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Lecture Series of World Class Professor
Faculty of Engineering, Universitas Indonesia
Mechanical Engineering Department

Polygeneration:
Energy Efficiency and Integration of Renewable Energy

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Universitat Rovira i Virgili

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Outline

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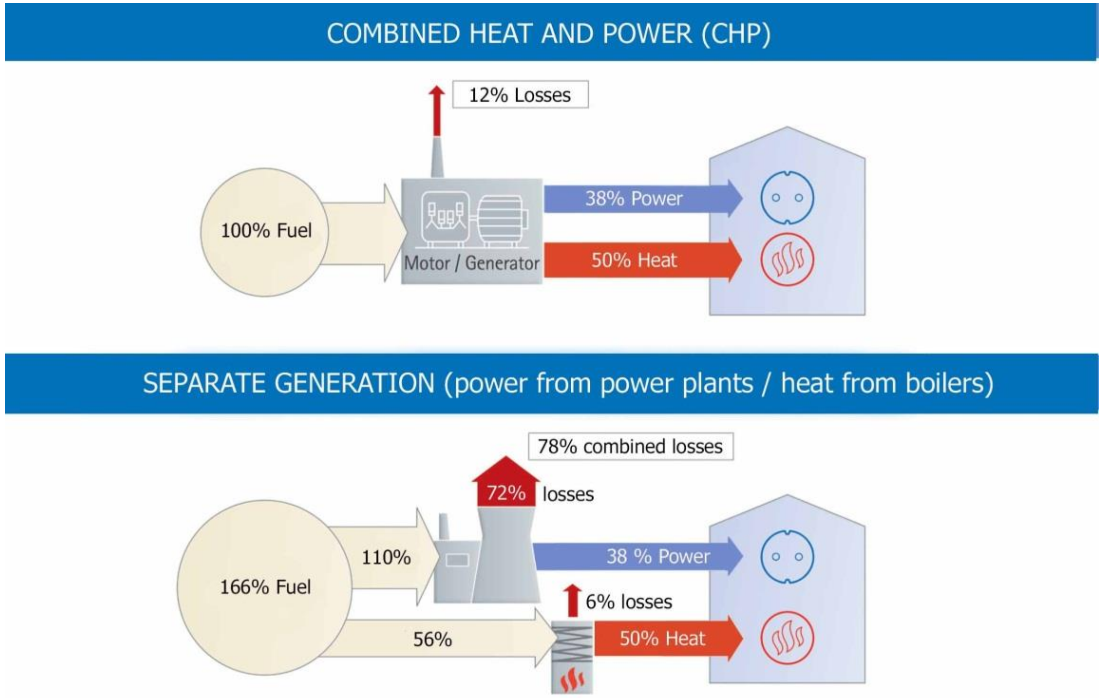
- **P**olygeneration technologies for distributed generation of energy and renewable energy integration
    - What is Polygeneration?
    - Polygeneration Systems
    - Polygeneration Technologies
    - Importance and Suitability of Polygeneration for Sustainable Communities
    - Optimisation of energy polygeneration systems
    - Implementation of Polygeneration Systems:
        - The Polycity Project
        - The HEGEL Project
    - Emerging Technologies for polygeneration: PV/T, Cold recovery from LNG-regasification for polygeneration applications,….

What is Polygeneration ?

The term '**Polygeneration**' is most widely used to describe the generalisation of the idea of '**cogeneration**' (i.e. the thermodynamically efficient use of fuel) in the form of systems which simultaneously produce electricity and useful heat.

Cogeneration or

Combined Heat and Power (CHP) is defined as "**the simultaneous generation in one process of thermal energy and electrical and / or mechanical energy**".



What is Polygeneration ?

POLYGENERATION: the **simultaneous generation** in an **integrated process** of **more than two energy carriers o services** by the use of **one or multiple primary energy sources** .

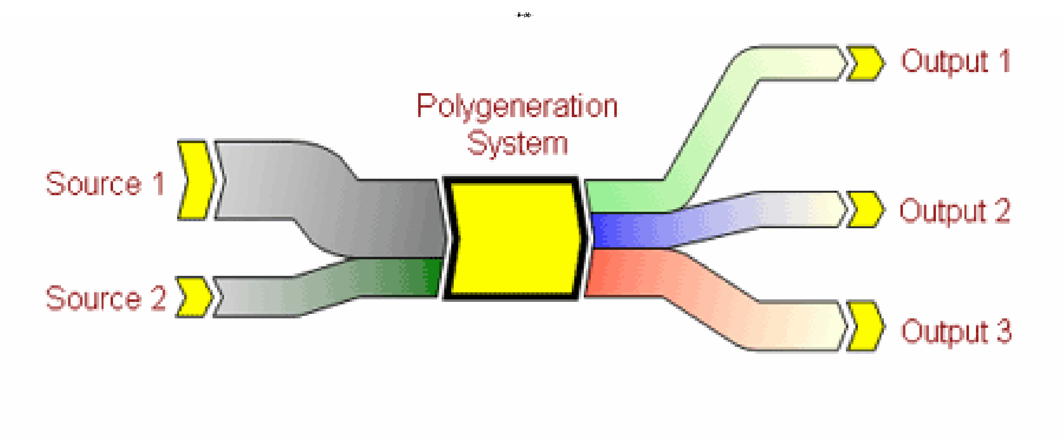
➢The term '**integrated process**' refers to multiple successive processes, where the output or by-product of one process is the input of another process. This succession of thermodynamic processes constitutes an '**energy supply system**' which can be understood in a broader sense.

Natural Gas or Biogas

Solar thermal energy

Biomass

Geothermal energy



electricity
hot water
refrigeration
steam,
air conditioning
potable or drinking water
biofuels

➢The idea of **polygeneration** can also be enlarged considering **fuel and material generation**. In some technologies like gasification processes based on biomass sources, some by-products may be used directly as fuel.

What is Polygeneration ?

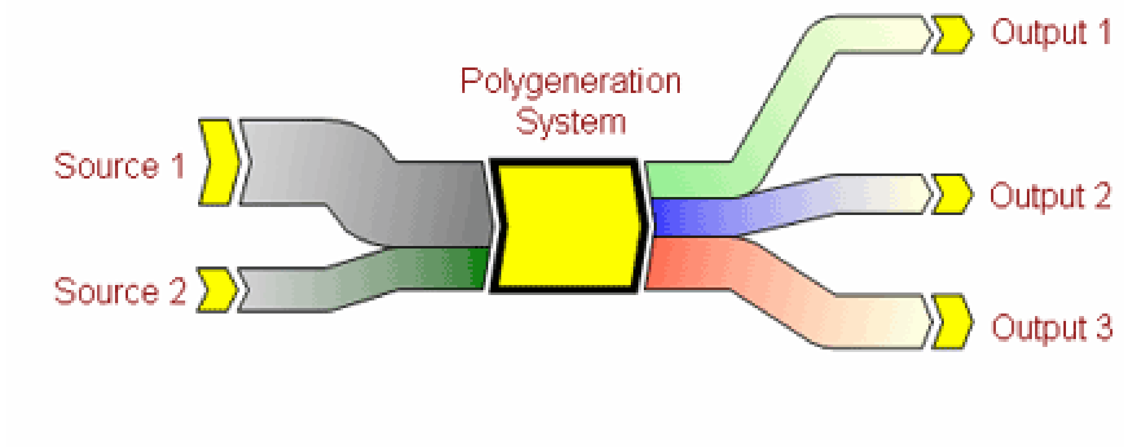
- If only **Power and Heat** is produced it is referred to as ”**Cogeneration**” or ”Combined Heat and Power” (CHP)

- or ”**Trigeneration**” or “Combined Heat, Cooling and Power “ (CHCP) if cooling is also one of the energy services delivered.

- In some cases to emphasize the **decentralised** nature of **Polygeneration** technologies with respect to central power stations these technologies are also named as ”**Distributed Generation**” technologies or ”**Distributed multi-generation**” technologies if the idea of **multiple energy outputs is to be highlighted.**

Polygeneration Systems

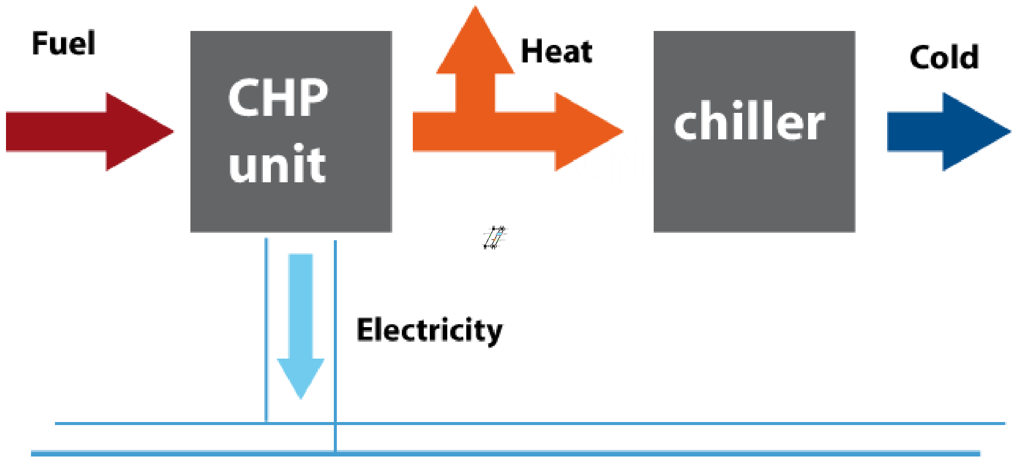
Input	Fuel	Fuel/Waste	Waste	Fuel	Fuel	Cereals
Process	**Trigeneration**	**Gasification**	**Biogas production**	**Water desalination**	**CO_2 harvesting**	**Bioethanol production**
Output 1	Heat	Heat	Fertiliser	Heat	Heat	Heat
Output 2	Cold	Cold	Biogas • heat • power	Power	Power	Bioethanol • heat • power
Output 3	Power	Industrial raw material		Water	Crops	Feedstock



Polygeneration Systems: Trigeneration

TRIGENERATION is a basic and most popular form of Polygeneration.

