy hub infrastructure is organized in tables with the following format:

- Short description
- Technologies involved
- Energy carriers involved
- Energy networks which could be involved
- Maturity [1]
- Level of deployment
- Costs
- Potential barriers
- References

[1] Information about TRL of technologies are provided by the Consortium on the basis of partners' experience on field, partners' knowledge and references provided

2.1 Connecting technologies: a definition

In the context of multi-carrier energy systems, connecting technologies are those which connect at least two energy networks so that one energy carrier in input is converted by that technology in at least two different energy carriers operating as many energy networks.
Figure 11 shows a holistic view of potential integration between energy networks in a district/LEC.

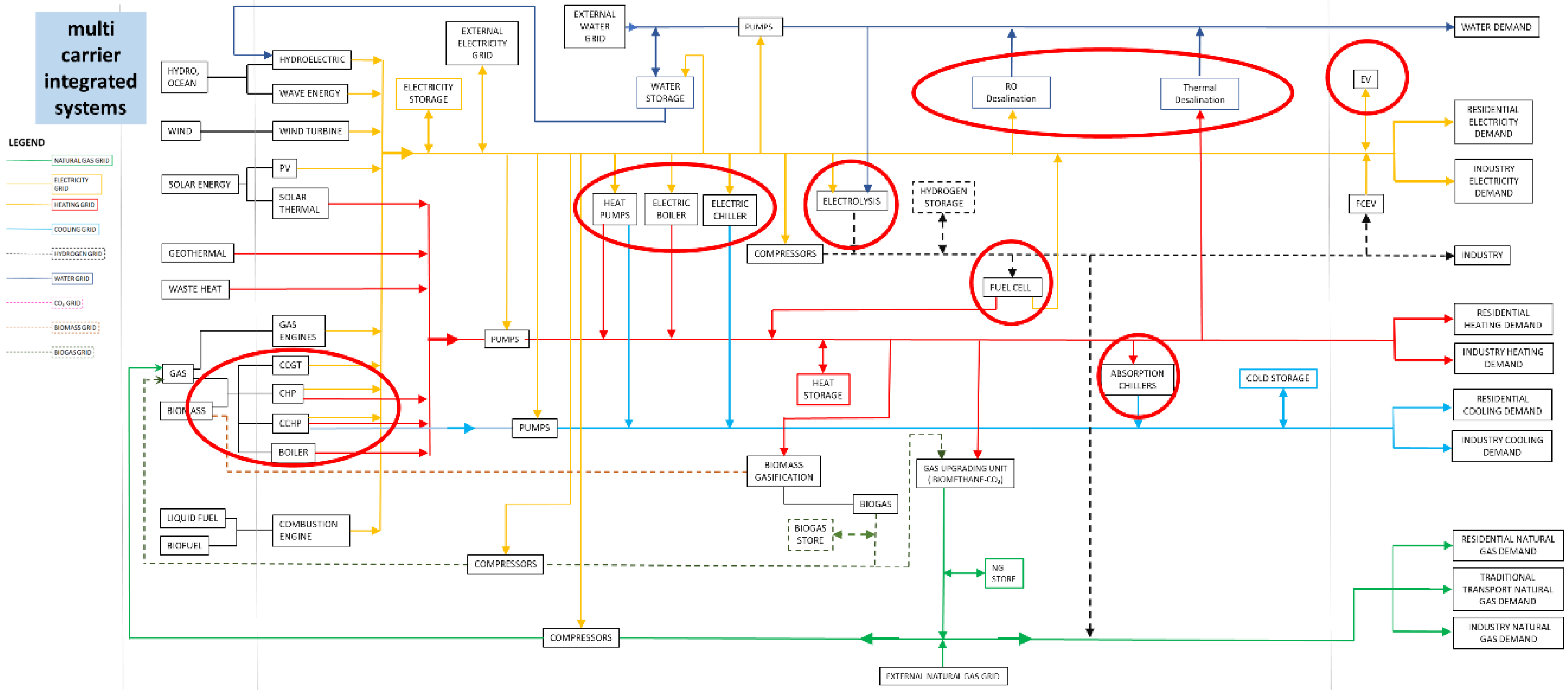


Figure 11 - Holistic view of potential integration between energy networks in a district/LEC

At the far right of the figure there are all the energy demands of the final users (residential, industrial…); the energy demands translate in a demand of an energy carrier (electricity, hot/chilled water, natural gas…); then, according to the technology selected to produce these energy carriers, the primary energy demand/mix will result. As an example, hot water is the most common energy carrier to meet thermal energy demand for heating purposes; anyway, the final user can decide to produce it with a natural gas boiler, an engine operating in cogeneration mode, a heat pump or a solar thermal panel thus burdening in one network or in another.

In this context, connecting technologies have a pivotal role in the energy transition since they enable potential synergies among different energy networks in the so called "Sector Coupling". EU identified two types of sector coupling: End-use sector coupling and Cross-vector coupling. The former refers mainly to the electrification of final uses while the latter refers to the integrated use of different energy carriers and networks. These two types of sector coupling perfectly fit with the eNeuron concept since end-users' sector coupling technologies are the ones installed in mEH, while cross vector sector coupling technologies are the ones installed at EH level.

In Figure 11 are also highlighted, circled in red, the main connecting technologies investigated both at mEH and EH level in the following subsections.

References

European Parliament. STUDY Requested by the ITRE committee. Sector coupling: how can it be enhanced in the EU foster grid stability and decarbonise?, Year 2018. https://www.europarl.europa.eu/RegData/etudes/STUD/2018/626091/IPOL_STU(2018)626091_EN.pdf

2.2 Micro energy hub technologies

Technology
Heat pumps
Short Description
Heat pumps are electricity-based space heating and cooling solutions and for the production of the domestic hot water. Their function is based on the reverse vapour compression cycle and are classified by the heat source and heat sink used: • Air-water: an air-to-water heat pump is used for producing domestic hot water, and for space heating and cooling purposes. The heat pump absorbs heat from outside air for heating the air inside the apartment/building through an intermediate fluid, usually water, which transfers the heat to the air inside the apartment/building by means of a heat exchanger (fan coils, radiant systems, etc.), and to the water inside a tank for domestic hot water applications. By reversing the cycle, air-to-water heat pumps can also operate as cooling systems • Air-air: an air-to-air heat pump absorbs heat from outside air for releasing that heat into the forced-air distribution system within the apartment/building. By reversing the cycle, air-to-air heat pumps can also operate as cooling systems • Water-water: a water-to-water heat pump uses water as a thermal source to recover heat to be used for heating/cooling and to produce domestic hot water. The source may be ground water, cooling water from an industrial process or event process water that needs to be chilled before use • Water-Air: a water-to-air heat pump uses water as thermal source for releasing heat into the forced-air distribution system within the apartment/building by means of a heat exchanger, and to produce domestic hot water. By reversing the cycle, water-to-air heat pumps can also operate as cooling systems • Ground source: a ground source heat pump absorbs heat from the ground for heating and/or cooling the air inside the apartment/building. In the case of the ground-water system, the heat extracted is used also to produce domestic hot water
Energy carriers involved
• Electricity • Hot water • Chilled water
Energy demand satisfied
• Heating • Cooling • Domestic hot water
Energy networks involved
• Electricity
Range size:
• Apartments <16 kWth

- Buildings <120 kWth
- Coefficient Of Performance (COP) range: 2-5 (based on EN1451)
- Energy Efficiency Ratio (EER) range: 2-4 (based on EN1451)
- Sanitary hot water COP: 1.5-4 (EN16147)
- Air-air - heating operation*: air in between -5°C and 24°C, air out up to 30°C; - cooling operation*: air in between 20°C and 52°C, air out between 18°C and 32°C
- Air-water - heating operation*: air temperature between -25°C and 35°C, water temperature between 18°C and 55°C; - cooling operation*: air temperature between 15°C and 40°C, water temperature between 8°C and 20°C
- Water source/Ground source - heating operation*: water in (source) between -8°C and 27°C, water out (user) between 25°C and 70°C; - cooling operation*: water in (source) between 25°C to 65°C, water out (user) between -8°C to 18°C

*based on technical datasheet of commercial heat pumps

Market maturity

TRL 9 - The technology of vapor compression heat pumps is mature, widely used for years and it is constantly evolving

Costs

- **Air source**: CAPEX between 450 €/kW to 850 €/kW for systems with capacity of 7-20 kW. Installation costs begin from 300 €/kW. OPEX is 3 c€/kWh
- **Water source**: CAPEX between 800 €/kW to 1600 €/kW and OPEX between 9 c€/kWh and 15 c€/kWh for systems with capacity of 7-20 kW. Installation costs can be high if water extraction wells are needed
- **Ground source**: CAPEX with installation costs between 1000 €/kW and 3000 €/kW and OPEX between 9 c€/kWh and 15 c€/kWh for systems with capacity of 8-12 kW

Techno-economic barriers

- The installation of heat pumps could involve high refurbishment levels of existing heating systems and the replacement of emission systems (fan coils, radiant systems, etc.), requiring significant cost investments
- Economically high dependent on the electricity-natural gas price ratio
- COP highly dependent on temperature of heat source and on pipes length
- Possible high acoustic noise
- Lower temperature levels of the produced water
- For water source heat pumps, the water source must be near the apartment/building with water of sufficient quantity to cover its requests. Moreover, the water supplied to the heat pump must be of good quality, in terms of impurities or mineral and biological content that could damage the system. If groundwater is used, the heat pump installation may be subject to restrictions and authorizations by the competent authorities
- For geothermal heat pumps, the construction cost is very high as they require long wells or excavations, and the efficiency of the system strongly depends on the ground properties. Moreover, their installation may be subject to restrictions and authorizations by the competent authorities

Future perspectives

- DR application: coupled with thermal storage could be even more convenient, thanks to the possibility to activate DR services and offer ancillary services to the electric grid
- Heat pumps is a pivotal technology in the electrification of energy demand (end-user sector coupling). Electrification can be used to decarbonise a major share of heat demand in buildings.

References

GREBE (Generating Renewable Energy Business Enterprise). Advice Notes on Ground & Air Source Heat Pumps Technology, September 2017. http://grebeproject.eu/wp-content/uploads/2017/10/GREBE-Advice-Notes-GSHP-ASHP.pdf

European Technology Platform – Renewable Heating & Cooling GEOTHERMAL PANEL- VISION 2020 - 2030. https://eurogeologists.eu/wp-content/uploads/2017/07/ETP-RHC_Geothermal-vision-2020.pdf

ETIP SNET New White Paper – Sector Coupling: Concepts, State-of-the-art and Perspectives, January 2020. https://www.etip-snet.eu/wp-content/uploads/2020/02/ETIP-SNEP-Sector-Coupling-Concepts-state-of-the-art-and-perspectives-WG1.pdf

Fischer D, Madani H. On heat pumps in smart grids: A review. Renew Sustain Energy Rev 2017;70:342–57. https://doi.org/10.1016/j.rser.2016.11.182

G.R. Aditya, O. Mikhaylova, G.A. Narsilio, I.W. Johnston. Comparative costs of ground source heat pump systems against other forms of heating and cooling for different climatic conditions. Sustain Energy Technol Assessments 2020;42:100824. https://doi.org/10.1016/j.seta.2020.100824

M. Forsén, Heat pumps: Technology and environmental impact. Eur Heat Pump Assoc Raphaela 2005:1–120

O. Terreros, J. Spreitzhofer, D. Basciotti, R.R. Schmidt, T. Esterl, M. Pober et al. Electricity market options for heat pumps in rural district heating networks in Austria. Energy 2020;196:116875. https://doi.org/10.1016/j.energy.2019.116875

C. Arpagaus, F. Bless, M. Uhlmann, J. Schiffmann, S.S. Bertsch. High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. Energy 2018, 152:985–1010. https://doi.org/10.1016/j.energy.2018.03.166

L. Romero Rodríguez, J. Sánchez Ramos, S. Álvarez Domínguez, U. Eicker. Contributions of heat pumps to demand response: A case study of a plus-energy dwelling. Appl Energy 2018;214:191–204. https://doi.org/10.1016/j.apenergy.2018.01.086

S. Kozarcanin, R. Hanna, I. Staffell, R. Gross, G.B. Andresen. Impact of climate change on the cost-optimal mix of decentralised heat pump and gas boiler technologies in Europe. Energy Policy 2020;140:111386. https://doi.org/10.1016/j.enpol.2020.111386

European Parliament. STUDY Requested by the ITRE committee. Sector coupling: how can it be enhanced in the EU foster grid stability and decarbonise?, Year 2018. https://www.europarl.europa.eu/RegData/etudes/STUD/2018/626091/IPOL_STU(2018)626091_EN.pdf

Technology
Hybrid heat pumps
Short Description
Hybrid heat pumps are technologies which couple existing technologies such as air-water heat pumps and condensing boilers. This solution mainly consists of an optimized control of the two technologies which permits to optimally manage the whole system by switching on the boiler whenever the heat demand cannot be satisfied by heat pumps or it's not convenient, or to use them both in hybrid mode.
Energy carriers involved
• Electricity • Hot water • Chilled water
Energy demand satisfied
• Heating • Cooling • Domestic hot water
Energy networks involved
• Electricity • Natural gas pipeline
Range size
• Apartments, buildings • Heating COP: 3-5 (based on EN1451) • Cooling EER: 2-4 (based on EN1451) • Condensing boiler efficiency: > 97 %
Market maturity
TRL 9 - The technology of vapor compression heat pumps is mature, widely used for years and it is constantly evolving
Costs
• 7000-11,500 € (for 22-31 kWth boiler and 4kWth heat pumps) • CAPEX **(manufacturer dependent)** • Installation & refurbishments **(manufacturer dependent)** • OPEX (5-10% of CAPEX)
Techno-economic barriers
• Refurbishment and replacements of heat exchanger • For geothermal constraints about cost and space availability and authorization
Future perspectives

- Demand Response (DR)
- Hybrid heat pumps is a pivotal technology in the electrification of energy demand (end-user sector coupling) in climates in which the use of heat pumps is not convenient. Electrification can be used to decarbonise a major share of heat demand in buildings.

References

Hybrid heat pumps, Final report for Department for Business, Energy& Industrial Strategy Hybrid_heat_pumps_Final_report-.pdf (publishing.service.gov.uk)

A. Uytterhoeven, G. Deconinck, A. Arteconi, L. Helsen, Hybrid heat pump scenarios as a transition towards more flexible buildings, Proceeding of the 10th International Conference on System Simulation in Buildings – SSB 2018, Year 2018

European Parliament. STUDY Requested by the ITRE committee. Sector coupling: how can it be enhanced in the EU foster grid stability and decarbonise?, Year 2018. https://www.europarl.europa.eu/RegData/etudes/STUD/2018/626091/IPOL_STU(2018)626091_EN.pdf

Technology

Electric boilers

Short Description

Electric boilers are appliances producing domestic hot water from electricity. Electric boilers are water storage thermally insulated in which water is kept at a defined temperature, usually set at 70°C. It acts as a thermal energy storage: when domestic hot water is required by final users, the boiler is discharged; the volume of water discharged is replaced by low temperature (12-15°C) tap water; the average temperature inside the boiler decreases and an electric resistance switches-on at full power in order to restore the set temperature

Energy carriers involved

- Electricity
- Heat
- Domestic hot water

Energy network involved

- Electricity

Energy demand satisfied

- Domestic hot water

Range size

Volume ranges of boilers water tank (in apartments, buildings):

10 liters	80 liters	200 liters
15 liters	100 liters	250 liters
50 liters	150 liters	300 liters

Market Maturity

TRL 9 – Electric boilers technology is mature, widely used for years TRL 7-8 - Smart electric boilers enabled for DR are available
Costs
• Low
Future perspectives
Smart electric boiler can be used as programmable loads in order to participate to DR program proposed by aggregators. Smart electric boilers use Artificial Intelligence (AI) to predict the profile of use of domestic hot water so that it keeps temperature at a lower value (e.g., 45°C rather than 70 °C) when it is not required. In this way it reduces thermal losses, and it activates potential flexibility. As an example, by "shifting" their electricity demand within the daily profile it is possible to create a match with the PV production and, consequently, cost-savings can be maximized. Smart boilers can act as both controllable loads and as thermal storages since they can regulate water temperature according In this context, it becomes crucial to know both the usage patterns and the state of charge of these thermal storages (internal temperature level).
References
L. Ciabattoni, G. Comodi, F. Ferracuti, G. Foresi, "A Methodology to Enable Electric Boiler as a Storage for Residential Energy Management," 2020 IEEE International Conference on Consumer Electronics (ICCE), 2020, pp. 1-2, doi: 10.1109/ICCE46568.2020.9043007