The term describes an energy conversion process with combined heat, cooling and power generation (CHCP).



Components: CHP module generating electricity and heat, and

a **heat-driven chiller generating cold**.

The chiller is driven with the heat delivered by the CHP.

Depending on the demand, the generated heat is either used for heating or cooling purposes or both.

Polygeneration Systems: Trigeneration

- **Trigeneration** systems find application wherever the demand for heat, cold and power occurs.
- The application area is very vast ranging from small residential, towards big commercial, office or other (tertiary, sports, entertainment centres, hospitals, schools, airports, hotels, etc.) buildings.
- **Trigeneration** can be beneficial in the **food industry** where often simultaneous need for **cooling, heating and power** exists (heating and cooling is usually needed for freezing, pasteurization etc.)
- **In buildings**, the CHCP system produces heat for domestic hot water, space heating or dehumidification and cold for space cooling or air conditioning.
- The distribution of heat and cooling to end-users using **District Heating and Cooling networks** (DHC) enhances high heat, cold and power generation efficiency

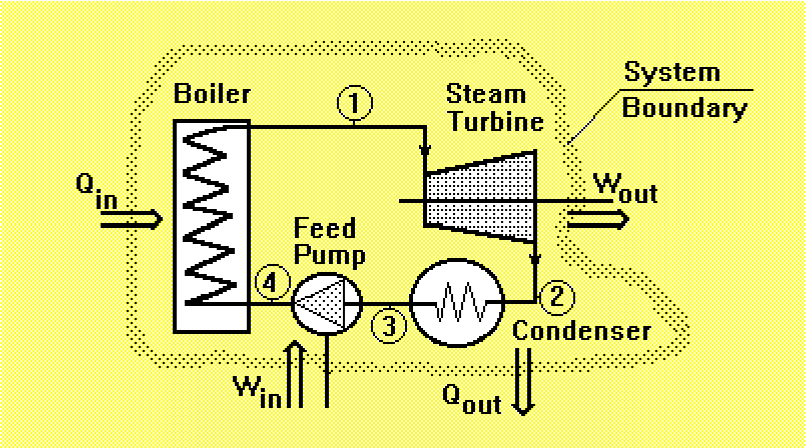
Polygeneration Technologies

Combustion engines for cogeneration

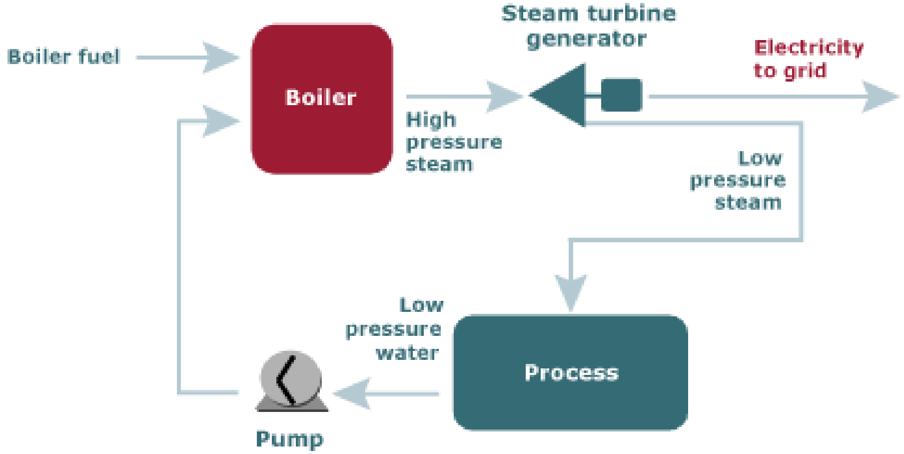
- Engines
  - External Combustión engines
    - Reciprocating → Steam engines
    - Rotary → Steam turbines
  - Internal Combustión engines
    - Reciprocating
      - Otto Cycle
      - Diesel Cycle
    - Rotary → Gas turbines

Polygeneration Technologies: Steam Turbines

ST for power generation



ST for power and heating



Electrical power capacity: 500 kW – 300 MW

Electrical efficiency: 7 – 20 %

Investment cost: 1000 – 2000 €/kW

Polygeneration Technologies: Reciprocating Combustion Engines

Least expensive and most commonly used CHP prime movers

Type of engines:

- Spark ignited: natural gas
- Compression ignition: diesel

Good part load operation

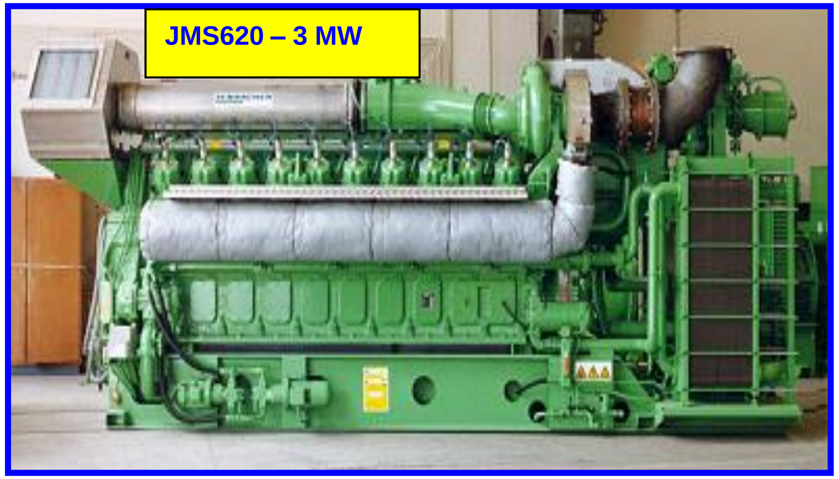
Heat available at two temp Levels:

Exhaust gases and jacket cooling fluid

Electrical power capacity: 5 kW – 20 MW

Electrical efficiency: 25 – 42 %

Investment cost: 350 - 1000 €/kW



Micro gas turbines

Small Capacity turbines with regeneration

Capacity range: 25 kW to 200 kW

Electrical Efficiency Range: 25% to 30%

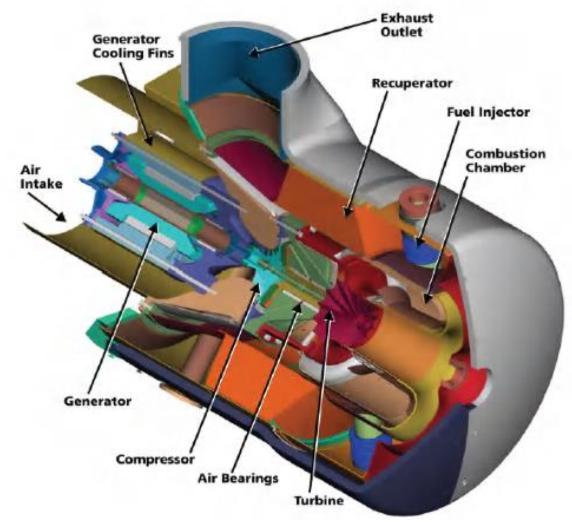
Waste Thermal Energy: exhaust gases

Advantages:

- Compact Size
- Low Emissions
- Fuel Flexibility
- Modular
- Lower Maintenance

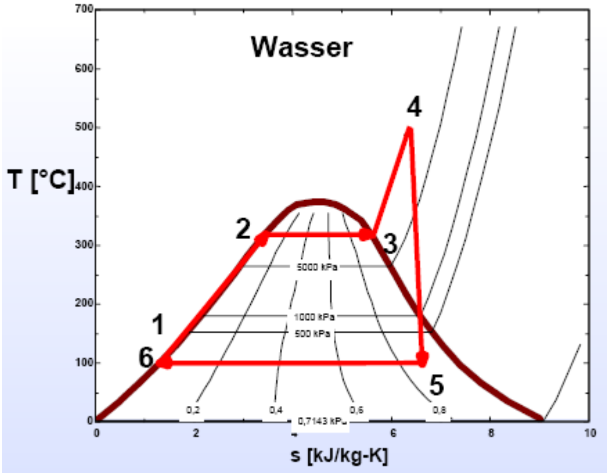
Disadvantages:

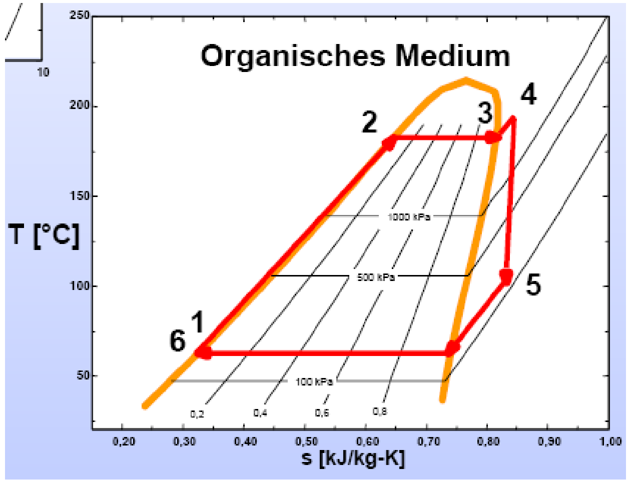
- Moderate Conversion Efficiencies
- Poor Part Load Operation

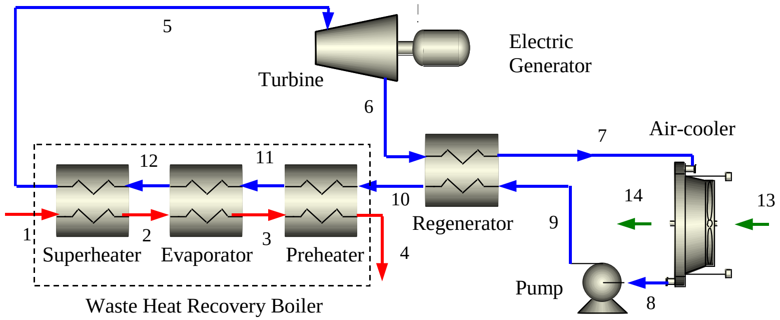


Organic Rankine Cycles

The Organic Rankine Cycle (ORC) is similar to that of a conventional steam turbine cycle, except for the fluid that drives the turbine, which is a high molecular mass organic fluid or fluids commonly used as refrigerants.







Good applications:

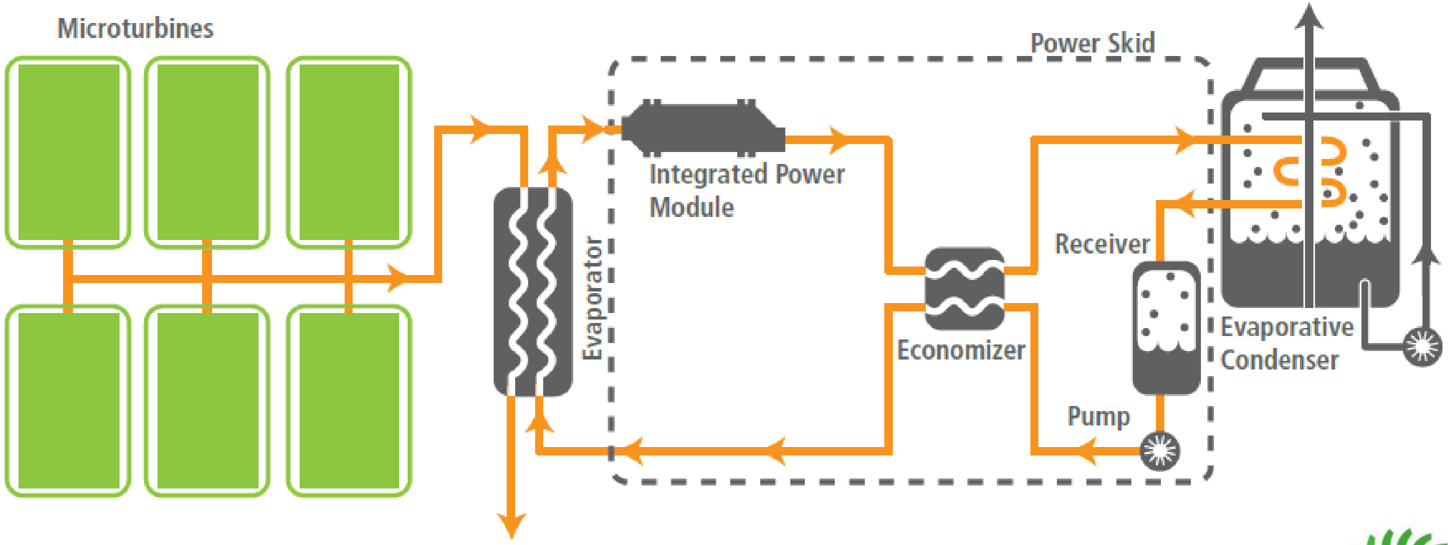
- Low temperature heat sources
- Small-medium size plants

Polygeneration Technologies: Micro-Combined Cycles

Micro-Combined Cycles: Micro Gasturbine and ORC

The exhaust gases of some microgasturbines can be used to drive a ORC unit.

A **500 kW** power plant can be built combining 6 micro-gasturbines of 65kW (Capstone C65) with a ORC unit (Capstone ORC WHG) of 125 kW with efficencies of 40%



Source: micropower europe

Heat-Driven Refrigeration Technologies:

Absorption and Adsorption

Absorption cooling technology

- well known and commercially implemented
- air-conditioning and refrigeration applications
- wide range of power
- use of low temperature heat driving sources

Absorption chillers

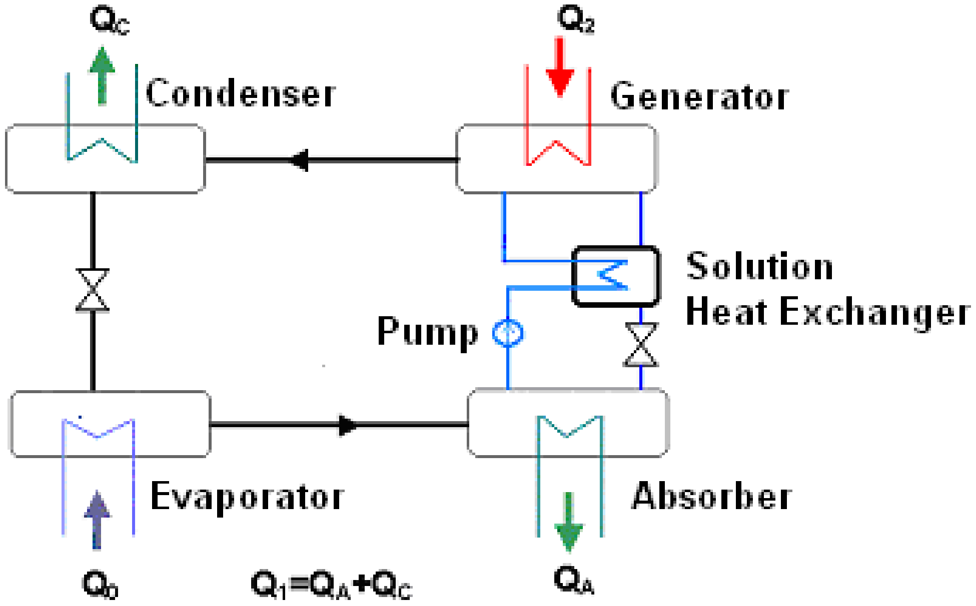
- Incorporate, in addition to an evaporator and a condenser, **a solution (refrigerant /absorbent mixture) circuit** including an absorber and a generator.
- Fluid mixtures used :
  - water/lithium bromide (Air-conditioning)
  - ammonia/water (AC and Refrigeration)
- **Single-effect** chillers

  COP = 0.6-0.7 ; Temp. heat source: 80-110 °C;

  Chilled water at 7/12°C and wet cooling
- **Double-effect** chillers (**water/LiBr**)

  COP = 1.-1.2 ; Temp heat source: 120-160 °C

  Chilled water at 7/12°C and wet cooling

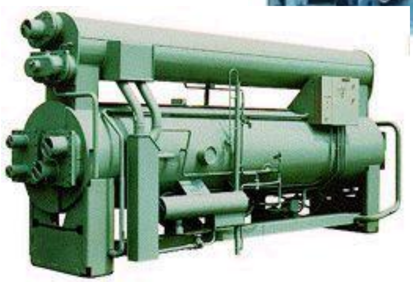


Market available LiBr absorption chillers

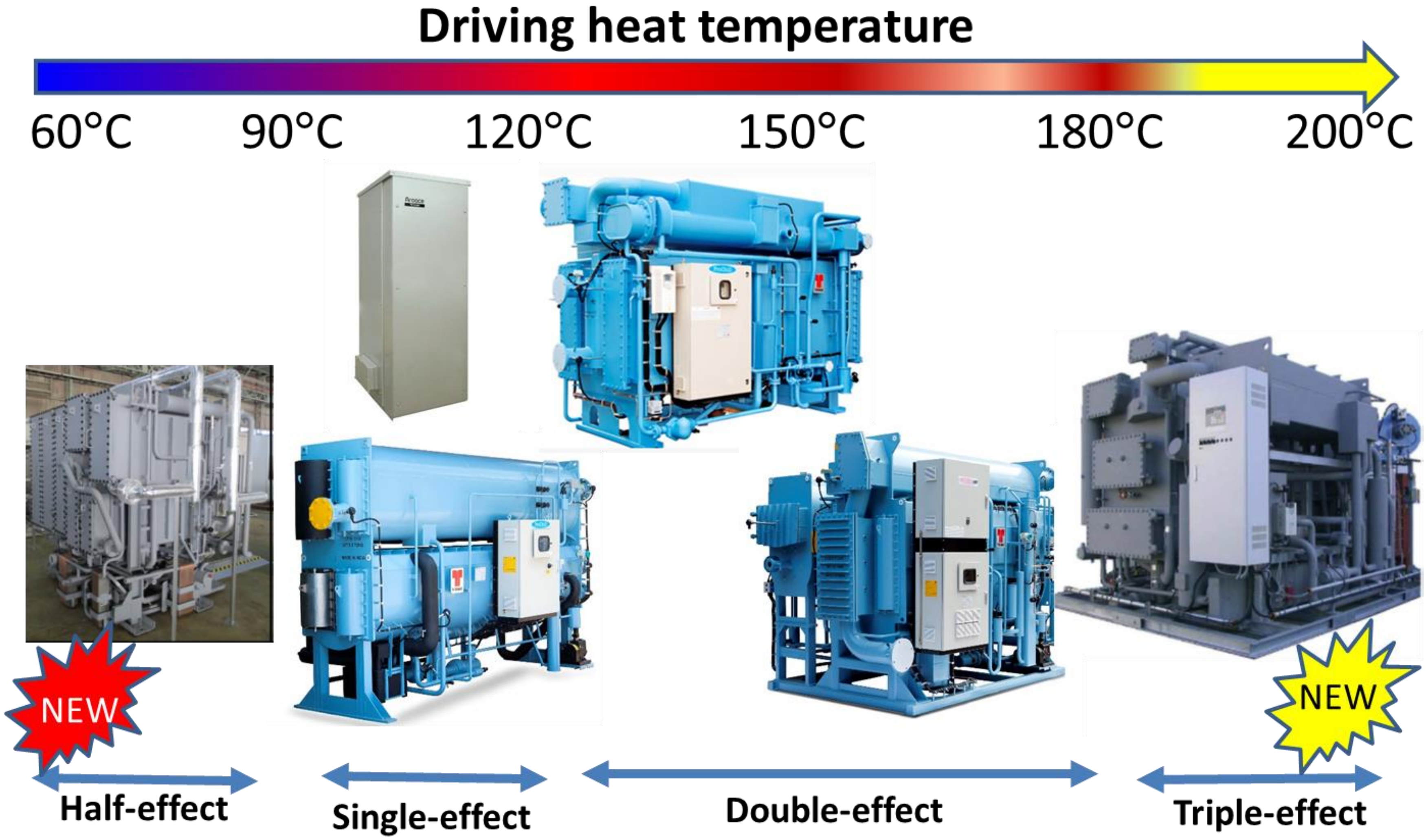
Single effect: Many products for operation driving by hot water or steam in the capacity range > 100 kW