Technology
Electric chillers
Short Description
Electric chillers are electricity-based space cooling solutions. Their function is based on the reverse vapour compression cycle and are classified by the heat source and heat sink used: • Air-water: an air-to-water electric chiller is used for producing chilled water for space cooling. The chiller removes the heat from the air inside the apartment/building through an intermediate fluid, usually water, by means of a heat exchanger (fan coils, radiant systems, etc.). The removed heat is transferred to the external environment • Air-air: an air-to-air electric chiller absorbs heat from inside air thanks to a forced-air distribution system within the apartment/building
Energy carriers involved
• Chilled water • Electricity
Energy network involved
• Electricity
Energy demand satisfied
• Cooling
Range size
• Apartments, detached houses, buildings
Market Maturity
TRL 9 - The technology of vapor compression electric chillers is mature, widely used for years and it is constantly evolving
Costs
• The technology has achieved a high maturity and economy of scale so that electric chillers are available at cheap price for most of consumers. In any case, the cost can increase when high target of efficiency are required
Techno-economic barriers
• Ongoing laws on Greehouse gases emissions and ozone depletion could push out of the market some working fluids, but new regulations are coming quickly
Future perspectives
Electric chillers can be used as controllable loads to provide flexibility to buildings (through an energy management system) or aggregators
References

L. Ciabattoni, G. Comodi, F. Ferracuti, G. Foresi, "AI-Powered Home Electrical Appliances as Enabler of Demand-Side Flexibility," in IEEE Consumer Electronics Magazine, vol. 9, no. 3, pp. 72-78, 1 May 2020, doi: 10.1109/MCE.2019.2956197

A. Arteconi, A. Mugnini, F. Polonara, Energy flexible buildings: A methodology for rating the flexibility performance of buildings with electric heating and cooling systems, Applied Energy,
Volume 251, 2019, https://doi.org/10.1016/j.apenergy.2019.113387

Technology
Home electric technologies
Short Description
Today, appliances, depending on their usage patterns and functions, can be classified into three categories as follows: 1) major appliances (white goods) such as washing machines, dishwasher, tumble dryers refrigerator, freezers, microwave oven, electric oven, and electric boilers 2) multimedia devices (brown goods), such as TVs, computers, radios, or games consoles 3) small appliances and lighting Only white goods are controllable loads which can provide flexibility for DR program
Energy carriers involved
• Electricity
Energy network involved
• Electricity
Energy demand satisfied
• not applicable
Range size
• Apartments • 1-5 kW
Market Maturity
TRL 9 – Home appliances technologies are mature, widely used for years and it is constantly evolving TRL 7-8 - Smart home appliances enabled for DR are available
Costs
• Very low (from hundreds up to thousand euro)
Future perspectives
Home electric technologies (mainly white goods) can enable demand-side flexibility through residential demand-side management in smart homes. To enable residential demand-side

flexibility, we may distinguish two main approaches: direct load control and price-based. In the first case, consumers agree to accept certain conditions imposed by an energy supplier to automatically adjust their consumption. This includes direct load control, interruptible service, and emergency demand response. On the other hand, a price-based system encourages customers to actively participate in demand response according to price information (e.g., real-time pricing). The customer can either shift the program manually or via a home energy management system, controlling the consumption of several appliances. This approach can be performed on the major appliances, such as electric water HVAC systems, refrigerators, washing machines, washer–dryers, and dishwashers

References

L. Ciabattoni, G. Comodi, F. Ferracuti, G. Foresi, "AI-Powered Home Electrical Appliances as Enabler of Demand-Side Flexibility," in IEEE Consumer Electronics Magazine, vol. 9, no. 3, pp. 72-78, 1 May 2020, doi: 10.1109/MCE.2019.2956197

Technology

Combined Heat and Power (CHP) - Combined Cooling Heat and Power (CCHP)

Short Description

CHP stands for the simultaneous electricity production and heat recovery, where the latter is considered as useful effect since, otherwise, it would be wasted. It is also possible to have cold energy though particular equipment that exploit the waste heat recovery from the exhausts, thus constituting the so-called CCHP units. So far, there are several technologies involved in the cogeneration process:

- **Internal Combustion Engine (ICE)**: the engine consists of a fixed cylinder and a moving part (piston) that transforms the chemical energy coming from the combustion of a fuel inside the engine itself into mechanical energy and, subsequently, electrical one
- **Micro Gas Turbine (MGT):** it consists of a small gas turbine that elaborates the exhausts coming from the combustion chamber (combustion energy) and supplies mechanical energy to a compressor, which is mounted on the same shaft increasing the air pressure that goes into the combustion chamber and produces useful work (electrical energy)
- **Fuel Cells (FC)**: an open electrochemical conversion system which elaborates a fuel gas (mainly H_2 but also CH_4 reformate, to a certain extent CO/CO_2 and fuel gas mixtures) via a redox reaction in a Membrane Electrode Assembly (MEA – anode|electrolyte|cathode) which generates electricity with very high efficiency (beyond the Carnot thermal limit) and null CO_2 emissions. Different electrolyte technologies lead to different operating temperatures (Low Temperature Fuel Cells (LTFC) between 60-200 °C: Alkaline Fuel Cells (AFC); Proton Exchange Membrane Fuel Cells (PEMFC); High Temperature Fuel Cells (HTFC) between 600-1000 °C: Molten Carbonate Fuel Cells (MCFC); Solid Oxide Fuel Cells (SOFC)) which can be exploited in CHP configurations with indirect heat recovery of the depleted electrode outlet streams or by recovery of the process heat itself (electrolyte operating temperature and exothermal heat generated in the redox reaction, heat generated by joule effect due to cell current). Such available heat can be converted to cooling power if sent to cryogenic units such as sorption pumps

Energy carriers involved

- Electricity
- Fuel (e.g., H_2, CO, natural gas, gasoline, diesel and biofuels)
- Hot water/Steam

Energy network involved

- Natural gas pipeline
- Other fuel gas networks (e.g., syngas, biogas, CO/H_2 mixtures)
- Power grid

Energy demand satisfied

- Heating (CHP) and cooling (CCHP)
- Electricity (self-consumption, on-grid stationary production, grid services, UPS)

Range size

- **ICE:** electric and thermal power of 1-10 kWe and 5-50 kWth, electric and thermal efficiencies of 11-23% and 57-59%, respectively
- **MGT:** electric and thermal power of 3-15 kWe and 6-25 kWth, electric and thermal efficiencies of 23-30% and 47-50%, respectively
- **FC:** modular units for any size of electrical power (from 1 kWe to several 100 kWe), thermal power depending on the FC technology (low grade heat for LTFC, high grade heat for HTFC), electric efficiency of 35-70% and thermal efficiency of 55-85% for LTFC and HTFC, respectively

Market Maturity

- **ICE:** TRL 9 ICE CHP systems are widely used in real systems
- **MGT:** TRL 9 MGT CHP systems are widely used in real systems
- **FC:** LTFC: TRL 8-9; HTFC: TRL 5-6 low temperature fuel cells (LTFC) are proven in operational environment; high temperature fuel cells (HTFC) has been validated in relevant environment

Costs

- **ICE:** CAPEX between 1,700 and 3,600 €/kWe, OPEX of 0.01-0.03 €/kWhe
- **MGT:** CAPEX between 1,300 and 3,000 €/kWe, OPEX between 0.06-0.09 €/kWhe
- **FC:** LTFC: CAPEX between 2,000 and 3,000 €/kWe; OPEX of 5 % CAPEX/year (excluding fuel cost); HTFC: CAPEX between 2,500 and 7,500 €/kWe; OPEX of 8% CAPEX/year (excluding the fuel cost)

Techno-economic barriers

Techno-economic barriers:

- **ICE:**

Acoustic noise
Diverse temperature level
High maintenance cost
High vibrations and emissions

Low efficiency at partial loads
Temperature and pressure dependent performance

- **MGT:**

Lower maintenance cost
Temperature and pressure dependent performance
Unavailability

- **FC:**

High CAPEX & OPEX cost
High fuel cost (especially pure H_2 for LTFC)
Low efficiency (close to 50 %)
Permitting issues related to safety of compressed hydrogen
Required implementation of pure H_2 network or high-grade purification units (LTFC)
Low grade heat available for CHP (LTFC)
Limited dynamic operation (HTFC)

Future perspectives

- **ICE:** modifications for being used with a blended H_2/CH_4 fuel
- **MGT:** modifications for being used with a blended H_2/CH_4 fuel
- **FC:** dispatchable energy storage & grid services (LTFC); reversible operation (HTFC); operation with a blended H_2/CH_4 fuel
- CO_2 networks in MCFC

References

M. Elbrahimi, A. Keshavarz, 2 – CCHP Technology, Combined Cooling, Heating and Power, Decision Making, Design and Optimization, 2015, 35-91

N.A. Diangelakis, C. Panos, E.N. Pistikopoulos, Design Optimization of an internal combustion engine power CHP system for residential applications, Comput. Manag. Sci (2014) 11:237-266

H.I. Onovwiona, V.I. Ugursal, A.S. Fung, Modeling of internal combustion engine based cogeneration systems for residential applications, Applied Thermal Engineering 27 (2007) 848-861

Micro-CHP Systems for Residential Applications: Final Report, United Technologies Research Center, Year 2006, Pages 123

P.A. Pilavachi, Mini- and micro-gas turbines for combined heat and power, Applied Thermal Engineering 22 (2002), 2003-2014

Micro Gas Turbine Technology, Research and Development for European Collaboration, Technology Summary, ETN Global, Pages 69

R. Padinger, S. Aigenbauer, C. Schmidl, Best practice report on decentralized biomass fired CHP plants and status of biomass fired small- and micro scale CHP technologies, IEA Bioenergy: Task 32: February 2019

G.P. Negreanu, I. Oprea, V. Berbece, Some design characteristics of micro steam turbines for agricultural biomass energy conversion, E3S Web of Conferences 180, 01017 (2020)

A. Monforti Ferrario, C. Amoruso, R. V. Robles, L. Del Zotto, E. Bocci, G. Comodi, Power-to-Gas from curtailed RES electricity in Spain: potential and applications 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Madrid, Spain, 2020, pp. 1-6, doi: 10.1109/EEEIC/ICPSEurope49358.2020.9160820

R.K. Pachauri, Y.K. Chauhan. A study, analysis and power management schemes for fuel cells. Renew Sustain Energy Rev 2015; 43:1301–19. doi:10.1016/j.rser.2014.11.098

A. Bartolini, F. Carducci, C. Boigues Muñoz, G. Comodi, Energy storage and multi energy systems in local energy communities with high renewable energy penetration, Renewable Energy, 2020;159:595-609, https://doi.org/10.1016/j.renene.2020.05.131

U.S. Department of Energy. Fuel Cell Handbook (7th edition). 7th ed. 2004. doi:10.1016/s0031-9422(00)82398-5

Energy USD of Fuel cells factsheet. FUEL CELL Technol Off Fuel 2015:23–54. doi:10.1007/978-1-349-04829-8_3

M. Cassir, D. Jones, A. Ringuedé, V. Lair. Electrochemical devices for energy: Fuel cells and electrolytic cells. vol. 2. 2013. doi:10.1533/9780857097347.3.553

Battelle Memorial Institute. Manufacturing cost analysis of 1 kW and 5 kW Solid Oxide Fuel Cell (SOFC) for auxiliary power applications 2014

S.J Mcphail, A. Aarva, H. Devianto, R. Bove, A. Moreno. SOFC and MCFC: Commonalities and opportunities for integrated research. Int J Hydrogen Energy 2010; 36:10337–45. doi:10.1016/j.ijhydene.2010.09.071

FUEL CELLS and HYDROGEN 2 JOINT UNDERTAKING (FCH 2 JU), Addendum to the Multi-Annual Work Plan2014–2020, Endorsed by the Governing Board on 15 June 2018. Available at: https://www.fch.europa.eu/sites/default/files/MAWP%20final%20version_endorsed%20GB%2015062018%20%28ID%203712421%29.pdf

Technology

EV charging stations (wall-box)

Short Description

The Electric Vehicle charging station or Supply Equipment (EVSE) is the main set of elements required to connect the EV to an electrical installation for charging purposes. Physically, the EVSEs can be found in two main configurations: wall box and charging post. The interface between the EVSE and the grid is directly hard-wired to a control device or a plug and protection box.

The level of power that an EVSE can deliver to an EV vary in each country depending on the distribution network and supply characteristics: voltage, current, frequency, and number of phases in the case of AC supply. This is defined mostly by national regulation and utilities' procedures. The IEC 61851 is an international standard dealing with EV conductive charging system, which has become a reference for EV infrastructure.

Part 1 of the previous standard categorises four charging modes:

- **Mode 1** represents the slowest charging level, where the EV is directly connected to standard wall electricity outlet and, therefore, it does not allow any control
- **Mode 2** is referred to the connection of an EV to a standard socket-outlet, but the connection cable needs to have a control pilot function and a safety system against the electric shock
- **Mode 3** offers a slow and accelerated charging type in AC through a specific EV supply equipment (EVSE) permanently connected to the AC network
- **Mode 4** is a DC fast charging method, which uses an external charger that converts AC into DC

Energy carriers involved

- Electricity

Energy demand satisfied

- Mobility

Energy networks involved

- Power grid
- (Mobility)

Range size

According to IEC 61851-1:2017

Mode	Charging type	Max. Voltage (V)	Max. Current (A)	Connection
1	AC (slow)	250 (1 ph), 480 (3-ph)	16	Standard socket
2	AC (slow)	250 (1 ph), 480 (3-ph)	32	Via special cable
3	AC (accelerated)	1000*	-*	Special cable through the EVSE
4	DC (fast)	1500*	-*	Dedicated socket through EVSE

* In accordance with the EVSE specification.

Typical values for modes 3 and 4 in Europe are the following:

- **Mode 3:** 230/400 V at 16, 32 or 64 A (between 3.7 and 44.3 kW)
- **Mode 4:** 400 V at 125 A (between 50 kW). Other supply powers currently exist. It is expected that this power will increase up to 150 kW for lighter vehicles and 500 kW for buses and lorries

Market Maturity/costs

TRL 9 per each mode (mode 4 up to 100 kW) – wall-boxes are widely used in operational environment

Costs

Considering the installation, the equipment and the grid connection referred to the year 2020, it follows:

- **Residentials:** 600-1,100 €
- **Workplaces:** 1,745 €
- **Public EV charging stations:** 3,400 € (3-7 kW) or 4,500 € (11-22 kW)

The previous bullet points belong to the slow charging EV; if the accelerated charging EV are considered as well, it follows:

- **Accelerated charging:** 4,500-6,000 €

Techno-economic barriers

- Introduction of government incentives to promote home charging
- Promotion of public infrastructure (1 EVSE per 10 EVs is given as approximate reference at EU level)

Future perspectives

- Use of locally available renewable resources like solar PV to charge EVs
- Use of a smart management system and smart grid
- Use of storage for fast charging installations
- Incomes by Vehicle-to-Grid (V2G) scheme

References

J. Martínez-Lao, F.G. Montoya, M.G. Montoya, and F. Manzano-Agugliaro, Electric vehicles in Spain: An overview of charging systems, Renewable and Sustainable Energy Reviews, Volume 77, 2017, Pages 970-983, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2016.11.239

H.S. Das, M.M. Rahman, S. Li, and C.W. Tan, Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review," Renewable and Sustainable Energy Reviews, Volume 120, 2020, 109618, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2019.109618

H. Shareef, M.M. Islam, and A. Mohamed, A review of the stage-of-the-art charging technologies, placement methodologies, and impacts of electric vehicles, Renewable and Sustainable Energy Reviews, Volume 64, 2016, Pages 403-420, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2016.06.033

Ö. Gönül, A.C. Duman, Ö. Güler, Electric vehicles and charging infrastructure in Turkey: An overview, Renewable and Sustainable Energy Reviews, Volume 143, 2021, 110913, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2021.110913

S. Deb, K . Tammi, K. Kalita, P. Mahanta, Review of recent trends in charging infrastructure planning for electric vehicles. WIREs Energy and Environment. 2018; 7:e306. https://doi.org/10.1002/wene.306

Recharge EU: how many charge points will Europe and its member states need in the 2020s, Transport & Environment, January 2020, https://www.transportenvironment.org/publications/recharge-eu-how-many-charge-points-will-eu-countries-need-2030

2.3 Energy hub level technologies

Technology
Combined heat and power
Short Description
Combined Heat and Power (CHP) stands for the simultaneous electricity production and heat recovery, where the latter is considered as useful effect since it would otherwise be wasted. There are several technologies involved in the cogeneration process: • **Combined Cycle (CC):** it consists of topping plus bottoming cycles, generally a Gas Turbine (GT) and a Heat Recovery Steam Generator (HRSG), respectively. The former is a gas turbine that elaborates the exhausts coming from the combustion chamber (combustion energy) and supplies mechanical energy to a compressor, which is mounted on the same shaft increasing the air pressure that goes into the combustion chamber and produces useful work (electrical energy), while the latter uses the exhausts heat to produce steam that is elaborated by a steam turbine, producing further useful work • **Gas Turbine (GT)**: it consists of a Bryton-Joule cycle, where a gas turbine elaborates the exhausts coming from the combustion chamber (combustion energy) and supplies mechanical energy to a compressor, which is mounted on the same shaft increasing the air pressure that goes to the combustion chamber and produces useful work (electrical energy) • **Internal Combustion Engine (ICE)**: same description as micro energy hub level • **Micro Gas Turbine (MGT):** same description as micro energy hub level • **Steam Turbine (ST):** it consists of a steam turbine that elaborates the steam coming from a boiler/steam generator and produces useful work (electrical energy) • **Fuel Cells (FC)**: same description as micro energy hub level
Energy carriers involved
• Electricity • Fuel (e.g., H_2, CO, natural gas, gasoline, diesel and biofuels) • Hot water/Steam
Energy demand satisfied
• Electricity • Heating • Heat for process
Energy networks involved
• Local/District Heating Network • Natural gas pipeline • Other fuel gas networks (e.g., syngas, biogas, CO/H_2 mixtures) • Power grid
Range size