Only few machines for lower capacities

Double effect : Often direct fired systems; very few products in the range <100 kW



Polygeneration Technologies: Commercial LiBr absorption Chillers



$COP_C =$ 0.4 | 0.7 | 1.3-1.4 | 1.7- 1.9

Typical operating conditions: chilled water produced at 8-10°C and cooling water at 28-30°C

Market available NH_3/H_2O absorption chillers

- Absorption chillers driven by hot water for small capacity cooling applications

Solar ICE 25 a 40 kW

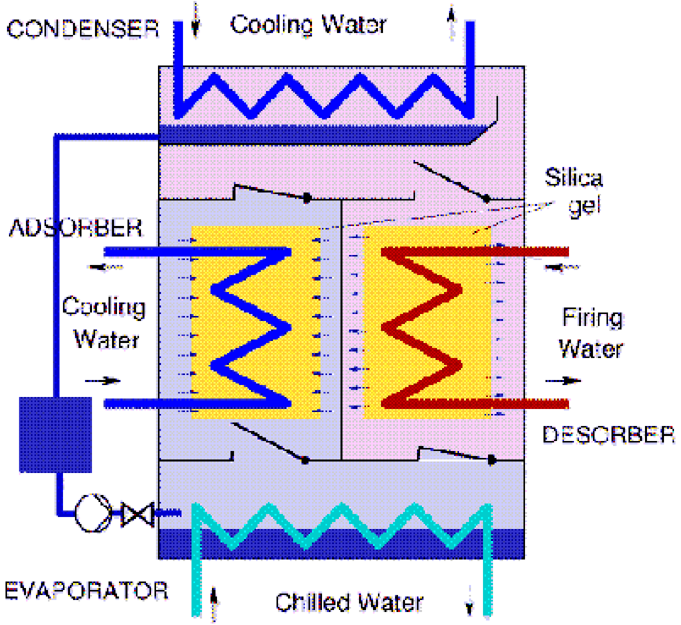
SOLARNEXT chillii PSC12, (12 kW)

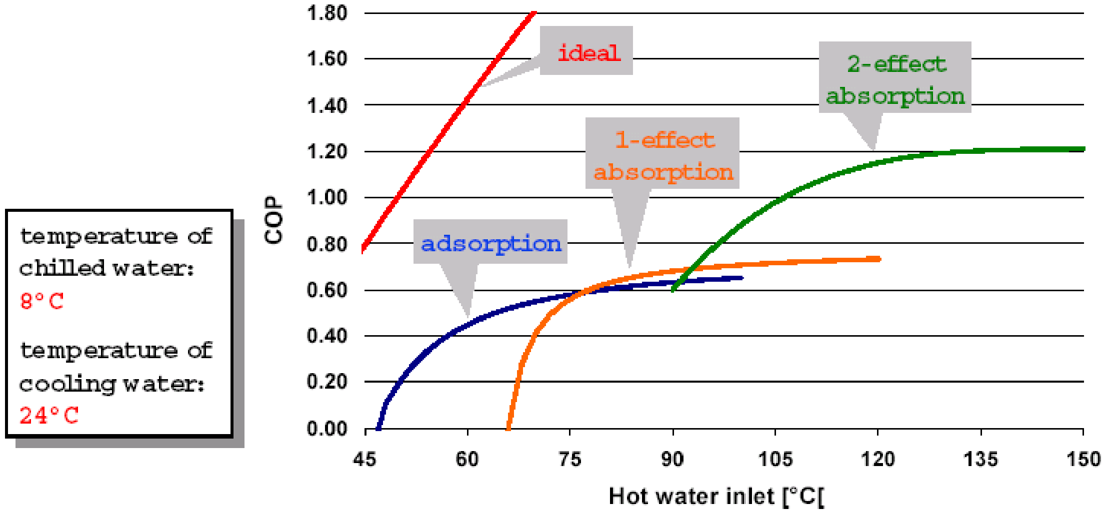
- **Absorption Refrigeration Systems for industrial applications at temperatures up to -60ºC** using waste heat of gas engines or gas turbines is a conventional application in various industries (like food, petrochemical) with large capacity systems.

Adsorption Technology

Adsorption chillers are driven by thermal energy like absorption chillers but a solid medium is used as sorbent instead of a liquid.

An adsorption chiller is by nature a discontinuous cycle. To obtain continuous cooling a multiple bed system is used, typically two adsorbent beds out of phase.





MARKET AVAILABLE ADSORPTION CHILLERS

- Only few manufacturers
- Driving temperature starting at 55^{o}C
- COP at design conditions 0.65
- Chillers driven by hot water with a capacity range 70 - 400 kW
- New developments of 8 and 15 kW

Nishiyodo NADAC-020

Mycom ADR-30 105 kW

SorTech AG

H_2O / zeolite

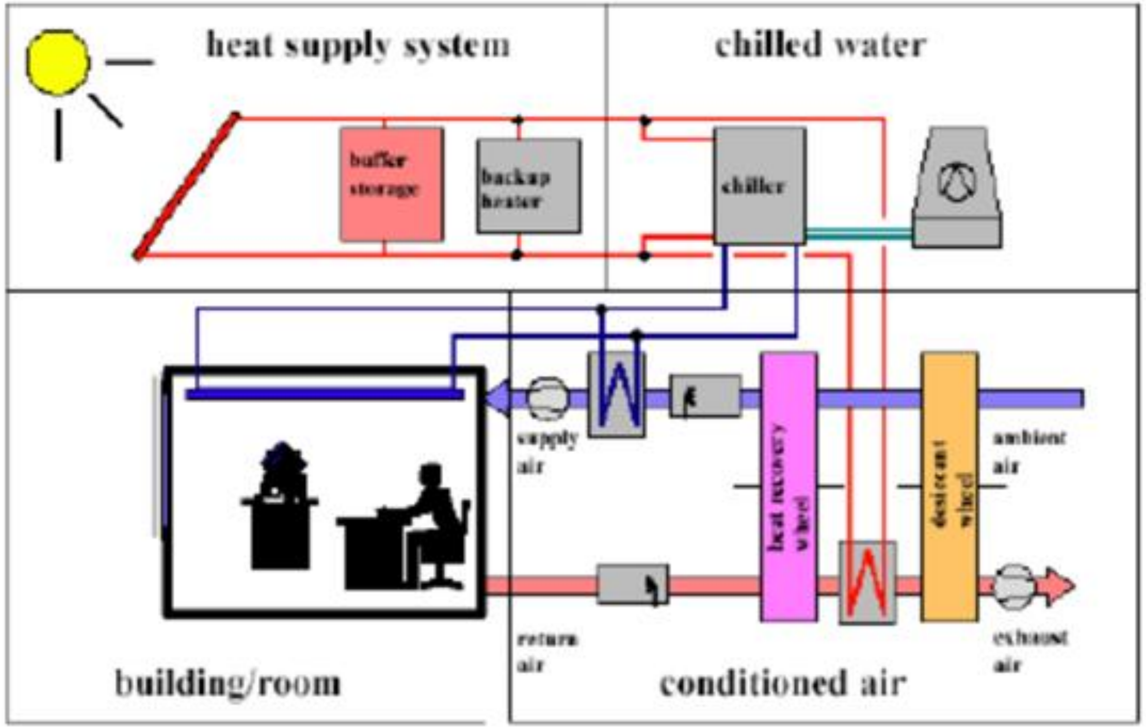
Polygeneration Technologies: dessicant cooling systems

Dessicant cooling systems

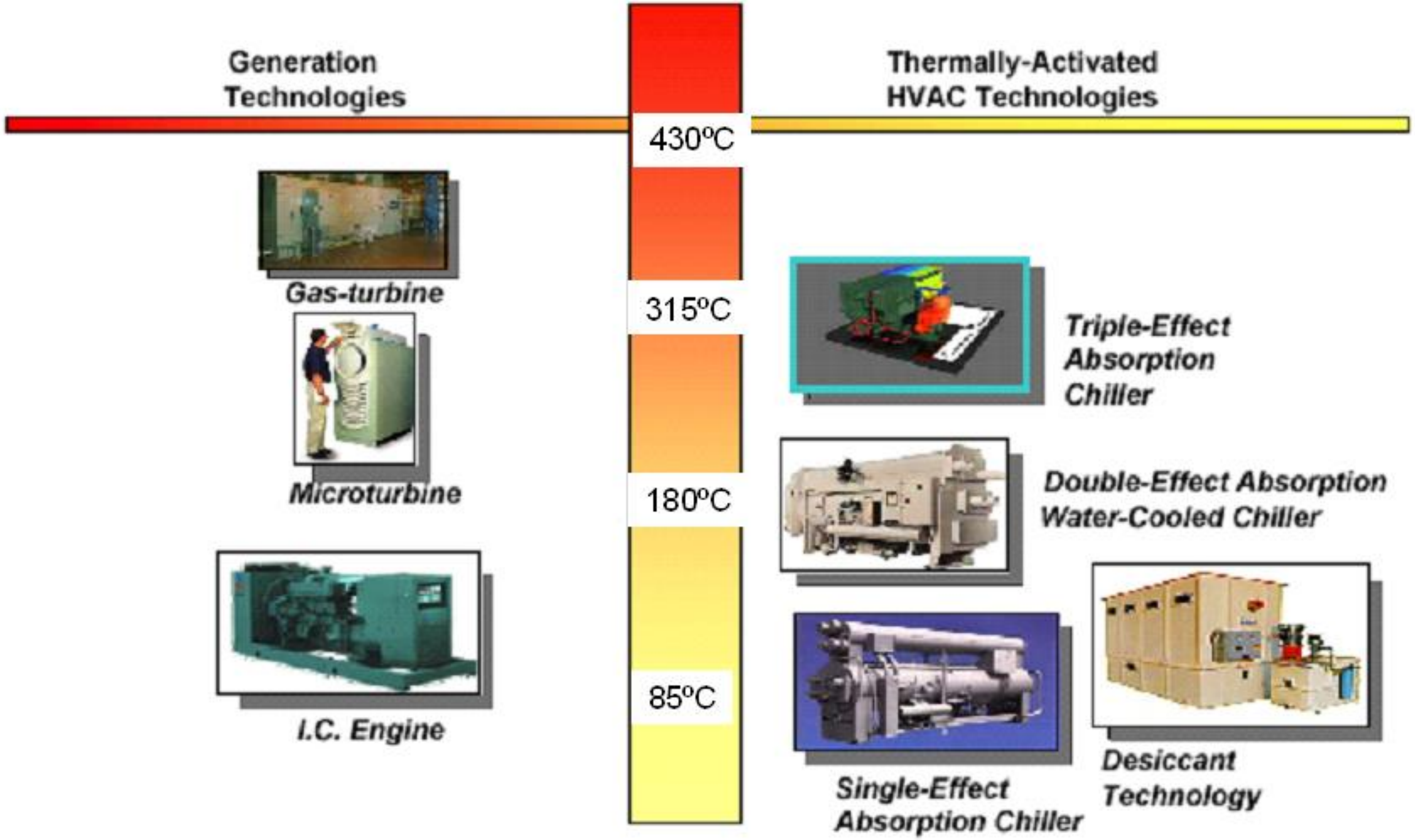
Chemical **dehumidification** removes the water vapour from the air by transferring it towards a desiccant material.

Desiccants are materials with high affinity for water vapour and may be solid or liquid.

Regeneration heat must be suppled i order to remove the adsorbed water form the desiccant material



Polygeneration Technologies: Power Engines & Heat-driven Chillers



Recoverable Energy Quality (Temperature) and HVAC Technology Match

Importance and Suitability of Polygeneration for Sustainable Communities

The European Union supports directly **Polygeneration**, with the "objective of providing more than two energy vectors, any combination of electricity, heat, cooling, and biofuels (solid, liquid or gaseous) for energy applications as well as materials."

Communities are thus choosing **Polygeneration** for two main reasons:

- **Optimisation of the use of primary energy sources**:

  One unit of primary energy source can be used to provide more useful energy than a single plant without Polygeneration.

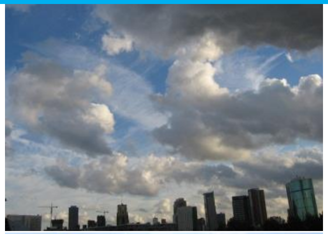
- **Use of local resources to cover local energy needs:**

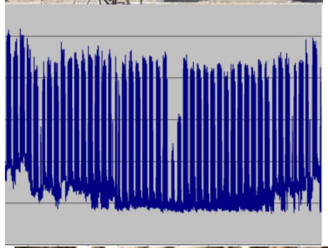
  Polygeneration can be used to convert local available energy or material resources (i.e. waste) into other forms of energy or materials, which ideally should also be used at local level.

Importance and Suitability of Polygeneration for Sustainable Communities

Suitability of type of Polygeneration depends on various factors such as:

- **Type of community (rural, urban,…)**
- **Type and mix of buildings (residential, offices,…)**
- **Demand profiles (continuous, daytime,…)**
- **Available resources (biomass, waste heat,…)**
- **Climatic situation**