- **CC:** electric and thermal power of 1-5 MWe and 0.8-3.7 MWth, electric and thermal efficiencies of 40-55% and 35-40%, respectively
- **GT:** electric and thermal power of 3.5-10 MWe and 6-12 MWth, electric and thermal efficiencies of 24-36% and 41-43%, respectively
- **ICE:** electric and thermal power of 50-500 kWe and 57-555 kWth, electric and thermal efficiencies of 35-45% and 40-50%, respectively
- **MGT:** electric and thermal power of 50-300 kWe and 76-490 kWth, electric and thermal efficiencies of 25-29% and 38-47%, respectively
- **ST:** electric and thermal power of 0.1-1 MWe and 1.4-11 MWth, electric and thermal efficiencies of 5-7% and 73-75%, respectively
- **FC*:** modular units for any size of electrical power (from 100 kWe to several MWe), thermal power depending on the FC technology (low grade heat for LTFC, high grade heat for HTFC), electric efficiency of 35-70% and thermal efficiency of 55-85% for LTFC and HTFC, respectively

*the performance parameters are not significantly affected by scaling up size due to the modularity of the FC technology

Market Maturity/costs

- **CC:** TRL 9 - CC CHP systems are widely used in real systems
- **GT:** TRL 9 - GT CHP systems are widely used in real systems
- **ICE:** TRL 9 - ICE CHP systems are widely used in real systems
- **MGT:** TRL 9 - MGT CHP systems are used in real systems
- **ST:** TRL 9 - ST CHP systems are used in real systems
- **FC:** LTFC: TRL 8-9, HTFC: TRL 5-6 low temperature fuel cells (LTFC) are proven in operational environment; high temperature fuel cells (HTFC) has been validated in relevant environment

Costs

- **CC:** CAPEX between 2200 and 5000 €/kWe, OPEX between 0.02 and 0.04 €/kWhe
- **ICE:** CAPEX between 1700 and 3500 €/kWe, OPEX between 0.01 and 0.03 €/kWhe
- **GT:** CAPEX between 1600 and 4000 €/kWe, OPEX between 0.01 and 0.02 €/kWhe
- **MGT:** CAPEX between 3000 and 4000 €/kWe, OPEX between 0.01 and 0.02 €/kWhe
- **ST:** CAPEX between 800 and 1500 €/kWe, OPEX between 0.008 and 0.015 €/kWhe
- **FC*:** LTFC CAPEX between 1000 and 2500 €/kWe; OPEX of 3 % CAPEX/year (excluding fuel cost); HTFC CAPEX between 2500 and 5000 €/kWe; OPEX of 8% CAPEX/year (excluding fuel cost)

*FC costs at district level are mainly affected by Balance of Plant scaling, since the stack technology is modular, and no significant direct cost decrease is foreseen with size

Techno-economic barriers

- **CC:**

Low electrical efficiency, but it improves with respect to using only ST
Poor partial load performance
Temperature and pressure dependent performance
Not easy and time demanding to obtain building/planning permit
Connection with external energy Infrastructure (electric and natural gas network)

- **ICE:**

Acoustic noise
Diverse temperature level
High maintenance cost
High vibrations and emissions
Low efficiency at partial loads
Permissions (for higher output power values)
Temperature and pressure dependent performance

- **GT:**

Lower maintenance cost
Permissions
Temperature and pressure dependent performance

- **MGT:**

Lower maintenance cost
Temperature and pressure dependent performance
Unavailability

- **ST:**

Low electrical efficiency
Low power to heat ratio and is used primarily with solid fuel boilers (it is required, on the other hand a steam source can be used)
Permissions
Poor partial load performance
Slow start-up

- **FC:**

High CAPEX & OPEX cost
High fuel cost (especially pure H_2 for LTFC)
Limited dynamic operation (HTFC)
Low efficiency (close to 50 %)
Low grade heat available for CHP (LTFC)
Permitting issues related to safety of compressed H_2
Required implementation of pure H_2 network or high-grade purification units (LTFC)

Future perspectives

- **CC:** modifications for being used with a blended H_2/CH_4 fuel (for GT)
- **GT:** modifications for being used with a blended H_2/CH_4 fuel (for GT)
- **ICE:** modifications for being used with a blended H_2/CH_4 fuel
- **MGT:** modifications for being used with a blended H_2/CH_4 fuel
- **FC:** dispatchable energy storage & grid services (LTFC), reversible operation (HTFC); operation with a blended H_2/CH_4 fuel

References

M. Elbrahimi, A. Keshavarz, 2 – CCHP Technology, Combined Cooling, Heating and Power, Decision Making, Design and Optimization, 2015, 35-91

N.A. Diangelakis, C. Panos, E.N. Pistikopoulos, Design Optimization of an internal combustion engine power CHP system for residential applications, Comput. Manag. Sci (2014) 11:237-266

H.I. Onovwiona, V.I. Ugursal, A.S. Fung, Modeling of internal combustion engine based cogeneration systems for residential applications, Applied Thermal Engineering 27 (2007) 848-861

Micro-CHP Systems for Residential Applications: Final Report, United Technologies Research Center, Year 2006, Pages 123

P.A. Pilavachi, Mini- and micro-gas turbines for combined heat and power, Applied Thermal Engineering 22 (2002), 2003-2014

Micro Gas Turbine Technology, Research and Development for European Collaboration, Technology Summary, ETN Global, Pages 69

R. Padinger, S. Aigenbauer, C. Schmidl, Best practice report on decentralized biomass fired CHP plants and status of biomass fired small- and micro scale CHP technologies, IEA Bioenergy: Task 32: February 2019

G.P. Negreanu, I. Oprea, V. Berbece, Some design characteristics of micro steam turbines for agricultural biomass energy conversion, E3S Web of Conferences 180, 01017 (2020)

Combined Heat and Power Technology Fact Sheet Series, Gas Turbines, U.S. Department of Energy, Energy Efficiency & Renewable Energy, Pages 4

A.W. Ordys, M.J. Grimble, I. Kocaarslan, Combined cycle and combined heat and power processes, Control Systems, robotics, and automation, Vol. XVIII, Pages 12

Combined Heat and Power Technology Fact Sheet Series, Overview of CHP Technologies, U.S. Department of Energy, Energy Efficiency & Renewable Energy, Pages 4

A. Monforti Ferrario, C. Amoruso, R. V. Robles, L. Del Zotto, E. Bocci and G. Comodi, Power-to-Gas from curtailed RES electricity in Spain: potential and applications 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Madrid, Spain, 2020, pp. 1-6, doi: 10.1109/EEEIC/ICPSEurope49358.2020.9160820

R.K. Pachauri, Y.K. Chauhan. A study, analysis and power management schemes for fuel cells. Renew Sustain Energy Rev 2015;43:1301–19. doi:10.1016/j.rser.2014.11.098

A. Bartolini, F. Carducci, C. Boigues Muñoz, G. Comodi, Energy storage and multi energy systems in local energy communities with high renewable energy penetration, Renewable Energy, 2020;159:595-609, https://doi.org/10.1016/j.renene.2020.05.131

U.S. Department of Energy. Fuel Cell Handbook (7th edition). 7th ed. 2004. doi:10.1016/s0031-9422(00)82398-5

Energy USD of. Fuel cells factsheet. FUEL CELL Technol Off Fuel 2015:23–54. doi:10.1007/978-1-349-04829-8_3

M. Cassir, D. Jones, A. Ringuedé, V. Lair. Electrochemical devices for energy: Fuel cells and electrolytic cells. vol. 2. 2013. doi:10.1533/9780857097347.3.553

Battelle Memorial Institute. Manufacturing cost analysis of 1 kW and 5 kW Solid Oxide Fuel Cell (SOFC) for auxiliary power applications 2014

J.S. McPhail, A. Aarva, H. Devianto, R. Bove, A. Moreno, SOFC and MCFC: Commonalities and opportunities for integrated research, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2010.09.071

FUEL CELLS and HYDROGEN 2 JOINT UNDERTAKING (FCH 2 JU), Addendum to the Multi-Annual Work Plan2014–2020, Endorsed by the Governing Board on 15 June 2018. https://www.fch.europa.eu/sites/default/files/MAWP%20final%20version_endorsed%20GB%2015062018%20%28ID%203712421%29.pdf

Technology
Combined Cooling heat and power / Absorption chiller, Adsorption chiller, Dessicant
Short Description
Combined Heat and Power (CCHP) stands for the simultaneous electricity production and heat recovery, where the latter is considered as useful effect since it would otherwise be wasted. When CHP technology is coupled with absorption chillers, it enables another energy carrier which is chilled water for cooling applications. The main CCHP technologies have been already discussed in detail in the respective table related to the micro energy hub level; however, since CCHP can provide also cooling, it follows a brief description of the most known systems commonly used: • **Absorption chiller:** the process is based on the properties of a pair of substances with a different volatility where heat is provided to separate the most volatile, used as refrigerant in the cycle. For instance, in the $LiBr\text{-}H_2O$ absorption chiller, water is the refrigerant (cooling temperature > 0 °C), while in the $NH_3\text{-}H_2O$ absorption chiller, ammonia is the refrigerant (cooling temperature < 0 °C) • **Adsorption chiller**: this system uses working pair materials, called adsorbent/adsorbate. The adsorbent is in solid form, capturing and releasing the adsorbate vapor in different stages. The most common working pair is silica gel (adsorbent) - water (adsorbate). Adsorption and desorption phenomena occur due to the cooling and heating of the adsorbent, respectively • **Dessicant dehumidifier**: it is the part of the cooling systems dedicated to dehumidification and it needs to be regenerated periodically to continue working. It uses the waste heat of different prime movers for the regeneration of the desiccant, whose cooling may be liquid type (absorption systems) or solid type (desorption systems)
Energy carriers involved
• Electricity • Fuel (e.g., natural gas, gasoline, diesel and biofuels) • Hot or cold water/Steam • Solar energy
Energy demand satisfied
• Electricity • Heating • Cooling
Energy networks involved
• District Heating/Cooling Network • Natural gas pipeline • Power grid • Standalone (e.g., hydro, PV panels, solar thermal, wind)
Range size

- **Absorption chiller:** installed in cycles having an electric power of 18 kWe-6 MWe and a COP of 0.7-1.5 for LiBr-H_2O refrigerant based, while an electric power of 10 kWe-6.5 MWe and a COP of 0.5-1.2 for NH_3-H_2O refrigerant based
- **Adsorption chiller:** installed in cycles having an electric power of 10 kWe-1 MWe and a COP of 0.55-0.70
- **Dessicant dehumidifier:** installed in cycles having an electric power of 1-5 kWe and a COP of 2-5

Market Maturity/costs

- **Absorption chiller:** TRL 9 – Absorption chillers are widely used in real trigeneration systems
- **Adsorption chiller:** TRL 8-9[2]
- **Desiccant dehumidifier:** TRL 4-7 -

Costs

- **Absorption chiller:** CAPEX between 170 and 360 €/kWe, OPEX between 5.5 and 11 €/kWhe
- **Adsorption chiller:** CAPEX between 610 and 1,220 €/kWe, OPEX between 60 and 120 €/kWhe
- **Desiccant dehumidifier:** CAPEX between 90 and 180 €/kWe, OPEX between 0.04 and 0.12 €/kWhe

Techno-economic barriers

- **Absorption chiller:** in some of mechanical compression equipment, such as pumps, lubricants are in direct contact with the refrigerant (possible contamination and reduction of performance). In addition, it requires a large and consistent stream of waste heat to work; indeed, industries are the most suitable candidates where an absorption chiller can be installed, but campuses, hospitals, and large hotels could be other opportunities that can benefit from its installation. Controls, mechanical components and heat transfer components must be properly maintained; in such a context, i) pump shaft seals require frequent checks for wear, ii) refrigerant lacks considering that the loss rate should not exceed 1%, iii) heat transfer surfaces have to be free of sludge and scale, iv) heat exchanger tubes must not have cracking, pitting and corrosion as well, and v) pump bearings replacement has to be done after a certain amount of operation. Partial load operation of an absorption chiller leads to higher energy consumptions due to the decrease of the COP
- **Adsorption chiller:** it is the costliest technology among the ones described so far for fulfilling a cooling demand
- **Desiccant dehumidifier:** the liquid desiccant system is less costly than the solid desiccant one (e.g., it provides the same dehumidification with lower regeneration air temperature, it produces less pressure drop and removes pollution for air as well). However, the liquid desiccant leads to corrosion and crystallization; the desiccant has to be replaced, refilled or reconditioned every 5-10 years of operation; filters must be replaced periodically (e.g., filter clogging affects the performance of the heater due to the lack of O_2, increases pressure drops and decreases the air flow to the consumer as well)

Future perspectives

[2] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/horizon-results-platform/30636;resultId=30636

- **Absorption chiller:** their coupling with renewables according to their flexibility in terms of produced energy
- **Adsorption chiller:** their coupling with renewables according to their flexibility in terms of produced energy
- **Desiccant dehumidifier:** the membrane fouling of the dehumidifier should be avoided, otherwise it reduces the vapor flux through the membrane and increases the operating costs significantly. The membrane is also extremely thin and flexible; thus, it is easy to deform, rupture, or leak. The deformation of the membrane greatly affects the flow distribution. Furthermore, the flow distribution plays a critical role in the module performance: to prevent the membrane deflection, the support grid and the membrane with a high modulus of elasticity are being currently studied. Additionally, the channel design of the dehumidifier can cause the bad distribution of both streams significantly

References

M. Elbrahimi, A. Keshavarz, 2 – CCHP Technology, Combined Cooling, Heating and Power, Decision Making, Design and Optimization, 2015, 35-91

A. Shukla, Combined Cooling, Heating, and Power (CCHP) or Trigeneration Technology: An Approach Toward Higher Energy Efficiency, Emission Reduction Potential and Policy, Energy Sustainability Through Green Energy, Springer, 2015

Y. Shi, M. Liu, F. Fang, Combined Cooling, Heating, and Power Systems: Modelling, Optimization, and Operation, John Wiley & Sons Ltd, 2017, ISBN 9781119283355

K.K. Roman, M. Hasan, H. Azam, CCHP System Performance Based on Economic Analysis, Energy, Conservation, and Emission Analysis, Intechopen, 2018, DOI: 10.5772/intechopen.77000

Y. Li, X. Kong, Introduction to CCHP Systems, Handbook of Energy Systems in Green Buildings, Springer, 2018

V.C. Mei, F.C. Chen, Z. Lavan, R.K. Collier, G. Meckler, An Assessment of Desiccant Cooling and Dehumidification Technology, OAK RIDGE NATIONAL LABORATORY, Tennessee 37831-6285, MARTIN MARIETTA ENERGY SYSTEMS, INC. for the U.S. DEPARTMENT OF ENERGY under contract No. DE-AC05-84OR21400. https://www.osti.gov/servlets/purl/10103029

X. Liu, M. Qu, X. Liu, L. Wang, Membrane-based Liquid Desiccant Air Dehumidification: A Comprehensive Review on Materials, Components, Systems and Performances. https://www.osti.gov/servlets/purl/1542214

Technology

Heat pumps

Short Description

Heat pumps are electricity-based space heating and cooling solutions and production of the domestic hot water.
Their function is based on the reverse vapor compression cycle and are classified by the heat source and heatsink used:

- Air-water
- Water-water
- Air-air
- Ground source

- Waste heat (high temperature heat pumps)

Energy carriers involved

- Electricity
- Hot water
- Chilled water

Energy demand satisfied

- Heating
- Cooling
- Domestic hot water

Energy networks involved

- Electricity
- District heating/cooling

Range size

- District
- COP range: 2-5 (based on EN1451)
- EER range: 2-4 (based on EN1451)
- Domestic Hot Water COP: 1.5-4 (based on EN16147)

Market Maturity/costs

Large-scale heat pumps are commercially available and thus their TRL is 9 but face market-design barriers. Lifting taxes on the electricity used in power-to-heat applications would facilitate their uptake.

It depends on the application. F gas regulation: phase out of HFC. In residential application R410A, R32, propane, CO_2 are possible alternatives. Ammonia can be used in industrial applications.