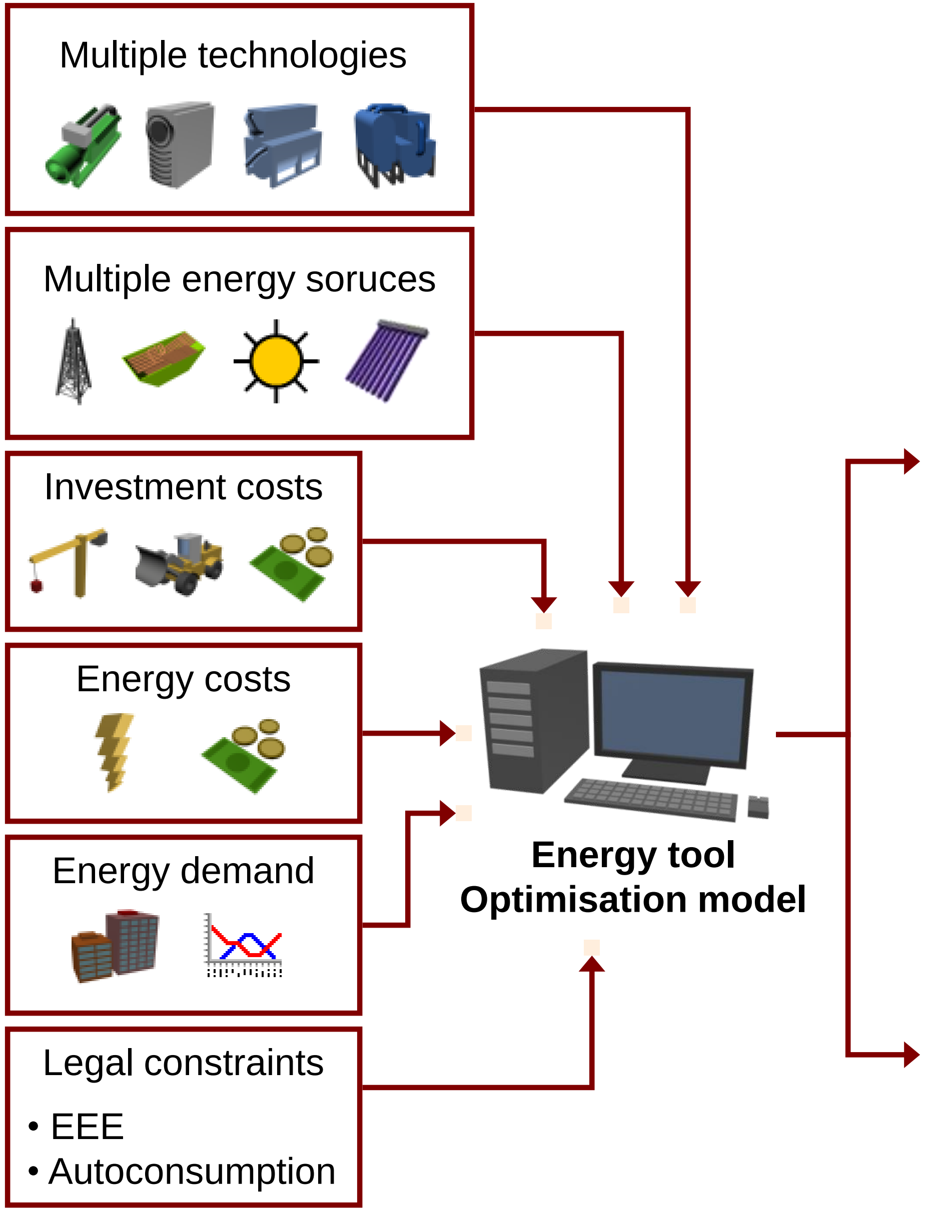


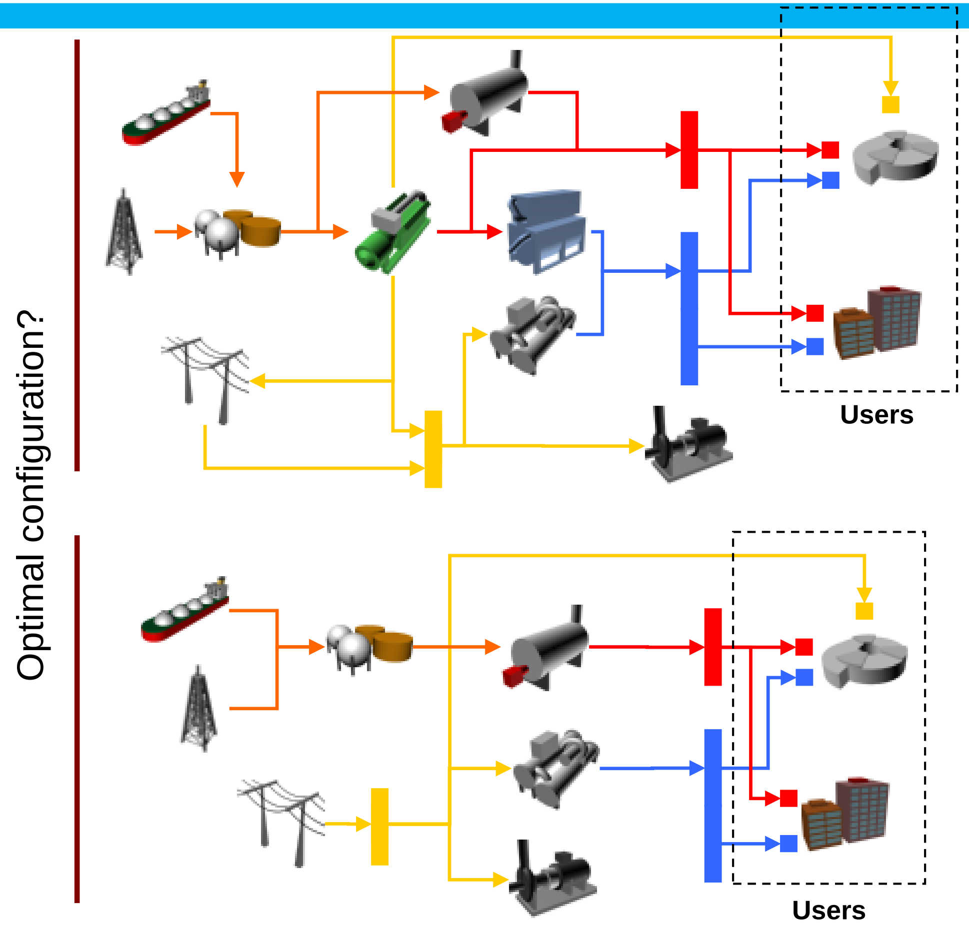
Importance and Suitability of Polygeneration for Sustainable Communities

Suitability – Which type of polygeneration for which community?

- There are a variety of polygeneration technologies and systems available.
- The appropriate system must be selected based on the type of community and the local resources.
- **In the design phase of a district energy concept**, the ambition of the energy experts is to design **an efficient energy system** which covers the overall energy needs whilst at the same time **minimising the use of primary resources**.
- Following this approach, **polygeneration technologies should be used to convert energy into energy carriers which are needed at local level** and these needs in turn depend on the type of community.

Optimisation of energy polygeneration systems (I)





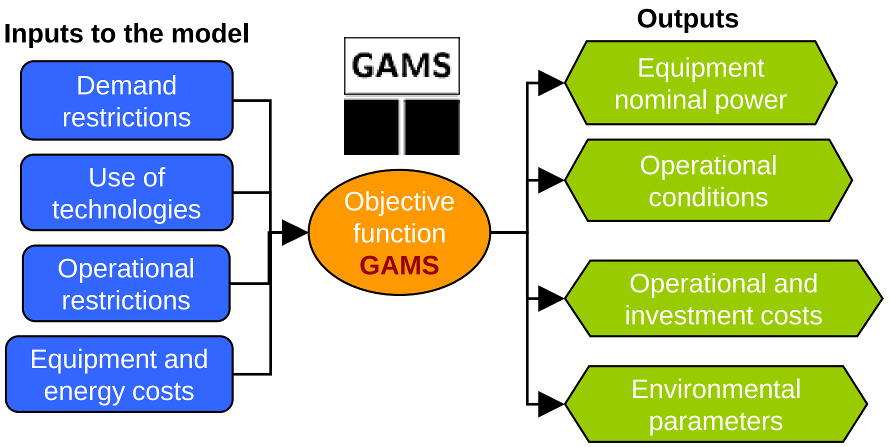
- Nominal capacities of the units
- Investment, operational and maintenance costs
- Optimal operation strategy
- Environmental balances

Optimisation of energy polygeneration systems (II)

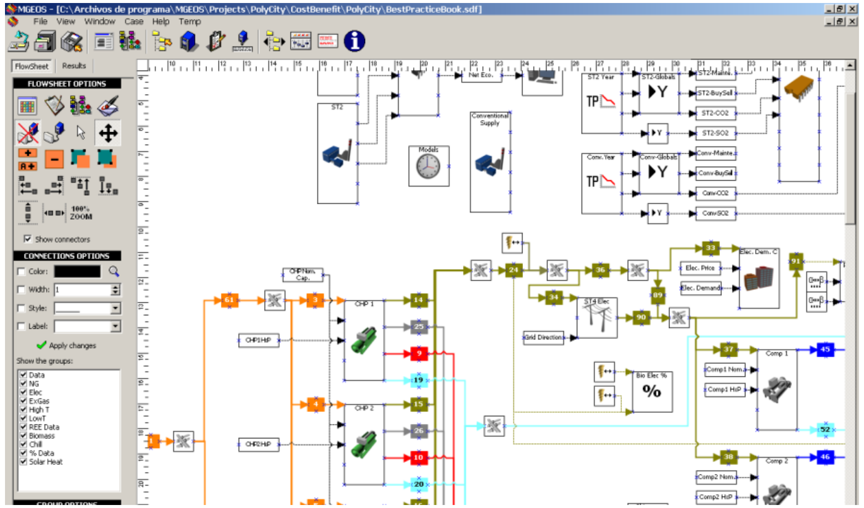
Development of optimization models using mathematical programming techniques for the optimal design and operation of polygeneration systems including economical and environmental parameters in the objective function.

The models can be used to select the type of units to be used in the polygeneration system, the optimal size of each unit or the operation strategy of the system, according to an energy demand and the cost of the energy and the units (cogeneration engines, chillers, energy storage…).

The optimization model for each unit is defined inside blocks with several input and outputs, by connecting these blocks any polygeneration system can be defined.



Inputs / output of the models

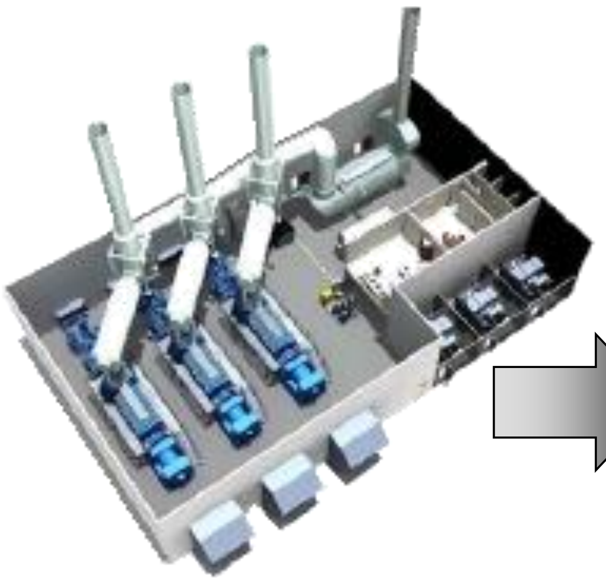


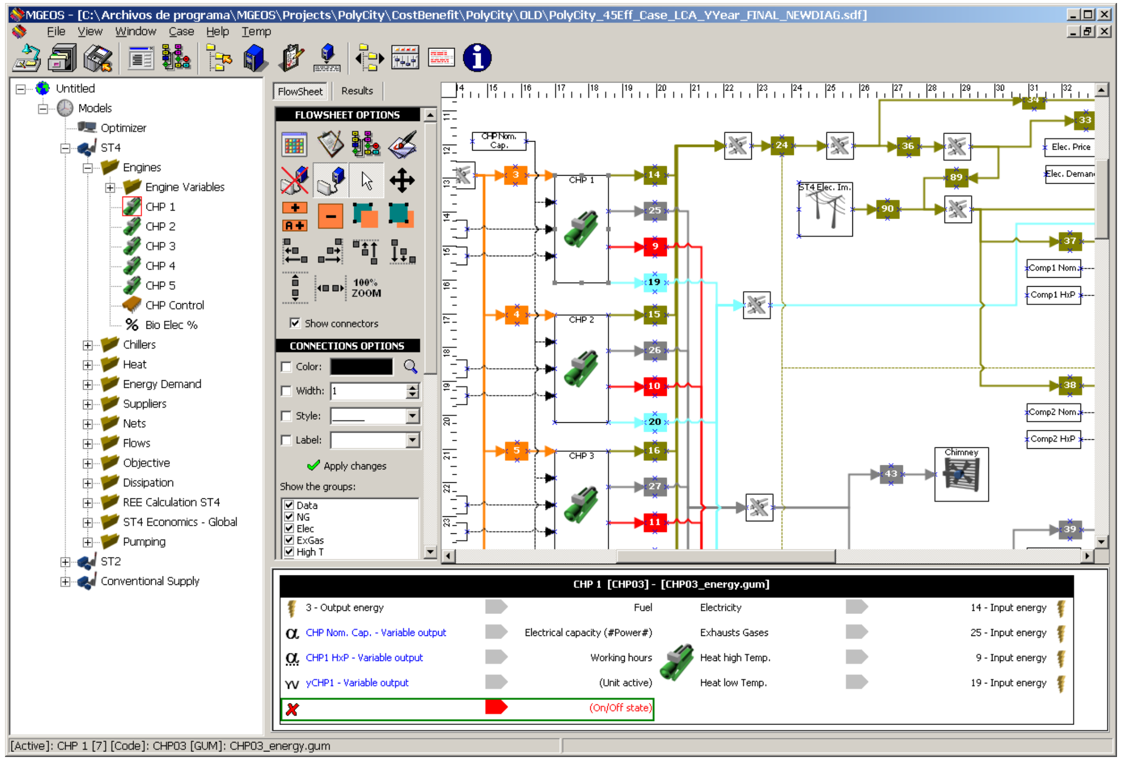
User friendly interface developed to define the polygeneration system

Optimization environment

The configuration of the polygeneration system (superestructure), the energy demand and the prices (energy, investment, maintenance) are the input data for the **optimisation environment**.