Operating conditions:

- Refrigerant: hydrofluorocarbons (HFC) dominant R134a, Ammonia R717. In residential application R410A, R32, propane, CO_2 are possible alternatives
- Heat source temp: -12 - 120 °C (Normal conditions: -20 - 40 °C)
- Heat sink temp: 0-160 °C (Normal conditions: 0-80 °C)

Costs

- **Ground Source**: CAPEX between 500 €/kW and 800 €/kW and OPEX between 5 c€/kWh and 10 c€/kWh for systems with capacity over 100 kW

Techno-economic barriers

- The heat pump performance is strongly dependent on the heat sink and source temperature. In particular, the heat sink temperature level will impact on the maximum temperature achievable at the source site and on the COP of the machine. Waste heat quantity and quality (i.e., temperature level) is paramount
- High electricity/gas cost ratio: the heat pump is normally electrically driven; therefore, the electricity price has a huge impact on the economic feasibility of this technology for

thermal energy production. Natural gas price and taxation can make a difference on the operating costs of heat pump systems
Future perspectives
• DR applications especially when coupled to thermal storage: the excess renewable electrical energy produced could be converted into thermal energy and stored in thermal energy storage, thereby reducing RES curtailment and making the electrical grid more stable to sudden variations of RES • Low Temperature District Heating with geothermal heat pumps
References
ETIP SNET New White Paper – Sector Coupling: Concepts, State-of-the-art and Perspectives, January 2020. Available at: https://www.etip-snet.eu/wp-content/uploads/2020/02/ETIP-SNEP-Sector-Coupling-Concepts-state-of-the-art-and-perspectives-WG1.pdf E. Popovski, A. Aydemir, T. Fleiter, D. Bellstadt, R. Büchele, J. Steinbach. The role and costs of large-scale heat pumps in decarbonising existing district heating networks e A case study for the city of Herten in Germany. Energy 180 (2019) 918-933 M. Jesper, F. Schlosser, F. Pag, T.G. Walmsley, B. Schmitt, K. Vajen. Large-scale heat pumps: Uptake and performance modelling of market-available devices. Renew Sustain Energy Rev 2021;137:110646. https://doi.org/10.1016/j.rser.2020.110646 A. Marina, S. Spoelstra, H.A. Zondag, A.K. Wemmers. An estimation of the European industrial heat pump market potential. Renew Sustain Energy Rev 2021;139:110545. https://doi.org/10.1016/j.rser.2020.110545 F. Schlosser, M. Jesper, J. Vogelsang, T.G. Walmsley, C. Arpagaus, J. Hesselbach. Large-scale heat pumps: Applications, performance, economic feasibility and industrial integration. Renew Sustain Energy Rev 2020;133:110219. https://doi.org/10.1016/j.rser.2020.110219

Technology
Electrolyzers
Short Description
Electrolysis is an electrochemical conversion process which allows to separate water into hydrogen and oxygen. A direct current current is fed to the electrolyzer core stack which is composed of a typical electrode|electrolyte|electrode assembly which catalytically activates the decomposition of the H_2O molecule. The most widespread technology operates at low temperature (between 60-100°C), using an alkaline or polymeric electrolyte and noble catalyst at the electrodes. The constituent materials of the electrolyzer determines operating envelopes in terms of temperature, pressure, current density, gas collection approach affecting both stack and balance of plant design. High temperature electrolysis (namely steam electrolysis) can provide part of the required energy in the form of heat, strongly reducing the specific energy consumption (below 40 kWh/kgH_2 respect to over 50-60 kWh/kgH_2 for low temperature electrolysis).
Energy carriers involved
• Electricity • Hydrogen

Energy networks involved
• Electricity • Hydrogen • Water (non-energy network) • Oxygen (non-energy network)
Range size
• ALK: < 4 MW (modular) • PEM: < 4 MW (modular) • AEM: kW-scale (modular) • SOEC: 200 kW (modular) • MCEC: 25 kW (modular)
• **Market Maturity/costs**
• ALK: TRL 8-9 • PEM: TRL 8-9 • AEM: TRL 5-6 • SOEC: TRL 6-8 • MCEC: TRL 4-6
Costs
• ALK: 500-1,000 €/kWe • PEM: 700-1,200 €/kWe • SOEC: 2,000-3,000 €/kWe • MCEC: n/a • AEM: n/a
Techno-economic barriers
• High CAPEX for reduced scale • Limited operating hours (<60,000 h with limited dynamic operation for ALK; < 50,000 h and/or 5,000 cycles for PEM) • Issues in stack durability and calendar/cycling degradation with the consequent efficiency reduction (%/hrs or %/year) • Not fully developed commercial maturity for high temperature technologies • Difficult implementation in non-industrial environments where steam is already available • High catalyst costs (low temperature) - noble metals • High current/low voltage operation - challenging for power electronic converters
Future perspectives
• Typical size and market volume increase to drive down CAPEX • New technologies for further specific energy consumption reduction • Reversible high temperature systems • Dynamic use with intermittent RES for grid services
References
IRENA. GREEN HYDROGEN COST REDUCTION. (2020)

F.I. Gallardo, *et al.* A Techno-Economic Analysis of solar hydrogen production by electrolysis in the north of Chile and the case of exportation from Atacama Desert to Japan. *Int. J. Hydrogen Energy* (2020) doi:10.1016/j.ijhydene.2020.07.050

IEA International Energy Agency. The future of fuel: The future of hydrogen. Report 2019. doi:10.1016/S1464-2859(12)70027-5

L. Bertuccioli, A. Chan, D. Hart, F. Lehner, B. Madden, El. Standen. Fuel cells and hydrogen Joint undertaking Development of Water Electrolysis in the European Union 2014

IRENA. Hydrogen From Renewable Power: Technology outlook for the energy transition. 2018

J. Proost. State-of-the art CAPEX data for water electrolysers, and their impact on renewable hydrogen price settings. Int J Hydrogen Energy 2018:1–8. doi:10.1016/j.ijhydene.2018.07.164

G. Cau, D. Cocco, M. Petrollese, S. Knudsen Kær, C. Milan. Energy management strategy based on short-term generation scheduling for a renewable microgrid using a hydrogen storage system. Energy Convers Manag 2014;87:820–31. doi:10.1016/j.enconman.2014.07.078

A. Monforti Ferrario, C. Amoruso, R.V. Robles, L. Del Zotto, E. Bocci, G. Comodi, Power-to-Gas from curtailed RES electricity in Spain: potential and applications 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Madrid, Spain, 2020, pp. 1-6, doi: 10.1109/EEEIC/ICPSEurope49358.2020.9160820

Ø. Ulleberg. Modeling of advanced alkaline electrolyzers: A system simulation approach. Int J Hydrogen Energy 2003;28:21–33. doi:10.1016/S0360-3199(02)00033-2

The Haeolus project. https://www.haeolus.eu/

FULEL CELLS and HYDROGEN 2 JOINT UNDERTAKING (FCH 2 JU), Multi-Annual Work PLan 2014-2020, 2018. https://www.fch.europa.eu/sites/default/files/MAWP%20final%20version_endorsed%20GB%201506201 8%20%28ID%203712421%29.pdf

Technology

EV charging stations

Short Description

For most daily charging activities, the energy demand from EVs is satisfied by the overnight slow charging using wall-boxes mainly installed at home or at work (Mode 1 and 2 as already mentioned in "EV charging stations (wall-box)" technology"), but for sporadic long-distance trips, EVs will require to be charged as conventional ICEs vehicles at gas stations, achieving 80-90% SoC in 15-30 minutes depending on the nominal power of the charging point and the EV battery capacity.

Although most of the chargers installed worldwide are slow chargers (<22 kW), in recent years fast charging stations-FC (50 kW) and ultra-fast charging stations-UFC (<400 kW) are being installed to meet the growing demand for EVs that require covering long distances, reducing range anxiety when traveling. At the end of 2019, there were installed around 9,000 FC and 640 UFC across Europe in the main transport network corridors.

According to the reference standard IEC 61851-1, DC power is only used for fast charging in mode 4, mainly using three different types of standardized sockets in the vehicle-side: CHAdeMO (usually

50 kW DC output in CHAdeM0 1.0 and 400 kW in CHAdeMo 2.0) and Combined Charging System (CCS), (200kW DC output for the American CCS1 type and over 300 kW DC output for the European CC2 option) and the Chinese option, GB/T (125 kW DC output). Additionally, Tesla has developed an additional socket for their models (over 300 kW in V3 superchargers).

Due to the high power involved during the charging process, conventional on-board chargers are not a feasible solution due to cost, size and weight issues and, for this reason, DC power is delivered to the EV battery by an isolated power converter located outside the vehicle, which includes additional control and protection functions.

EV charging stations usually have several charging units that allow charging 10-12 EVs at the same time. For this reason, FC-UFC charging points are directly connected to medium voltage (MV) grid. From the MV/LV transformer, these charging units can share a common LV-AC link, using independent rectifiers for each charging unit, or use a centralized rectifier, using a common DC link within the charging station.

The power delivered from the charging station to the EV is limited by the charge acceptance of the batteries of each specific EV, the nominal ratings of the charger, the connector (the maximum connector rate is defined by the standard) and the cable between the vehicle and the charger. High charging currents require larger cable diameters to avoid overheating and this issue increase the cable weight (9 kg for a 50 kW-400 V fast charger)

Energy carriers involved

- Electricity

Energy demand satisfied

- Mobility

Energy networks involved

- Power grid
- (Mobility)

Range size

Range size:

- 50 kW (CSS Type 1, 2 - CHAdeMo 1.0)
- 120 kW (Tesla Supercharger)
- 250 kW (Tesla V3 Supercharger)
- 350 kW (CSS)
- 400 kW (CHAdeMO 2.0)
- 900 kW (ChaoJi: CHAdeMo 3.0 - GB/T 2.0)

Market Maturity/costs

- TRL 9 for 1-2-3 modes
- TRL 8 for Mode 4 in the range 50 - 180 kW

Costs

- **Fast charging:** 6,000 – 60,000 €
- **Slow charging:**
  - 3 – 7 kW (public): 3,400 €
  - 11 – 22 kW (public): 4,500 €
  - 50 kW: 31,000 €
  - 150 kW: 75,000 €
  - 250 – 350 kW: 150,000 – 200,000 €

Techno-economic barriers

- Interoperability. Nowadays, it is difficult to ensure a seamless and reliable charging, particularly at European level
- Prices can be too high. To amortize the UFC installation, energy prices are too high reducing the competitiveness of EVS (in some situations, the fuel cost of ICE based vehicles is cheaper than the cost of the energy demanded by EVs at the EV charging points)
- Impact on the power grid, such as voltage imbalance and fluctuations, flicker, harmonics (current and voltage distortion), etc.
- Power quality standards for this type of FC and UFC systems still have not been developed)

Future perspectives

- Increase charging power (and battery voltage) to allow faster charging times with lower current requirements
- Additional static battery storage can be required to reduce the impact of FC on the grid (mitigating the large-pulsating load at FC) and decrease the required UFCs' grid connection capacity
- Develop local renewable generation (particularly, PV systems) to fulfil the FC and UFC energy requirements

References

S. Habib, M.M. Khan, F. Abbas, L. Sang, M.U. Shahid, H. Tang, "A Comprehensive Study of Implemented International Standards, Technical Challenges, Impacts and Prospects for Electric Vehicles," in IEEE Access, vol. 6, pp. 13866-13890, 2018, doi: 10.1109/ACCESS.2018.2812303

H. Tu, H. Feng, S. Srdic, S. Lukic, "Extreme Fast Charging of Electric Vehicles: A Technology Overview," in IEEE Transactions on Transportation Electrification, vol. 5, no. 4, pp. 861-878, Dec. 2019, doi: 10.1109/TTE.2019.2958709

Transport & Environment, "Recharge EU: how many charge points will Europe and its member states need in the 2020s", January 2020, https://www.transportenvironment.org/publications/recharge-eu-how-many-charge-points-will-eu-countries-need-2030

L. Wang, Z. Qin, T. Slangen, P. Bauer, T. van Wijk, "Grid Impact of Electric Vehicle Fast Charging Stations: Trends, Standards, Issues and Mitigation Measures - An Overview," in IEEE Open Journal of Power Electronics, vol. 2, pp. 56-74, 2021, doi: 10.1109/OJPEL.2021.3054601

M. Nicholas, "Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas", The International Council on Clean Transportation, ICCT, 2019, https://theicct.org/sites/default/files/publications/ICCT_EV_Charging_Cost_20190813.pdf

ISO 18246: Electrically propelled mopeds and motorcycles — Safety requirements for conductive connection to an external electric power supply

SAE J1772: SAE Electric Vehicle Conductive Charge Coupler

IEC 62196: Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles

IEC 61851: Electric vehicle conductive charging system

. Martínez-Lao, F.G. Montoya, M.G. Montoya, F. Manzano-Agugliaro, Electric vehicles in Spain: An overview of charging systems, Renewable and Sustainable Energy Reviews, Volume 77, 2017, Pages 970-983, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2016.11.239

Technology
Electric Planes, Electric Ferries, Hydrogen transport such as trains, vessels, and lorries

Short Description

The replacement of ICE (or thermal) powertrains by Battery Electric Vehicle (BEV) to achieve zero-emission mobility is unstoppable. But this movement is performed at different speeds. While the automotive sector is making a good progress, other sector such as road transportation, maritime and aviation are only just getting started.

For last-mile urban parcel delivery, most manufacturers have developed electrified vans, but in road transportation, based on diesel engines for long-distance freight transport, the situation is different, and it is just beginning. Different types of diesel-electric hybridization have been developed to reduce fuel consumption and emissions, but full electrified long-haul trucks are still under development. Some European manufacturers have initially focused on medium-sized, short-distance trucks (Volvo, Mercedes, Renault), with battery capacities from 180-300 kWh and with a range around 250-300 km, but other U.S. manufacturers, such as Tesla or Nikola, are developing trucks with larger battery capacity (around 750-1,000 kWh), reaching 500-800 km of range. These trucks will require a new charging infrastructure based on new mega-chargers or charging-on-the-move (using an overhead catenary, a contacted rail or a dynamic inductive charging). An alternative is H_2 and fuel cell electric trucks, although it still needs to be developed.

Most of the European railways are already electrified, but there are new developments using fuel cell technology will allow to run on both electrified and non-electrified rails. Alstom has built a first fuel cell train prototype which is currently be tested on ÖBBs (Austrian Federal Railways) regional lines).

Maritime transport generates around 940 million tonnes of CO_2 annually and it is responsible for about 2.5% of global Greenhouse gases emissions. In Europe, shipping emissions represent around 13% of the overall EU greenhouse gas emissions from the transport sector.
The first step to decarbonize the sector is to increase energy efficiency through more efficient designs, increasing propulsion efficiency, installing wind assisting devices or reducing the traveling speed. Other efficiency measure is to supply demanded energy for the auxiliary loads from the electric grid (known as shore-side electricity), when the vessels are moored in ports, avoiding fossil-fuels based on-board power generation. With this actions, Greenhouse gases emissions and noise are reduced in harbour area. Depending on the size of the ship, the required electric demand that must be covered by the electric grid is very high and, and for this reason, not all ports have this

shore-side electricity installations, making it less attractive for the ship owner to invest in retrofitting their ships to be shore-side electricity compatible. In addition, depending on the country where the port is located, the price of energy purchased directly from the grid may be more expensive than burning heavy fuel on board to generate electricity at berth, therefore it is necessary to develop policies to promote shore-side electricity infrastructure in European harbours.

The second step is to electrify the propulsion systems using hybrid and all electric solutions. Today, 80% of oceangoing ships are hybrids with a fuel-electric transmission system. A diesel generator produces electricity on-board which drives the electric motors for propulsion, but due to low-energy density and high cost of electrical batteries, the use of full electric drive is still limited to vessels operating in coastal areas or in a shuttle-type of activity. These ferries are recharged only when they are docked, while loading/unloading, requiring fast charging points and a dedicated infrastructure.

In Norway there are 130 active ferry routes, transporting passenger and cargo vehicles across fjords with the shortest connection around 200 m and longest about 109 km.

Figure 12 – Example of electric ferry

The first full-scale ferry "Ampere" started regular operation in 2015, covering 5 km distance and transporting 120 cars on-board. The ferry uses lithium-ion batteries: one is installed on-board (500 kWh) and one battery (350 kWh) at each pier serving as buffers. The buffers were necessary due to fairly limited grid capacity and reduce load for the grid from 1.2 MW to 0.2 MW during 10 min charging. The ferry has two main propulsion electric motors, 450 kW each. It is estimated that annual consumption is about two million kWh of electricity, saving about million litres of diesel fuel and 570 tons of CO_2.

Operation of the first ferry proved to be successful, and by the end of 2020 it was already 30 ferries in regular service and this figure is expected to be doubled during 2021.

There are three types of charging infrastructure:

1. Wired charging systems, with alternate current charging systems, which are constrained to small ships such as fishing and leisure boats, with an on-board charger, while direct current charging systems are used in bigger vessels which require fast charging, with off board chargers (without limitations in size, weight, and power)

2. Wireless charging systems, which avoid using cables and plugs (and additional maintenance due to corrosive sea ambient), but they have lower efficiency and are very sensitive to distance and misalignment
3. Battery-swapping systems, that allow to recharge batteries at off-peak periods reducing the impact on the electric grid. The main drawback is the time required to swap the batteries and the additional cost of doubling the additional battery packs

Even though batteries are still not efficient enough and are too heavy for the full electrification of large transoceanic cargo ships, several manufacturers are developing full electric cargo ships. In 2017, China developed the first 2,000-metric-ton fully electric container ship to transport coal to generating stations along the Pearl River. The 70.5 m ship has 2,400 kWh Li-ion batteries and can travel at 12.8 kilometres per hour, with zero emission. Other manufacturers are developing similar vessels for on inland waterways in Norway and Netherland.

Hydrogen (H_2) is another option to decarbonize the maritime sector. H_2 can be used in several ways to power ships:

- It can be used in retrofitted ICE, but inevitably this combustion with air produces NOx that can be post-treated.
- Burning H_2 with oxygen (stored in a pressurized tank) in a turbine. This turbine drives an electric generator, producing electricity to be used in the propeller electric motors. This scheme has been previously tested in trains and it does not produce pollutant emissions.
- Fuel cells, which chemically converts H_2 into electricity, heat and water.

The main drawbacks of hydrogen are cost (green hydrogen generated using renewable energy is still very expensive, around 4-8 times the price of very low sulphur fuel oil), it is highly flammable, its storage is complicated because it requires temperatures below -250°C and it takes 8 times more space than marine fuel oil. A solution is to produce other renewable fuels from green hydrogen, such as ammonia, methanol and other synthetic hydrocarbons. Ammonia (NH_3) is easier to store, and it is denser than H_2, taking up around half of space to store. It can be converted back to hydrogen on board, allowing to use this H_2 in fuel-cells. In a similar way, LOHC (liquid organic hydrogen carriers) can be saturated with renewable hydrogen, and the H_2 extracted when needed for the end application. But the main limitation of H_2 (and other synthetic fuels produced from it) is the overall energy efficiency (lower than 25 %, due to the different energy conversion steps required).

Finally, solar powered propulsion systems have been used in recreational boats and as a proof of concept. In 2012, "Tûranor PlanetSolar" was the first solar-powered boat to sail around the world in a 585 day's journey.

Aviation has doubled its emissions in Europe since 1990 and, due to the estimated growth in passengers and flights in the following years, it is expected to increase the fuel demand in the following years. Different regulating policies such as increasing carbon prices, introducing different types of taxation (such as fuel taxation for kerosene, taxation per flights, etc.) can help to reduce the fuel demand, decreasing global aviation CO_2 emissions. Other complementary policies are being currently introduced in Europe such as Norwegian objective to operate all domestic flights up to 90 minutes with electric aircrafts by 2040 or French proposal to suspend all domestic flights on routes that can be covered by direct train in less than two and a half hours. As in the maritime case, the first step in aviation decarbonisation starts with improving energy efficiency, improving the airplane design and by operational improvements taken by airlines and airports in their day-

to-day operations (reducing the weight of on board equipment, selecting the most efficient fuel routes or electrifying the ground phase of the flight (i.e., taxiing), allowing a significant reduction of pollutant emissions and noise in the airports. All electric planes, where the battery is the main energy storage will be limited to commuter segment (19 PAX, 500 km), but for higher flight ranges, hybrid-electric systems will be an intermediate solution. In this case, gas turbine engines are used for propulsion, power generation and for charging batteries, and batteries will be used as energy buffers providing energy during different phases of flight.
Hydrogen can be used in several ways: for regional aircrafts (20-80 PAX, < 2000 km) fuel cell and battery hybrid powered planes are a feasible solution. For longer range aircrafts, such as short-range (81-165PAX, < 4500 km), fuel cells are combined with modified gas turbines which burn hydrogen. In this configuration, fuel cell is the main power source during cruise mode and hydrogen turbine is designed to deliver the required thrust during take-off and climbing modes.

Hydrogen Combustion Propulsion (HCP) is feasible for medium-range aircrafts (166-250PAX, < 10,000 km). In this case, the propulsion is generated from the direct combustion of hydrogen fuel to create thrust and fuel cell is only used to feed auxiliary loads.

For the long-range segment aircrafts (>250PAX, < 18,000 km), the current solution is to develop Sustainable Aviation Fuels (SAFs), with a chemistry very similar to traditional fossil jet fuels. The main barrier is not technical, but economic, SAFs are not yet produced at competitive cost compared to conventional fuels.

Solar powered airplanes have been also developed for small single-seated aircrafts. In 2016, Solar Impulse 2 travelled 25,000 around the world.

Energy carriers involved

- Electricity
- Hydrogen

Energy demand satisfied

- Mobility

Energy networks involved

- Distribution network and local batteries as buffers

Range size

- Propulsion motors: 450 x 2 kW and higher
- On-board batteries: 500 kWh

Market Maturity/costs

TRL 8-9

Costs

- Compatible with conventional ferries (from 100 to 3,000 k€ with a maximum capacity of 15 and 150 persons, respectively)

Techno-economic barriers

- Limited capacity in local distribution grids require additional onshore batteries acting as buffers
- Green hydrogen cost
- Hydrogen storage (requires cryogenic temperatures and space)

Future perspectives

- 30 ferries are already in commercial operation and about 60 are expected by the end of 2021. It is possible to electrify 50 of the existing 130 ferry lines in Norway

References

M. Istad, H. Sæle, S. Garnås, M. G. Jaatun, "Flexibel nettdrift: Resultater fra FlexNet-prosjektet," SINTEF Energi AS, Trondheim, 2018

H. Sæle, M. Istad, S. Garnås, "The benefit of batteries in a flexible distribution grid: Results from FlexNett project," SINTEF Energi AS, Trondheim, 2018

S. Karimi, M. Zadeh, J.A. Suul, "Shore Charging for Plug-In Battery-Powered Ships: Power System Architecture, infrastructure, and Control," in IEEE Electrification Magazine, vol. 8, no. 3, pp. 47-61, Sept. 2020, doi: 10.1109/MELE.2020.3005699

H. Xing, C. Stuart, S. Spence, H. Chen. “Fuel Cell Power Systems for Maritime Applications: Progress and Perspectives”. Sustainability 2021, 13, 1213. https://doi.org/10.3390/su13031213

J. Felez, C. GarcíA-Sanchez, J. A. Lozano, "Control Design for an Articulated Truck With Autonomous Driving in an Electrified Highway," in IEEE Access, vol. 6, pp. 60171-60186, 2018, doi: 10.1109/ACCESS.2018.2875904

International Transport Forum, (2020), “Navigating Towards Cleaner Maritime Shipping: Lessons from the Nordic Region”, International Transport Forum Policy Papers, No. 80, OECD Publishing, Paris

H. Xing, C. Stuart, S. Spence, H. Chen. Fuel Cell Power Systems for Maritime Applications: Progress and Perspectives. Sustainability 2021, 13, 1213. https://doi.org/10.3390/su13031213

Transport& Environment, “Roadmap to decarbonising European Aviation” (2018)

J.K. Noland, "Hydrogen Electric Airplanes: A Disruptive Technological Path to Clean Up the Aviation Sector," in IEEE Electrification Magazine, vol. 9, no. 1, pp. 92-102, March 2021, doi: 10.1109/MELE.2020.3047173

M. Lukic et al., "State of the Art of Electric Taxiing Systems," 2018 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC), Nottingham, UK, 2018, pp. 1-6, doi: 10.1109/ESARS-ITEC.2018.8607786

IATA, “Aircraft Technology Roadmap to 2050” https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/technology20roadmap20to20205020no20foreword.pdf

Technology

Desalination

Short Description

The desalination process removes salts from water to make it ultrapure or drinkable. Different water qualities are obtained through membrane or thermal technologies and the plants are designed according to the sector in which the desalination process is involved, like industrial or municipal wastewater, seawater, brackish groundwater, surface water or potable water. Main solutions include:

- **Membrane processes:**

Reverse Osmosis (RO): it consists of reversing the flow of osmosis using a hydraulic pressure higher than the osmotic one related to a solution: the water moves from high solute region to a low-solute one through a semi-permeable non-porous membrane (no phase changes occur)

- **Thermal processes:**

Multi Effect Distillation (MED): it consists of cells, called effects, at decreasing pressure and temperature from first to last (from 90 to 65°C): the lower pressure in each stage allows the water to evaporate at low temperatures as the boiling point of water decreases with pressure
Multi-Stage Flash (MSF): flash evaporation of part of the feed as it moves through multiple stages that have sequentially higher temperatures and a pressure, in each stage, lower than the vapor one; evaporation and crystallization technology, where a heat source for evaporation is required

Energy carriers involved

- Electricity
- Fuels (e.g., natural gas, gasoline, diesel and biofuels)
- Hot water
- Natural gas
- Renewables (geothermal, ocean energy, solar, wind)

Energy demand satisfied

NONE – Desalination technologies connect electric and “thermal” networks to water supply network which is a non-energy network. Desalination technologies satisfy demand of water (both drinkable or not)

Energy networks involved

- District Heating Network
- Natural gas pipeline
- Power grid
- Standalone (e.g., hydro, PV panels, solar thermal, wind)

Range size
Water production: From 20 m^3/day to 500,000 m^3/day **Energy consumption:** • **Membrane processes:** Reverse Osmosis (RO): 1-15 kWh/m^3 per day • **Thermal processes:** Multi Effect Distillation (MED): 14-22 kWh/m^3 per day Multi-Stage Flash (MSF): 18-29 kWh/m^3 per day
Market Maturity/costs
• **Membrane processes:** **Reverse Osmosis (RO):** TRL 9 • **Thermal processes:** **Multi Effect Distillation (MED):** TRL 9 **Multi-Stage Flash (MSF):** TRL 9
Costs
• **Membrane processes:** **Reverse Osmosis (RO):** CAPEX of 800-2300 €/m^3 per day; OPEX of 0.30-0.90 €/m^3, cost of water production between 0.75-2 €/m^3 • **Thermal processes:** **Multi Effect Distillation (MED):** CAPEX of 1200-2300 €/m^3 per day, OPEX of 0.13-0.30 €/m^3, cost of water production between 1.35-1.83 €/m^3 **Multi-Stage Flash (MSF):** CAPEX of 1700-3100 €/m^3 per day, OPEX of 0.25-0.37 €/m^3, cost of water production between 1.24-2.12 €/m^3
Techno-economic barriers
• Brackish or seawater must be easily accessible • Both CAPEX and OPEX affect the environment deeply • Considerable initial cost, as well as energy and its price to be produced • Cost of water provisioning will increase year by year (water is not infinite) • Fuel availability • Noticeable know-how is mandatory • Wastewater reuse is applied only to the agricultural sector • Working conditions of desalination plants

Future perspectives

- Coupling PV panels with membrane processes, and solar thermal with thermal processes as well; up to now, the specific plant cost (euro/m^3 per day) and water production costs are too high
- Decreasing CAPEX, OPEX and water costs in those zones with no access to electricity
- Lowering scale effect sensitivity

References

F.E. Ahmed, R. Hashaikeh, N. Hilal, Hybrid technologies: The future of energy efficient desalination – A review, Vol. 495, Desalination, 2020, Article 114659

H. Nassrullah, S.F. Anis, R. Hashaikeh, N. Hilal, Energy for desalination: A state-of-the-art revie, Desalination, Vol. 491, Year 2020, Article 114569

K. Elsaid, M. Kamil, E.T. Sayed, M.A. Abdelkareem, T. Wilberforce, A. Olabi, Environmental impact of desalination technologies: A review

E.J. Okampo, N. Nwulu, Optimisation of renewable energy powered reverse osmosis desalination systems: A state-of-the-art review, Renewable and Sustainable Energy Reviews, Vol. 140, Year 2021, Article 110712

Almar water solutions, Center of Mediterranean Integration, Desalination Technologies and Economic: CAPEX, OPEX & Technological Game Changers to Come, Mediterranean Regional Technical Meeting, Marseille CMI, December 12-14, 2016

Water Global Practice – Technical paper, The Role of Desalination in an Increasingly Water-Scarce World, World Bank Group, March 2019

2.4 Energy hub infrastructure

Technology/Infrastructure
Natural gas network as H_2 storage
Short Description
The energy-related use of H_2 in the upcoming years will be an important aspect with which several countries worldwide will deal with as a potential technology for decarbonization. It can be used in multiple applications such as in stationary/mobility fuel cell systems, integrated in many industrial sectors; used as fuel substitute in the heat sector; used as long-term bulk energy storage media, etc. In such a context, blending hydrogen into the existing natural gas pipeline network has been proposed as a means of increasing the penetration of renewable energy systems; indeed, if implemented with relatively low concentrations (5-15 % of hydrogen by volume) this strategy of storing and delivering renewable energy to the gas sector appears to be viable and without safety and reliability issues of end-use technologies as well as assuring the durability and integrity of the existing natural gas pipeline network. Also, being extremely rich in energy on a mass basis, the re-separation of pure H_2 is of interest, which can be extracted from the natural gas blend, using downstream separation and purification technologies, close to the point of end use
Technologies involved
• **CHP technologies (previously described in the respective sections at both micro energy hub and energy hub levels):** 1. Combined Cycle (CC) 2. Gas Turbine (GT) 3. Internal Combustion Engine (ICE) 4. Micro Gas Turbine (MGT) 5. Steam Turbine (ST) 6. Fuel Cells (FC) • **Natural gas fired boilers** • **Natural gas fed mobility (ICE) for dual fuel (NG/H_2)** • **HST to separate H_2 & CH_4 at final users:** It is worth of notice that the hydrogen separation techniques are same adopted in the Carbon Capture (CC), therefore the tech-economic development in the CCS provide advantage also in the hydrogen separation process. 1. Pressure Swing Adsorption (PSA): the separation is based on absorbent material which is used to absorb the non-hydrogen component at elevated pressure. It is the most mature HST, however it's highly energy intensive (20kWh/kgH_2 from 10% hydrogen blended mixture) and expensive, especially when the Hydrogen content is low. A significant cost impact is regarding the need of two compressors, one for reach the absorption pressure for the process and the second one for the reinjection of natural gas back into the grid.

2. Temperature Swing Absorption (TSA): is a cycle composed of four working processes i.e., adsorption, preheating, desorption and precooling. It has similar characteristics and maturity of the PSA tech.
3. Electrochemical Hydrogen separation (EHS) or hydrogen pumping, being used mainly with PEM electrolyzers: it consists of two electrodes, i.e., the anode and the cathode, the feed enters the unit at the anode, where the hydrogen is split into protons. As the transport of protons through the PEM is significantly faster than the diffusive transport, purified hydrogen can be withdrawn at the cathode. Two technologies are currently used: a Nafion-based membrane system and a polybenzimidazole (PBI) system. This technology is an improvement of TSA and is less energy-intensive, but the separated hydrogen may have a lower purity.
4. Amine-based separation: it is a very mature and commercialized tech, which uses an aqueous amine solution to capture the hydrogen, but it has several disadvantages as the solution is corrosive and harmful and there's significant loss of the amine solution due to volatility and degradation issues.
5. Cryogenic distillation process: it is a low-temperature separation process which uses the difference in boiling temperatures of the feed components to affect the separation. This technology has the advantage to be deployed in large scale but is requires high investment in equipment cost.
6. Membrane separation technologies: because of their physical properties, the membrane are barriers which allows only selected materials to across them; based on the material, they can be divided in four types: polymer, metallic, carbon and ceramic membranes, where the polymer one is also called organic membranes and the rest inorganic ones. They are gaining more and more interest because they are energy-efficient, lightweight and require lower investment than other technologies, especially palladium-based membranes that grant a high purity hydrogen, however currently they are not ready at the industrial level

Energy carriers involved

- Natural gas
- Hydrogen
- Heat

Energy networks which could be involved

- Natural gas pipeline
- Power grid

Maturity

- Up to 15% blending, TRL 5-6
- Higher than15 % blending, TRL 5

Level of deployment

- Poor

Costs

- CHP technologies: previously described in the respective sections at both micro energy hub and energy hub levels

- Hydrogen separation technologies:
    - PSA: 3.3-8.3 euro/kgH_2
- Site preparation: 5 euro/kWgas (Hydeploy project)

Potential barriers

So far, H_2-CH_4 blending could achieve concentrations up to 20% in order to not have a bad impact on end-use systems. In particular, the following aspects must be addressed when dealing with H_2-CH_4 blending:

- The H_2 compatibility with material must be verified, estimating the lifetime of materials (e.g., steel and polyethylene) when blends are used and possible leakages (H_2 is more mobile than CH_4 in many polymer materials, including plastic pipes and elastomeric seals involved in natural gas networks)
- Life-cycle analysis, in terms of emission and usage of synthetic gas with respect to natural gas, together with a proper techno-economic analysis
- Safety and reliability are two important key points, since H_2 has the potential for increased probability of ignition and, furthermore, end-use technologies must be able to deal with H_2-CH_4 mixtures
- Downstream extraction of H_2 from mixtures in natural gas pipelines could be needed

References

M.W. Melaina, O. Antonia, M. Penev, Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues, National Renewable Energy Laboratory, Technical Report NREL/TP-5600-51995, Year 2013, Pages 131

J. Jaworski, P. Kulaga, T. Blacharski, Study of the Effect of Addition of Hydrogen to Natural Gas on Diaphragm Gas Meters, Energies, 2020, 13, Article 3006

M. Pellegrini, A. Guzzini, C. Saccani, A Preliminary Assessment of the Potential of Low Percentage Green Hydrogen Blending in the Italian Natural Gas Network, Energies, 13, Article 5570

NRA Survey on Hydrogen, Biomethane, and related Network Adaptations - Evaluation of Responses Report, ACER (Agency for the Cooperation of Energy Regulators), 2020, Pages 59

Technical and economic conditions for injecting hydrogen into natural gas networks, Final report 2019, Pages 45

M. Jentsch, T. Trost, M. Sterner, Optimal Use of Power-to-Gas Energy Storage Systems in an 85% Renewable Energy Scenario, Energy Procedia, 2014, 46, Pages 254-261

S. Adhikari, S. Fernando. Hydrogen membrane separation techniques. Ind Eng Chem Res 2006; 45:875 81 https://doi.org/10.1021/ie050644l

N.W. Ockwig, T.M. Nenoff. Membranes for hydrogen separation. Chem Rev 2007; 107:4078–110

https://doi.org/10.1021/cr0501792

M. Nordio, S.A. Wassie, M. Van Sint Annaland, D.A. Pacheco Tanaka, J.L. Viviente Sole, F. Gallucci, Techno-economic evaluation on a hybrid technology for low hydrogen concentration separation and purification from natural gas grid. Int J Hydrogen Energy 2020. https://doi.org/10.1016/j.ijhydene.2020.05.009

M. Shahbaz, T. Al-Ansari, M. Aslam, Z. Khan, A. Inayat, M. Athar, et al. A state of the art review on biomass processing and conversion technologies to produce hydrogen and its recovery via membrane separation. Int J Hydrogen Energy 2020;45:15166–95. https://doi.org/10.1016/j.ijhydene.2020.04.009

L. Jiang, R.Q. Wang, A. Gonzalez-Diaz, A. Smallbone, R.O. Lamidi, A.P. Roskilly. Comparative analysis on temperature swing adsorption cycle for carbon capture by using internal heat/mass recovery. Appl Therm Eng 2020;169:114973. https://doi.org/10.1016/j.applthermaleng.2020.114973

B. Ohs, L. Abduly, M. Krödel, M. Wessling. Combining electrochemical hydrogen separation and temperature vacuum swing adsorption for the separation of N2, H2 and CO2. Int J Hydrogen Energy 2020;45:9811–20. https://doi.org/10.1016/j.ijhydene.2020.01.218

C.J. Quarton, S. Samsatli. Should we inject hydrogen into gas grids? Practicalities and whole-system value chain optimisation. Appl Energy 2020;275:115172. https://doi.org/10.1016/j.apenergy.2020.115172

Technology/Infrastructure

Electric vehicle Infrastructure

Short Description

The use of electricity in the future will be a crucial point to lower the emissions into the atmosphere, mainly due to its production through renewables or other low-carbon fuels. In such a context, a new electric infrastructure should be thought with the aim of receiving a greater number of end-users that will not be classified only by sectors (e.g., residential, industrial, etc.), but also by mobility.