The library of components allow to represent the polygeneration system in the optimization environment.



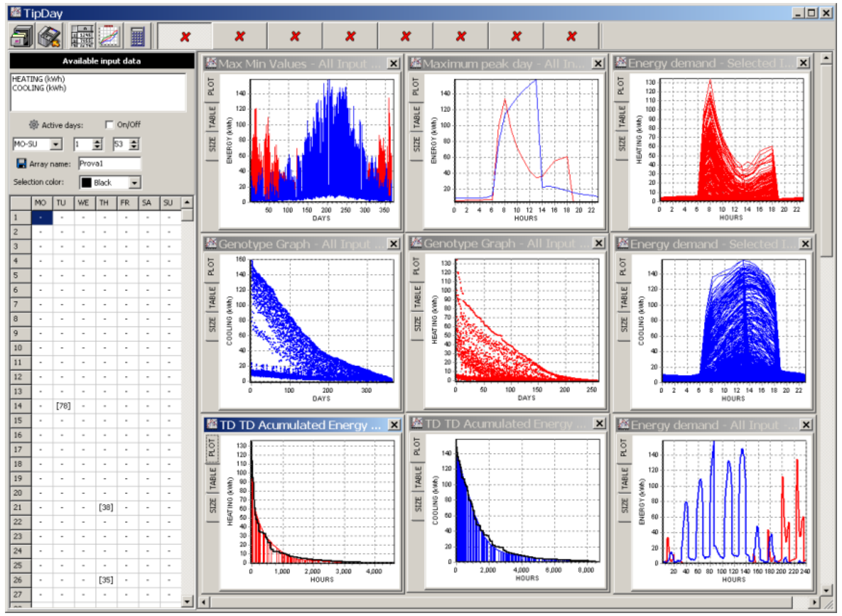


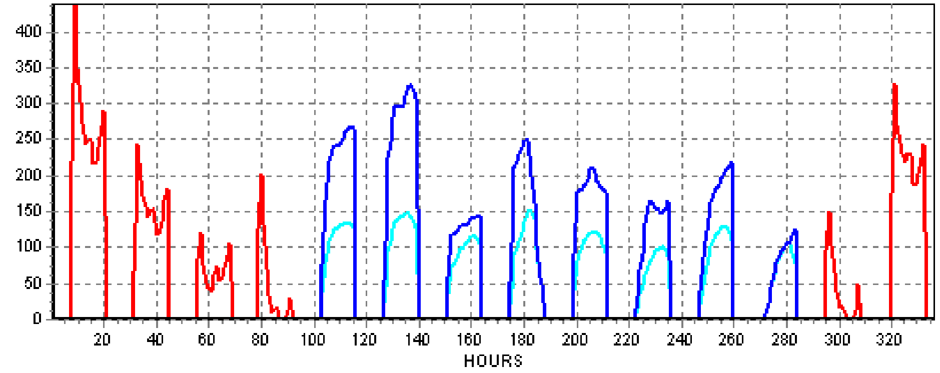
Energy Demand

One of the main factors that make an optimisation model difficult to solve is the number of periods.

These periods are defined by the number of different energy demands that have to be covered, and the periodicity considered in the model (hourly, weekly, monthly). When a high number of time periods must be analysed, the model must be simplified or the number of time periods reduced.

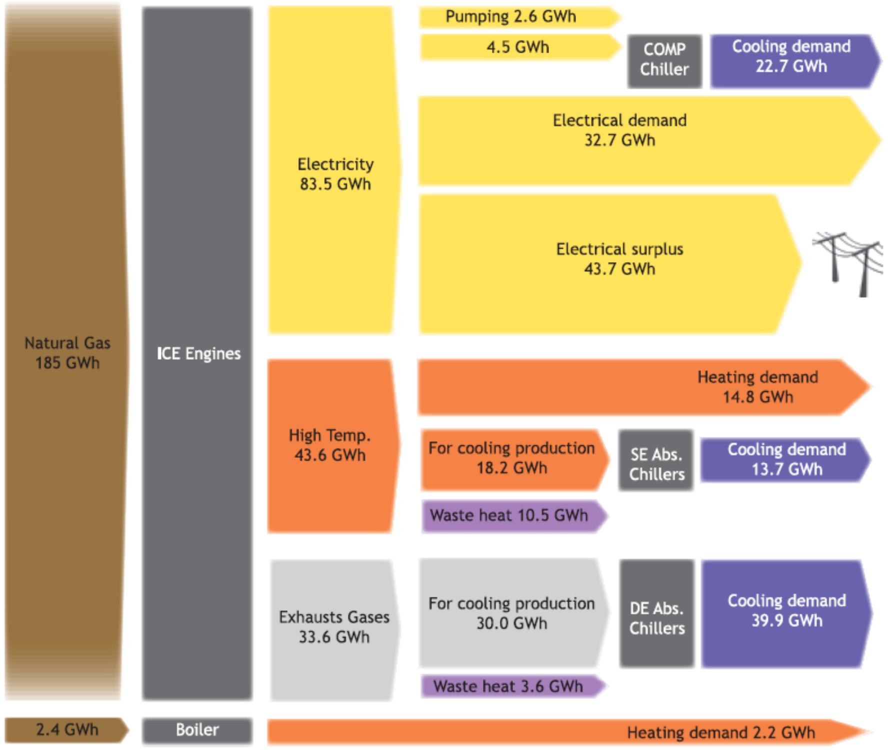
A method and a tool have been developed for selecting typical energy demand days (and the number of repetitions) in order to represent in the optimisation model the behaviour of the whole day.



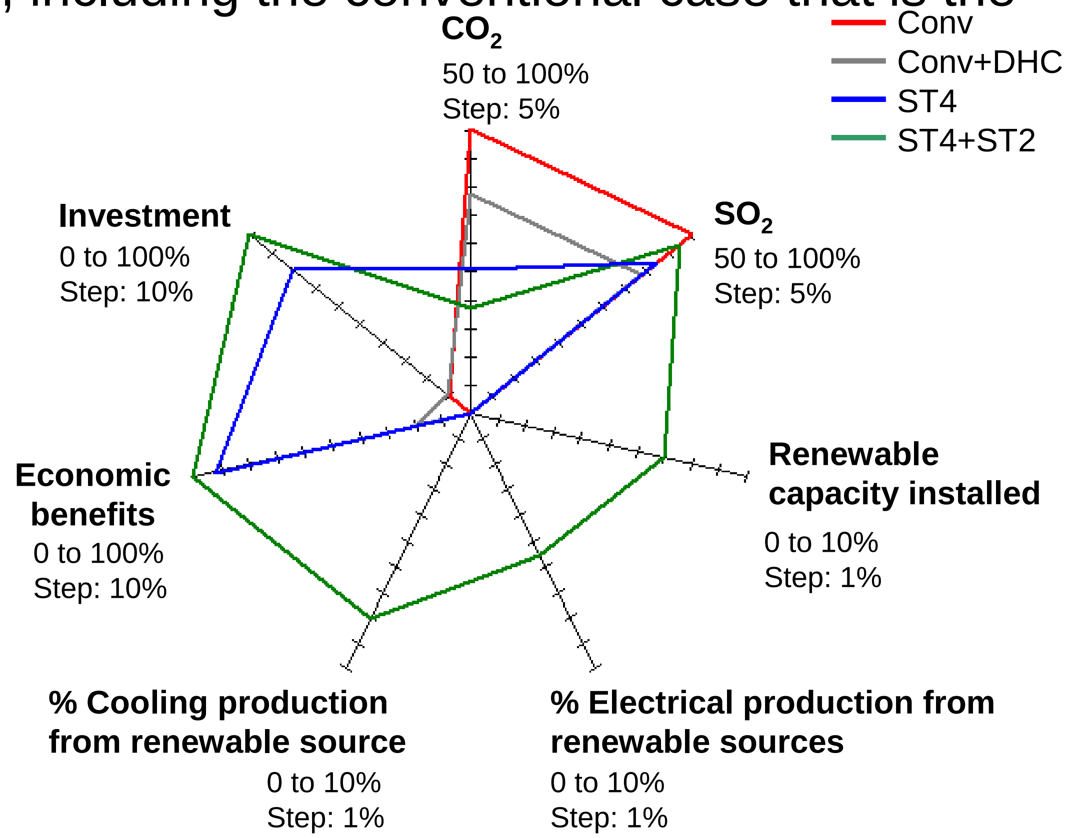


Results of the optimization process

As a result, the optimal configuration, size and operation is obtained, as well as several parameters allowing to compare between different alternatives, including the conventional case that is the reference energy supply system.