For instance, recent studies are focused on the research of Autonomous Vehicles (AV) capable of interacting one to each other, thus incentivizing the use of public means of transports or the so-called Shared Autonomous Mobility (SAM). On the other hand, if people have their personal car, they will anyhow assist their owner in the daily routines completely.

Up to now, it is very important to determine whether potential transportation improvements can be done and how to act because road pricing, zoning, licensing and insurance must be considered in this phase; nevertheless, keeping the infrastructure assets in good repair is a fundamental aspect to keep in mind.

Vehicular communication technologies strive to give communication models that can be employed by vehicles in different application contexts such as Energy communities. Vehicular communication technologies strive to give communication models that can be employed by vehicles in different application contexts.

Furthermore, sensors capable of sending signals to AVs and helping them to navigate city streets, knowing as Vehicle-to-Infrastructure (V2I) are mandatory and different technologies/systems such as Dedicated Short-Range Communications (DSRC) and Cellular Vehicle-to-Everything (C-V2X) are being currently studied.

Cellular-V2X (C-V2X) as initially defined as LTE V2X in 3GPP Release 14 is designed to operate in several modes. It provides one solution for integrated V2V, V2I and V2P operation with V2N by leveraging existing cellular network infrastructure:

- Device-to-device is Vehicle-to-Vehicle (V2V), Vehicle-to-(Roadway) Infrastructure (V2I) and Vehicle-to-Pedestrian (V2P) direct communication without necessarily relying on network involvement for scheduling
- Device-to-cell tower is another communication link which enables network resources and scheduling and utilizes existing operator infrastructure. Device-to-cell tower communications constitute at least part of the V2I proposition and are important to end-to-end solutions
- Device-to-network is the V2N solution using traditional cellular links to enable cloud services to be part and parcel of the end-to-end solution

Collectively, the transmission modes of shorter-range direct communications (V2V, V2I, V2P) and longer-range network-based communications (V2N) comprise what it is called Cellular-V2X.
The interaction between the various involved entities requires the information exchange to use proper communication protocols, such as the IEEE 802.11p and LTE-V2V standards, designed to support vehicle transmissions

Technologies involved

- Vehicle-to-Infrastructure (V2I)
- Short-Range Communications (DSRC)
- Cellular Vehicle-to-Everything (C-V2X)
- Shared Autonomous Mobility (SAM)

Energy carriers involved

- Electricity

Energy networks which could be involved

- Electricity
- Mobility

Maturity

Electric infrastructure for EVs: TRL 8-9
V2G: TRL 7-8

Level of deployment
High
Potential barriers
• Curb modifications • Long-term planning • Mobility hubs • Need of large support facilities • Need of staging area to avoid congestions
References
T. Duvall, E. Hannon, J. Katseff, B. Safran, T. Wallace, A new look at autonomous-vehicle infrastructure, Capital Projects & Infrastructure Practice, McKinsey & Company, 2019, Pages 6 H. Engel, R. Hensley, S. Knupfer, S. Sahdev, Charging ahead: electric-vehicle infrastructure demand, McKinsey center for future mobility, McKinsey & Company, 2018, Pages 8 S. Micari, A. Polimeni, G. Napoli, L. Andaloro, V. Antonucci, Electric vehicle charging infrastructure planning in a road network, Renewable and Sustainable Energy Reviews, Vol. 80, Year 2017, Pages 98-108 P. Morrisey, P. Weldon, M. O'Mahony, Future standard and fast charging infrastructure planning: An analysis of electric vehicle charging behaviour, Energy Policy, Vol. 89, Year 2016, Pages 257-270 3GPP TR 22.885 Study on LTE Support for Vehicle to Everything (V2X) Services C. Han, M. Dianati, R. Tafazolli, R. Kernchen, X. Shen. Analytical Study of the IEEE 802.11p MAC Sublayer in Vehicular Networks. IEEE Trans. Intell. Transp. Syst. 2012, 13, 873-886. A. Bazzi, C. Campolo, B.M. Masini, A. Molinaro, A. Zanella, A.O. Berthet. Enhancing Cooperative Driving in IEEE 802.11 Vehicular Networks Through Full-Duplex Radios. IEEE Trans. Wirel. Commun. 2018, 17, 2402–2416 R. Molina-Masegosa, J. Gozalvez. LTE-V for Sidelink 5G V2X Vehicular Communications: A New 5G Technology for Short-Range Vehicle-to-Everything Communications. IEEE Veh. Technol. Mag. 2017, 12, 30-39 A. Bazzi, G. Cecchini, A. Zanella, B.M. Masini. Study of the Impact of PHY and MAC Parameters in 3GPP C-V2V Mode 4. IEEE Access 2018, 6, 71685–71698 S. Park, B. Kim, H. Yoon, S. Choi. RA-eV2V: Relaying systems for LTE-V2V communications. J. Commun. Netw. 2018, 20, 396–405 A. Bazzi, B.M. Masini, A. Zanella, I. Thibault. On the Performance of IEEE 802.11p and LTE-V2V for the Cooperative Awareness of Connected Vehicles. IEEE Trans. Veh. Technol. 2017, 66, 10419–10432

3 Planning and managing tools for LEC

3.1 Introduction

Local energy planning is a research topic that has been investigated since several years, mainly addressing local scale policies to meet environmental goals. At the beginning, local energy planners and research institutions carried out studies and projections by adjusting planning tools initially thought to investigate national energy policies and contexts.
Progressively, a high number of tools has been developed to specifically address local energy planning of distributed energy resources in well identified areas such as districts, cities, energy islands (both geographical and not).
Chang et al. reviewed 54 energy systems modelling tools for planning energy transition. When modelling LEC, the main constraint is to have a comprehensive overview of the interactions and synergies among distributed energy resources and different energy carriers and networks. In the last few years, the rising penetration of non-programmable renewable energy production increased the needs of flexibility both in supply and demand side of the energy systems. This entailed the growing interest in technologies enabling flexibility strategies such as storages or the connecting technologies already discussed in Section 2. Klemm et al. reviewed 145 modelling tools finding that only 13 were suitable to be used in planning LEC. According to this work, the main features of a planning tool should: i) implement optimization algorithms; ii) address multi-energy districts; iii) operate with an at least hourly temporal resolution. Moreover, iv) follow a bottom-up or hybrid analytical approach. Several planning tools could be also used to optimize the operation of energy systems.

The main goal of the eNeuron project is to develop innovative tools for the optimal design and operation of LECs, integrating distributed energy resources and multiple energy carriers at different scales. This section presents a critical review of the existing planning tools developed both for commercial or for research purposes. The last part of the section provides some outcomes and suggestions for the further development of the eNeuron planning tool.

References

G. Comodi, L. Cioccolanti, M. Gargiulo. Municipal scale scenario: Analysis of an Italian seaside town with MarkAL-TIMES. Energy Policy 41, 303-315

G. Comodi, L. Cioccolanti, F. Polonara, C. Brandoni. Local authorities in the context of energy and climate policy. Energy policy 51, 737-748

Open energy modelling framework. Enhancing energy system modelling. **https://oemof.org/**

M. Chang, et al. Trends in tools and approaches for modelling the energy transition. Appl. Energy 290, (2021)

C. Klemm, P. Vennemann, Modeling and optimization of multi-energy systems in mixed-use districts: A review of existing methods and approaches. Renew. Sustain. Energy Rev. 135, 110206 (2021)

3.2 Planning tools investigated

Tool
EnergyPlan

Short Description
EnergyPlan is a free software which simulates the operation of national energy systems on an hourly basis, including the electricity, heating, cooling, industry, and transport sectors. It is developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University, Denmark
Type
Free
Geographical distribution of the tool
Worldwide
Type of users
Academic researchers
Existing community /community driven
No
Originally designed/thought for LEC or adapted from national planning tool
National planning
Network modelled and energy carriers
• Electricity • Heating • Cooling • Transport
Demand modelled
• Electricity • Heat • Cooling • Transport
Possibility to customize
No possibility to customize the involved energy carriers
Objective functions:
• Financial • Environmental
Functionalities
Design of energy systems size
Scale and approach
Scale modelled: local to continental Approach: bottom-up

Mathematical approach
Linear programming
Temporal resolution
Hourly
Time horizon
Years
Modularity
No
User-friendly interface/ GUI
Yes
Pro and cons in application to LEC
EnergyPlan is a user-friendly software that allows the planning of energy systems. It is not an optimization tool. It is already widely used among academic researchers; however, it does not permit to customize the energy carriers involved. It is originally designed for national scale planning instead of local energy community therefore some details of local scale could be omitted.
Reference/Website
EnergyPLAN | Advanced energy systems analysis computer model

Tool
DER-CAM
Short Description
Distributed Energy Resources-Consumer Adoption Model (DER-CAM) is a mixed-integer optimization tool for investment and planning decision support in micro-grids, which is written and executed in the General Algebraic Modeling System (GAMS). It is continuously being developed and maintained by Lawrence Berkeley National Laboratory, since 2000. Recently, a web-based version of DER-CAM, called DERs Web Optimization Service (WebOpt), as well as DER-CAM+, have been made also available. User's input includes: • Hourly end-use load profiles for a typical year (electric, cooling, refrigeration, space heating, hot water, and natural gas loads) • Electricity tariff, natural gas prices, and other relevant price data • Capital, operating and maintenance (O&M), and fuel costs of various available technologies, together with the interest rate on customer investment • Basic physical characteristics of alternative generating, heat recovery and cooling technologies, including the thermal-electric ratio that determines how much residual heat is available as a function of generator electric output • Information on the site's topology and distributed heating infrastructure (only for multi-node models)

The DER-CAM outputs include:

- Optimal selection and capacity of DER to be installed
- Optimal placement of DER inside the microgrid (for multi-node models)
- When and how the available DER should be dispatched (both to maximize economic performance and meet resiliency and reliability targets)
- Detailed cost breakdown of supplying end-use loads
- Detailed breakdown of carbon emissions associated with supplying end-use loads
- DER-CAM is being widely used for problems related to optimal investment and scheduling of DER as well as for economic and environmental analysis of DER in the context of local energy systems

Type

Open and free

Geographical distribution of the tool

Local (buildings and multi-energy microgrids). Districts can only be modelled if they are assessed as microgrids

Type of users

Academic researchers and local energy planners

Existing community /community driven

Community-driven

Originally designed/thought for LEC or adapted from national planning tool

Originally designed for local energy systems

Network modelled and energy carriers

- Electricity
- Heating
- Cooling
- Fossil fuels

Demand modelled

Any (aggregated)

Possibility to customize

Possible to modify objective function

Objective functions:

Financial and environmental: although the objective function of DER-CAM can be easily modified - or even replaced by a multi-objective analysis - it is mainly financial defined as a site's total annual cost of energy supply. This includes costs associated with both new and existing DER, operation and maintenance costs, fuel costs, and all costs related to utility imports either fixed, time-dependent, energy-based, or power-based. Additionally, all value streams associated with the optimal DER dispatch determined by DER-CAM are considered in the objective function, both in the form of avoided costs and market participation

Functionalities
Design and scheduling
Scale and approach
Scale modelled: Local Approach: Bottom-up
Mathematical approach
Mixed Linear Integer Programming
Temporal resolution
Temporal resolution of a year, but reference days with minute-level resolution may be defined
Time horizon
Max 20 years
Modularity
Yes
User-friendly interface/ GUI
Yes
Pro and cons in application to LEC
The approach used in DER-CAM is fully technology-neutral and can include energy purchases, on-site conversion, both electrical and thermal on-site renewable harvesting, and partly end-use efficiency investments. It allows to find the best combination of equipment and its operation over a typical year (average over many historical years) that minimizes the site's total energy bill or CO_2 emissions, typically for electricity plus natural gas purchases, as well as amortized equipment purchases. Another key output is hourly operating schedule, as well as the resulting costs, fuel consumption, and CO_2 emissions. Given its optimization nature and technology-neutral approach, DER-CAM can capture both direct and indirect benefits of dealing with multi-energy systems. Moreover, a wide range of generation, conversion and storage technologies is included in the database. Another pro to be considered is that it is user-friendly and free to access. Regarding drawbacks to overcome in eNeuron tool, they are listed below: • It does not allow to deal with the optimal design of DH networks • Although it allows to make environmental assessments, it does not rely on multi-objective approach in the optimization problem • In a multi-node configuration, the optimal design approach is centralized, and not distributed • It does not allow to simulate peer-to-peer energy transactions • It does not consider uncertainties related to renewable energy output • It is no possible for the user to include new custom components • Energy market interaction is not addressed
Reference/Website
DER-CAM | Grid Integration Group (lbl.gov)

Tool
HOMER
Short Description
HOMER (Hybrid Optimization of Multiple Electric Renewables) can simulate and optimize stand-alone and grid-connected local energy systems comprising of wind turbines, solar PV, hydro, biomass, conventional generators as well as energy storage. For the optimal design problem, it allows to identify what components are required to be included in the system as well as the number and size of each component, according to the objective function selected. Power sources that can be modelled include solar photovoltaics , wind turbines, hydro power, diesel, gasoline, biogas, alternative, co-fired and custom-fuelled generators, electric utility grids, microturbines, and fuel cells. Storage options include battery banks and hydrogen. HOMER can be defined as a community-scale tool, originally developed to support design of off-grid community scale electrical energy systems but expanded to model grid-connected and thermal systems. In HOMER, investment and operation costs as well as techno-economic and emission constraints are considered for the optimal sizing of hybrid renewable energy systems and community micro-grid. HOMER has been originally developed by National Renewable Energy Laboratories (NREL) in 1992 and further enhanced by HOMER energy. User inputs include load curve (electrical, thermal) up to 1 min resolution, technology efficiencies and features, O&M costs, emission constraints and sensitivity parameters. The software output includes optimization and sensitivity analysis of the system involving energy production, fuel consumption, emissions and costs with graphs and detailed data report
Type
Commercial
Geographical distribution of the tool
Local
Type of users
Academic researchers and local energy planners
Existing community /community driven
Community-driven
Originally designed/thought for LEC or adapted from national planning tool
Originally designed for local energy systems
Network modelled and energy carriers
Microgrids and distributed power systems that can include a combination of renewable power sources, storage, and fossil-based generation (either through a local generator or a power grid). The focus is on electrical energy carrier
Demand modelled

Electrical and thermal
Possibility to customize
Possibility to add custom components
Objective functions:
Mainly financial
Functionalities
Design
Scale and approach
Scale modelled: local Approach: bottom-up
Mathematical approach
Proprietary optimization algorithm
Temporal resolution
Minute
Time horizon
Several years
Modularity
Modular architecture, including customized modules
User-friendly interface/ GUI
Yes
Pro and cons in application to LEC
One of the main pros related to HOMER is that it is user-friendly and does not need users' specific engineering skills. Moreover, it is based on a modular architecture, giving the possibility to include customized modules. It can also count on a supply profile generator, generating the supply profile from the resource input (e.g., climate) and the device specifications. The drawbacks to overcome with eNeuron tool are listed below: • It does not rely on a wide range of heat and cooling technologies, since the focus is on electrical sector • It does not allow to analyze DH networks configurations • It allows mainly to do optimization studies from the financial point of view, and it does not rely on multi-objective approach considering environmental objectives in the optimization problem • In a multi-node configuration, the optimal design approach is centralized, and not distributed • It does not allow to simulate peer-to-peer energy transactions • It does not consider cooling loads

• The user must pre-define the possible technologies and their sizes/capacities and then HOMER sorts these combinations according to their results. Therefore, only user predefined combinations of technologies can be considered in the financial analysis • Energy market interaction is not addressed
Reference/Website
HOMER - Hybrid Renewable and Distributed Generation System Design Software (homerenergy.com)

Tool
Calliope
Short Description
Calliope is open and highly community driven framework to build energy system models, designed to analyse systems with arbitrarily high spatial and temporal resolution, with a scale-agnostic mathematical formulation permitting analyses ranging from single urban districts to countries and continents. The basic process of modelling with Calliope is based on three steps: • Building a model • Running a model • Analysing a model It provides both a command-line interface and an API for programmatic use, to be useful both for users experienced with Python and those with no Python knowledge. The Calliope model is made of *.yaml* and *.csv* files where the first ones describe the technologies, locations and constraints while the latter ones are input demand data, once created the model Calliope pass the model through Pyomo for constructing the optimization problem, a back-end interface which can use both open or commercial solvers
Type
Open
Geographical distribution of the tool
Local to continental
Type of users
Academic researchers and local energy planners
Existing community /community driven
Community driven
Originally designed/thought for LEC or adapted from national planning tool
LEC
Network modelled and energy carriers
User defined

Demand modelled
User defined
Possibility to customize
Yes
Objective functions:
Mainly economic
Functionalities
Design/planning and scheduling
Scale and approach
Scale modelled: user defined Approach: bottom-up
Mathematical approach
Linear programming
Temporal resolution
User defined (no limits)
Time horizon
User defined (no limits)
Modularity
Yes
User-friendly interface/ GUI
No
Pro and cons in application to LEC
Calliope, being an open software, is highly community driven software and so it has a prompt support and improvement by its community. Its design cleanly separates the general framework (code) from the problem-specific model (data). The user has a very large freedom in the modelling (time resolution, technologies, networks involved, etc.) which enable the ability to have high temporal and spatial resolution and it permits to execute several runs on the same model. The main con is that it does not have graphic interface and requires some basic skill in programming in order to handle properly the modelling. As a continuing improving software, guided by the community, different bugs can occur
Reference/Website
Calliope: a multi-scale energy systems modelling framework — Calliope 0.6.6-post1 documentation

Tool
EnergyPRO
Short Description
EnergyPRO is a complete modelling software package for combined techno-economic analysis and optimisation of both cogeneration and trigeneration projects as well as other types of complex energy projects with a combined supply of electricity and thermal energy (steam, hot water or cooling) from multiple different energy producing units. EnergyPRO is typically used for techno-economic analysis of energy projects such as district heating cogeneration plants with gas engines combined with boilers and thermal storage, industrial cogeneration plants supplying both electricity, steam and hot water to a site, cogeneration plants with absorption chilling (trigeneration), biogas fuelled CHP plants with a biogas store, biomass cogeneration plants. Other types of projects, e.g., geothermal, solar collectors, photovoltaic or wind farms can also be analysed and detailed within the software
Type
Commercial
Geographical distribution of the tool
Worldwide
Type of users
Academic researchers and local energy planners
Existing community /community driven
No
Originally designed/thought for LEC or adapted from national planning tool
LEC
Network modelled and energy carriers
Electricity, heating, and cooling
Demand modelled
Any (aggregated)
Possibility to customize
No
Objective functions:
• Financial • Energy efficiency • Technical • Social/economic criteria
Functionalities

Design
Scale and approach
Scale modelled: local to regional Approach: bottom-up
Mathematical approach
Dynamic programming
Temporal resolution
Minutes
Time horizon
Max 40 years
Modularity
No
User-friendly interface/ GUI
Yes
Pro and cons in application to LEC
The results from Energy Pro are in a printable format that can be accepted by the World Bank and international investment banks. With its flexible and generic structure, Energy Pro can be used to model any type of energy plant virtually. It does not provide the modularity that allows to integrate customized additional modules for developing new functionalities of the software
Reference/Website
Modules | EMD International

Tool
eTransport (Integrate)
Short Description
Integrate (previously eTransport) is a software system for the optimisation of integrated energy systems. It can be used to optimise the development of an energy system, while considering the projections in energy demand and the different technological possibilities for energy supply, conversion between energy carriers, distribution, storage, end-use measures and restrictions on CO_2 emissions. The solution methodology is a combination of Linear Programming (LP) and Dynamic Programming (DP/SDP). The result from the model is a cost-effective development plan, as well as a model of the operation of the system hour by hour in different seasons. Integrate is used to study local energy systems, such as a housing association or a district. There is also an associated model for the entire European energy system: Integrate Europe
Type
Commercial
Geographical distribution of the tool
District level. An up-scaled model for covering country level and above is under development.
Type of users
Energy system planners is the main target group
Existing community /community driven
No
Originally designed/thought for LEC or adapted from national planning tool
The tool was initially developed for optimising local energy system at a district level
Network modelled and energy carriers
The software is modular and is not limited to the existing set of networks. The existing networks: electricity, district heating/cooling, gas, hydrogen (test) and biomass (test)
Demand modelled
No input data are used
Possibility to customize
Yes
Objective functions:
Cost minimization
Functionalities
ETransport calculates the optimal development plan for a given period (for example the next 50 years).

The tool was initially developed for optimising local energy system at a district level
Scale and approach
Local scale, regional under development
Mathematical approach
Combination of Linear Programming (LP) and Dynamic Programming (DP/SDP)
Temporal resolution
One hour
Time horizon
Up to 50 years
Modularity
Yes
User-friendly interface/ GUI
Yes, the present version of the software uses GUI from MS Visio
Pro and cons in application to LEC
Modularity allows to introduce new components, which can be very specific, and refine the existing, but the model does not consider physical constraints (e.g., congestions or/and voltage violations in electric grid). However, considering the previous cons, the eNeuron tool will be cloud-based and it will allows LECs to design an optimal system using a scenario-based operational optimisation and performing stochastic daily operational optimisation for a multi-energy carrier confined energy system as well. Furthermore, the optimisation stage will be developed following a modular approach, where modules will correspond to energy carriers (e.g., electric part, district heating and cooling, gas etc.), thus being capable to interact with the peer-to-peer market and forming the loop of the hybrid operational optimisation for both LEC and its actors
Reference/Website
https://www.sintef.no/en/software/integrate/

Table 1 - Synoptic view of planning tool features

Tool	Type	Distribution of users	Community	Originally designed for LEC	Network modeled	Customizable	Objective functions	Energy carriers	Functionalities:	Scale	Temporal resolution	Time horizon	Modularity	User-friendly interface
EnergyPlan	Free	Worldwide users (academic researchers, policy maker, planners)	No	Adapted from national planning tools	Electricity, Heat, Fossil resources	No	Economic, environmental, Energy efficiency, Social	Electricity,heat,cold,hydrogen,fuel	Operation, No smart options	National	hour	year	No	Yes
DER-CAM	Open	Academic researcher	yes	NO	Electricity Heating Cooling Fossil fuels	Yes (possible to modify the objective function)	Economic and environmental	Electricity Heating Cooling Fossil fuels	Design and scheduling	Local	Year (but reference days with minute-level resolution may be defined)	Max 20 years	Yes	yes
Calliope	Open	Worldwide	Yes	NO	Electricity, Heat, Fossil resources, Hydrogen	Yes	Economic	User-defined	Both	User-defined	User-defined	User-defined	Possible	No
HOMER	Commercial	Worldwide users (academic researchers, policy maker, planners)	Community tools (blogs, forums, webinars, and live events)	LEC (optimizing microgrid design)	Electricity, Heat, Fossil and Renewable resources	Network model and scenario. Adjustable technology parameters	Economic, environmental, Energy	Electricity (DC & AC), Heat, Hydrogen, Biomass, Fuel	Operation, no Smart functions (inside tool or external by Matlab Link)	Loc. To regional (isolated or grid-connected microgrids	User defined (hours, minutes)	User defined (up to several years)	Yes	Yes
EnergyPro	Commercial	Worldwide	No	LEC	Electricity, Heat, Fossil resources	No	Economic	Electricity, Heat, Fossil resources	Operation, no Smart functions	Loc. To regional	minutes	Max 40 years	No	Yes
eTransport (Integrate)	Commercial	Energy systems planners	No	NO	Electricity District heating/cooling Gas Hydrogen and biomass.		Economic	Electricity District heating/cooling Gas Hydrogen and biomass	Design and scheduling	Local	Hour	Max 50 years	Yes	Yes

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 957779.

Table 2 – Features of planning tools investigated

		Energy carriers modeled				Objective function				Time resolution			
Tool	**Originally designed for LEC**	**Electricity**	**Natural gas**	**District heating/cooling**	**hydrogen**	**economic**	**environmental**	**User defined**	**Multi objective**	**minutes**	**hours**	**Reference day**	**User defined**
EnergyPlan	✗	✓	✓	✓	✓	✓	✓	✗	✗	✗	✓	✗	✗
DER-CAM	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✗	✓	✗
Calliope	✗	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗	✓
HOMER	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗	✗	✗
EnergyPro	✓	✓	✓	✓	✗	✓	✗	✗	✗	✓	✗	✗	✓
eTransport (Integrate)	✓	✓	✓	✓	✓	✓	✗	✗	✗	✗	✓	✓	✗

3.3 Recommendations for eTransport (Integrate) tool

From the critical review of the suitable existing tools, eTransport software (which is going to change its name in Integrate) has most of the features required for LECs' optimal planning. Anyway, some possible suggestions can be recommended

1. *The tool should be flexible according to the different type of users and of conflicting interests*

Optimal cost functions can vary according to the stakeholders (a local utility may want to minimize costs of operations; final users may want to lower the energy bill; the local authority may want to reduce environmental impact; etc.). For this reason, it is preferable that the tool would be able to model conflicting interests

2. *Environmental and sustainability objectives must be considered*

In eTransport emissions are caused by a subset of components (power plants/combined heat and power plants (CHP), boilers, road/ship transport, etc.) that are defined as emitting CO_2, NOx, CO, and SOx. Further environmental consequences can be defined. Emissions are calculated for each module and accounted for as separate results. When emission penalties are introduced by the user (e.g., a CO_2 tax), the resulting costs are included in the objective function and thus added to operating costs

3. *User interface*

A user-friendly interface for the software can encourage, facilitate and spread the use of the tool among local authorities

4. *Common format for input data and user defined constrains*

A common format for providing input data and user defined constrained can be useful to harmonize activities and data collection among pilots

5. *Possibility to introduce new user-defined technologies and to modify existing ones.*

eTransport tool already considers a variety of technologies. However, it can be recommended the opportunity to introduce new user-defined technologies and to modify existing ones. Indeed, as highlighted in Section 2, within the same technologies some differences can exists in terms of size, efficiencies, cost and O&M

This project has received funding from the European Union's Horizon 2020
research and innovation programme under grant agreement N° 957779.

4 Overview of the eNeuron pilots

This section provides overview of the four pilots in which the eNeuron tools will be tested. Each pilot is presented in a subsection and all the subsections present the same structure:

- "Overview of the pilot" which presents a brief description of the demo site;
- "eNeuron concept deployment" which presents how the eNeuron concept will be tested in the real environment of the demo
- "Technologies involved in the pilot" reporting a table and a scheme showing the energy carriers involved and the connecting technologies enabling cross sector interactions in the pilot

4.1 Pilots overview

4.1.1 Polish Pilot

4.1.1.1 Overview of the pilot

The pilot covers the area of city of Bydgoszcz and its major energy nodes, connected to both LV and MV grid. Most of them are newly constructed buildings with some degree of energy self-sufficiency; they are also equipped with smart meters registering 15 minutes energy consumption profiles and 10 minutes phase voltage profiles.

Nearly all MV/LV in the project area stations are at present equipped with balancing meters, connected to central Advanced metering infrastructure (AMI) system by means of cellular network. 10 minutes voltage and 15 minutes energy import/export profiles are available with minimum delay (minutes), and on-demand measurements are possible (actual power P, reactive power Q, voltage V, current I, etc.).

All actual P, Q, V, I measurements are available directly from substations, or indirectly from SCADA system and AMI system, so that near real-time energy flow tracking management is achievable and can be superimposed over detailed GIS map. This will deliver full insights into MV operation in visual way and lay foundation for the Polish Pilot demonstration.

4.1.1.2 eNeuron concept deployment

The high-level management architecture proposed for the LEC is based on central, master application concept, controlling mEHs installed at each energy node (asset). The central application will coordinate the mEHs so that they can act together and provide several functions, such as:

- Local energy management - in terms of loads and generation
- Grid flexibility management
- Maximization of local generation – reduction of energy in-flow from DSO

The polish pilot focuses on the eight buildings of in the town of Bydgoszcz. Objects are equipped with smart meters registering 15 minutes energy consumption profiles and 10 minutes phase

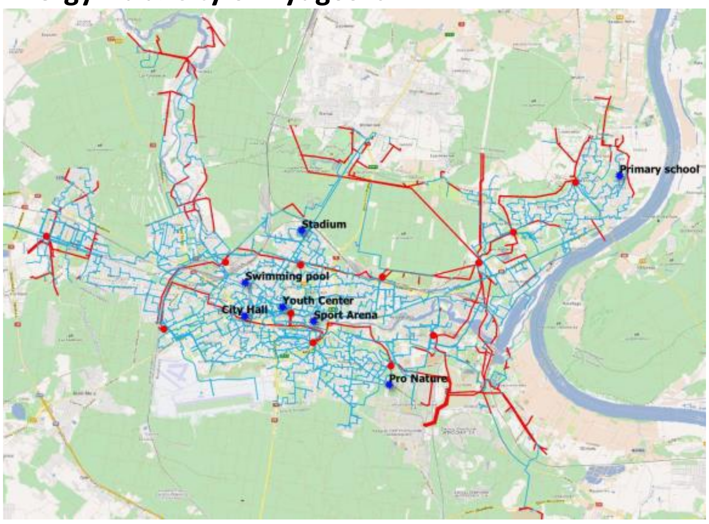
voltage profiles. Each building will be treated as a mEH. The hardware devices will be installed at the level mEH to collect energy data and events from PV, heat pumps, CHP, etc., and to transmit control commands where possible. A connection to the local BMS will also be provided. Data from devices installed at mEH will be transmitted to the central application coordinating the operation of mEHs and managing the entire EH. It is also planned to equip secondary substations with monitoring devices at the MV and LV level, transmitting data to the central application directly or via the SCADA system.
Table 3 below presents a brief energy description of the buildings:

Table 3 Energy description of the buildings

No.	Object	Description
1	Bydgoszcz City Hall building	PV (10.5 kWp), UPS, backup power generator units (160 kW, 80 kW), solar collector (hot water)
2	Łuczniczka Sports and Entertainment Complex	energy storage (lead-acid), PV (40 kWp) – ongoing
3	Zawisza Sports and Entertainment Complex	PV (50 kWp) – ongoing
4	Astoria Recreation Centre	PV (143 kWp), HVAC, UPS, backup power generator unit; BMS (Building Management System)
5	Primary School No. 9	passive users with no DER
6	Palace of Youths in Bydgoszcz	PV (18 kWp)
7	School Complex no. 28 with swimming pool	CHP (2x20 kWe/38.7kWt), heat storage (957l), HVAC; BMS (Building Management System)
8	Animal Shelter in Bydgoszcz	PV (18 kWp), energy storage (lead-acid), 3xheat pumps (5.97 kWe/20.63kWt), electric furnace (24 kW), electric boiler (electric heater 2x9 kW, tank: 500l, 800l)
9	Municipal Waste Thermal Treatment Plant in Bydgoszcz.	CHP 13 MWe/27.7MWt (thermal waste processing plant - 200 MWh/day, 2GJ/day)

Figure 13 - Location of buildings

Energy Hub: City of Bydgoszcz



Micro-energy hubs:

1. Bydgoszcz City Hall building
2. Łuczniczka Sports and Entertainment Complex
3. Zawisza Sports and Entertainment Complex
4. Astoria Recreation Centre
5. Primary School No. 9
6. Palace of Youths in Bydgoszcz
7. School Complex no. 28 with swimming pool
8. Animal Shelter in Bydgoszcz
9. Municipal Waste Thermal Treatment Plant in Bydgoszcz.

4.1.1.3 Technologies involved in the pilot

Table 4 - Technologies involved in the Polish pilot

	Electricity	Natural gas	Heating	Cooling	Hydrogen	Mobility	Water
Electricity		CHP	Heat pumps,	HVAC	-	-	Heat pumps,

			Electric boiler, electric furnace				Electric boiler
Natural gas			CHP	-	-	-	-
Heating				-	-	-	Solar thermal
Cooling					-	-	-
Hydrogen						-	-
Mobility							-
Water							

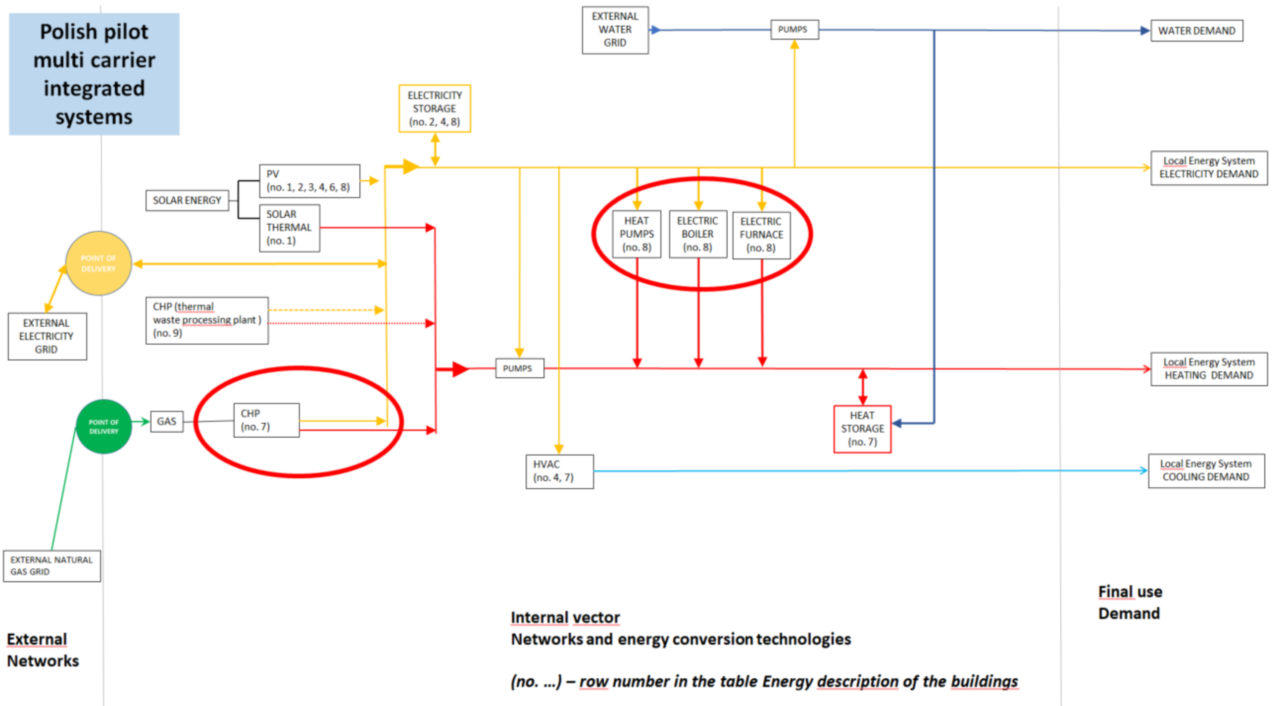


Figure 14 - Technologies involved in the Polish pilot

4.1.2 Norwegian Pilot (Sintef, Skagerak)

4.1.2.1 Overview of the pilot

The Norwegian demo will be deployed at industrial size installation at operational football stadium, so-called "Skagerak Energy Lab", combining a big-scale (800 kW) PV generation plant, with battery energy storage system, BESS (1 MWh) and power electronics allowing several operational modes for the unit, including fully islanded operation. The adjacent area includes several commercial and household end-users and several EV charging units. The planned demonstration will be closely coordinated with Skagerak Nett, which operates the installation, and aligned with the planned test and development program.

4.1.2.2 eNeuron concept deployment

The demonstration intends to utilize two important high TRL assets – the physical installation at the stadium and eTransport optimization tool, in order to study:

- Using eTransport for operational optimization of the installation in different modes, including (preliminary):
  - optimization of PV production and consumption
  - use of the installation as a flexibility resource
  - islanded operation: supplier of the emergency power
- Using eTransport for development and comparative evaluation of alternative expansions of the installation through using additional energy carriers, which would allow to maximize the RES-based generation and maintain secure and reliable power supply
- Input to further development of eTranport based on data and learnings from the demonstration

The results and learnings from the pilot will provide input to the overall validation of the decarbonization solution and its optimization potential in the present and extended configuration, where extension scenarios can be evaluated.

Energy Hub: Skagerak Energy Lab (Skagerak)	**Micro-energy hubs:** **1.** Football stadium; **2.** Grocery stores; **3.** Offices; **4.** Apartment buildings.

4.1.2.3 Technologies involved in the pilot

Table 5 - Technologies involved in the Norwegian pilot

	Electricity	Natural gas	Heating	Cooling	Hydrogen	Mobility	Water
Electricity			Heat pumps, electric boilers		Electrolyzer/storage/fuel cell	EV charging station	
Natural gas							
heating							
cooling							
hydrogen							
Mobility							
water							

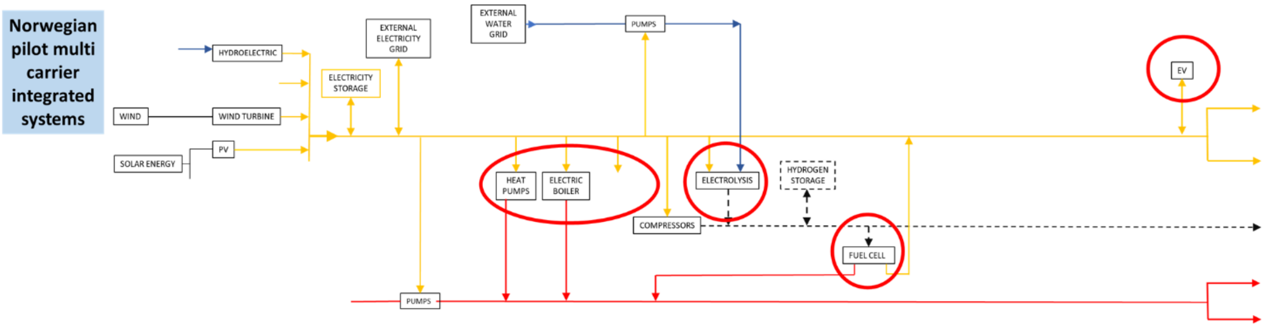


Figure 15 - Technologies involved in the Norwegian pilot

4.1.3 Portuguese Pilot (EDP Labelec, Navy)

4.1.3.1 Overview of the pilot

The envisioned demonstration comprises a local energy system – a urban district – within the Lisbon's Naval Base campus, property of the Portuguese Navy – Marinha Portuguesa.
The proposed pilot site presents the opportunity to optimize the electricity system operation in eNeuron with other energy carriers, not just electricity but also heating/cooling, transport and/or industry in a sector-coupling approach, increasing the hosting capacity for RES at local level. The Hub's border will be a MV/MV substation, since the military facility has its own distribution grid. The substation powers two different networks, a 6kV / 50Hz network, comprising residential and industrial loads – naval station buildings and the department of propulsion and energy workshops, and a 6kV / 60Hz network, comprising the docks and the battleships.
From the different types of loads available we may consider, lighting circuits, HVAC systems, boilers, and industrial appliances, e.g., ovens. Distributed generation to consider is a PV system in carport parking and an EV charging station.

4.1.3.2 eNeuron concept deployment

The high-level management architecture proposed for the local energy system is based on a master-slave approach, where a system aggregator for the entire Hub will coordinate and manage micro–Energy Hubs, i.e., small scale systems comprised by a secondary-substation and its LV circuits, or a small campus and its cluster of buildings.
Slave micro–Energy Hubs will be governed in an automated way, targeting a certain degree of self-optimization and functional independence, taking into consideration the characteristics of the available assets and flexible.
The main applications to explore will be:

- Local energy and flexibility forecasting
- Peer-to-peer energy and flexibility trading
- Metering equipment integration to enable Consumption forecast adaptative model and dynamic prescriptive measures regarding energy efficiency

Energy Hub: Lisbon's Naval Base Energy Hub	**Micro-energy hubs:**

	1. Department of propulsion and energy; 2. Buildings of the naval station; 3. Wharfs. Military facility has its own distribution grid. Master-slave approach, where a system aggregator for the entire Hub coordinates and manages micro Energy Hubs. Slave micro Energy Hubs is governed in an automated way.

4.1.3.3 Technologies involved in the pilot

Table 6 - Technologies involved in the Portuguese pilot

	Electricity	Natural gas	Heating	Cooling	Hydrogen	Mobility	Water
Electricity		-	HVAC Ovens	Electric chiller	-	EV Charging Station	Circulation pump Boiler
Natural gas			Ovens	-	-	-	Boiler
heating				-	-	-	Solar Thermal
cooling					-	-	-
hydrogen						-	-
Mobility							-
water							

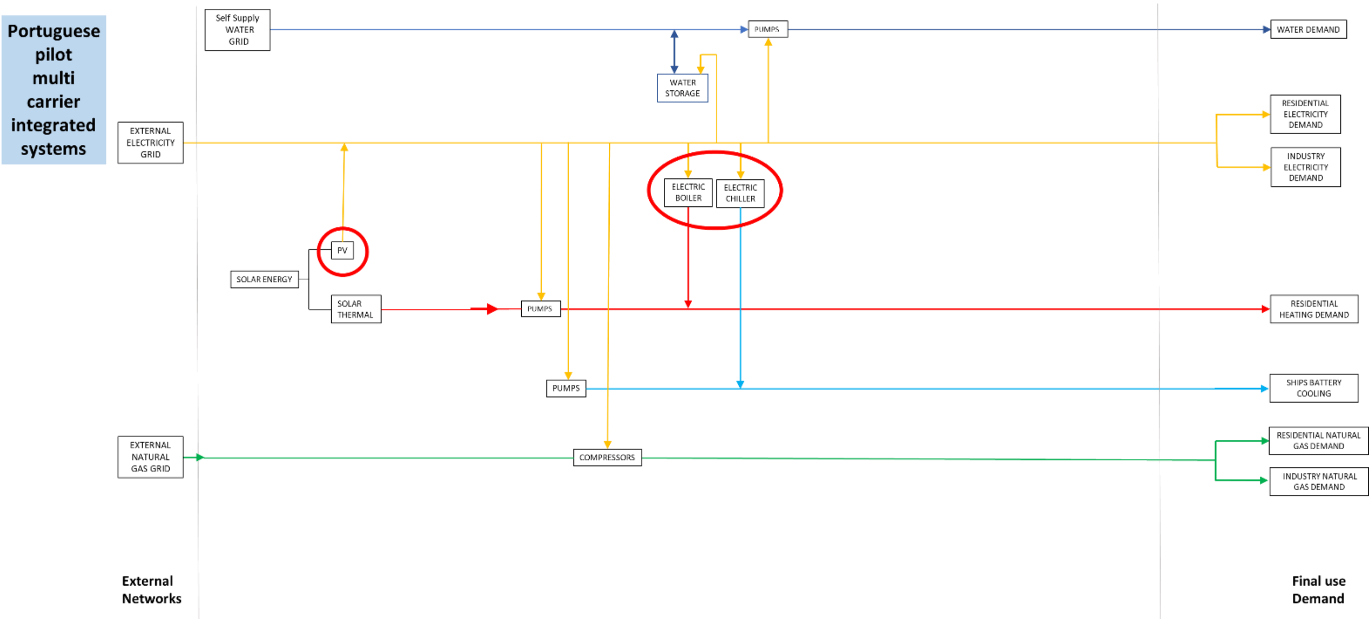


Figure 16 - Technologies involved in the Portuguese pilot

4.1.4 Italian Pilot (UNIVPM)

4.1.4.1 Overview of the pilot

Università Politecnica delle Marche (UNIVPM) is in the Marche Region, in Central Italy. It has different campuses spread in the Region. UNIVPM can be considered as an EH with four sub hubs in sites spread over the city of Ancona (Italy). UNIVPM accounts for a total of around 17,000 people among students and staff. These sites consist mostly of school and offices, and among these the site of Monte Dago is a multi-energy microgrid (mEH).

4.1.4.2 eNeuron concept deployment

The Italian demo focuses on the four main campuses of UNIVPM in the town of Ancona.
For the sake of the project the University will act as an EH while the four sites will act as micro-energy hubs.

<table>
<tr>
<td>Energy Hub: UNIVPM University


</td>
<td>UNIVPM micro-energy hubs:

Montedago multi-energy microgrid (three faculties: Engineering, Life Sciences and Agriculture);
Faculty of Economics;
Faculty of Medical Sciences;
UNIVPM Rectorate (headquarter).

Micro-energy hubs 2, 3 and 4 are almost passive users with no DER. Site 1 is a multi-energy microgrid</td>
</tr>
</table>

Table 7 - Technologies involved in the Italian pilot

	Electricity	Natural gas	Heating	Cooling	Hydrogen	Mobility	Water
Electricity		CHP	CHP Heat pumps Electric boiler (for SHW)	Heat pumps	Electrolyzer Fuel cell	EV charging station	Circulation Pumps Electrolyzer
Natural gas			CHP	-	-	-	-
heating				Absorpion chillers	Fuel cell	-	-
cooling					-	-	-
hydrogen						-	Electrolyzers
Mobility							-
water							

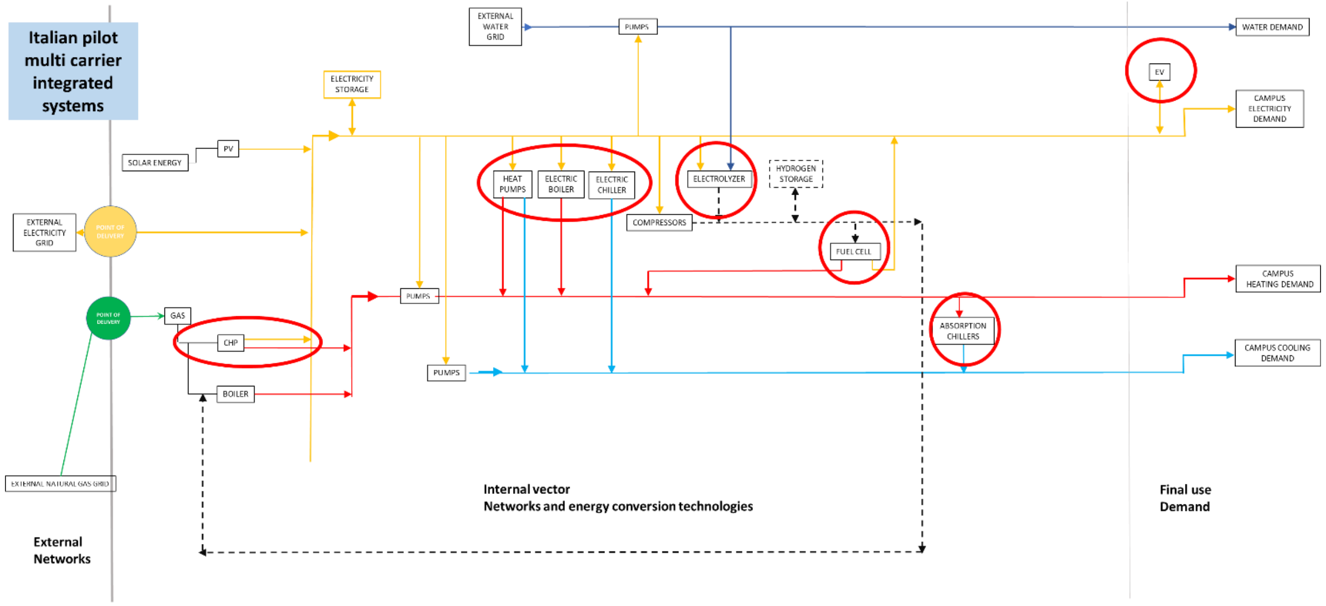


Figure 17 - Technologies involved in the Italian pilot

Conclusions

This deliverable provides a comprehensive review of technological solutions that could better enable the establishment of local energy systems by achieving synergies among different energy conversion systems. These solutions have been contextualized within the “energy hub” and “micro-energy hub” paradigms which are at the basis of the eNeuron concept proposed for Local Energy communities. In particular, the deliverable focuses on those technologies, with high TRL, connecting more energy carriers/networks. The objective is to provide a comprehensive techno-economic catalogue of technologies enabling multi carrier integrated systems.
Since optimal planning is one of the key issues for the development of future local energy communities, the deliverable also reports a critical review of existing planning tools and provides recommendations for the enhancement of eTransport (Integrate) that is centered at the core of eNeuron tool and which is part of the activity of WP3. In particular the main recommendationsfor eTransport (Integrate) tool are: i) the tool should be flexible according to the different type of users and of conflicting interests; ii) environmental and sustainability objectives must be considered; iii) develop a user friendly interface to encourage and facilitate the use of the tool among local authorities; iv) develop a common format for input data and user defined constrains; v) possibility to introduce new user-defined technologies and to modify existing ones.
The last part of the deliverable reports an overview of the four pilots by presenting the technologies involved and the deployment in real environment of the eNeuron concept.
This deliverable lays the technical foundations for the future project activities related to identification of the “Local Integrated Energy Community” subject and definition of the Use Cases (WP3) and for the “Analysis, design and operation optimization of the local energy systems: emergence of energy hubs” (WP4).