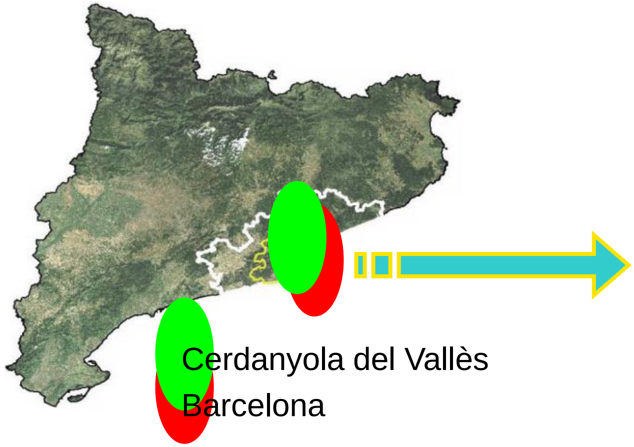


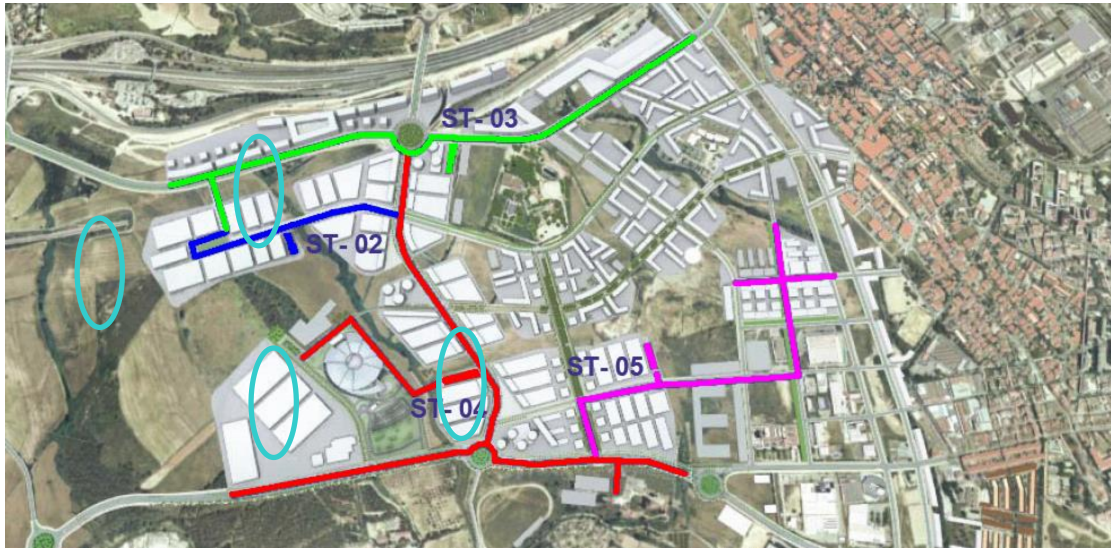
Energy balances



Comparison of several alternatives

Implementation of Polygeneration Systems: The Polycity Project





Polygeneration plants

District heating and cooling network

A new technological and scientific park is being constructed with the following characteristics: (Phase I-II)

Ground surface: 340 ha

Roof area: 1,890,000 m^2

Residential area for 15,000 inhabitants

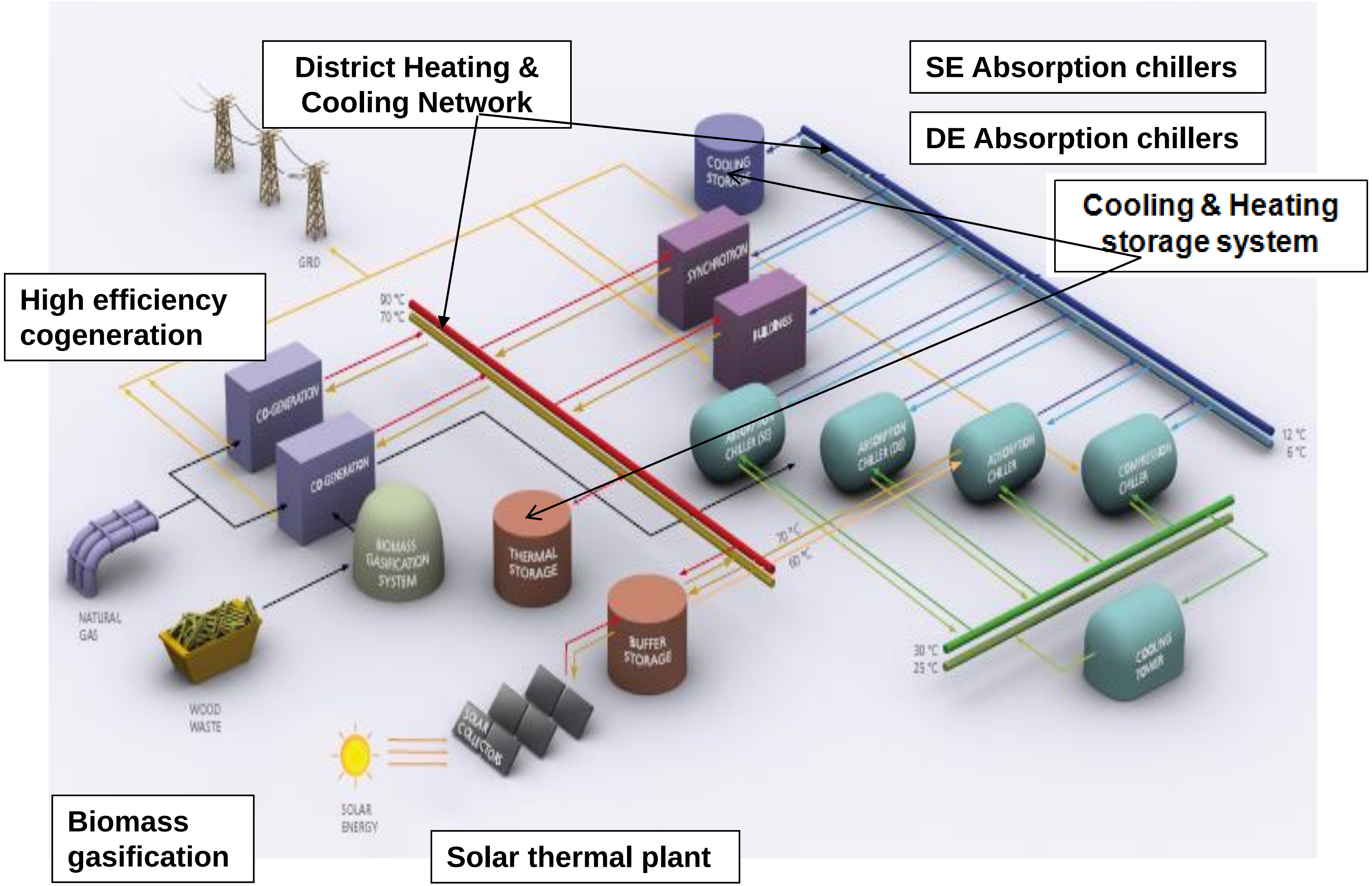
Science and Technology Park

Synchrotron Light Facility (ALBA)

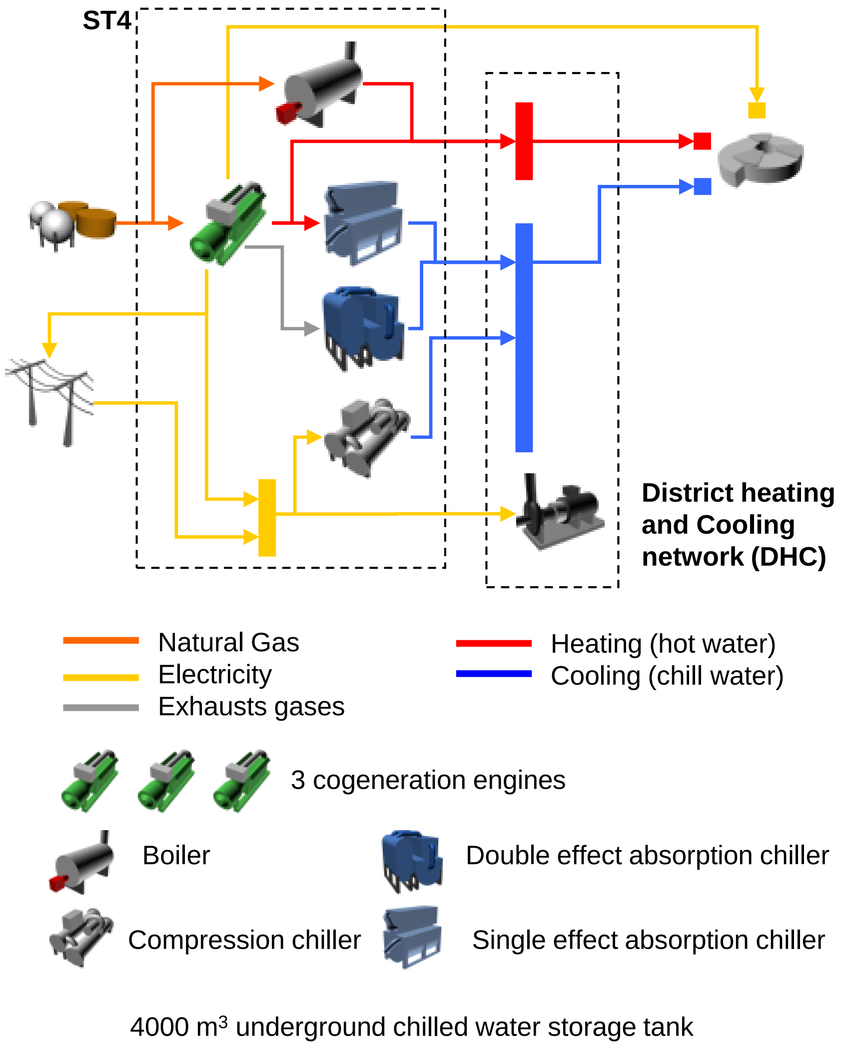
The first power plant constructed is the ST-04 plant, start-up September 2010

The system consists of distributed polygeneration plants including renewable energy sources connected to a district heating and cooling network (DHC) and exporting electricity to the grid.

Implementation of Polygeneration Systems: The Polycity Project

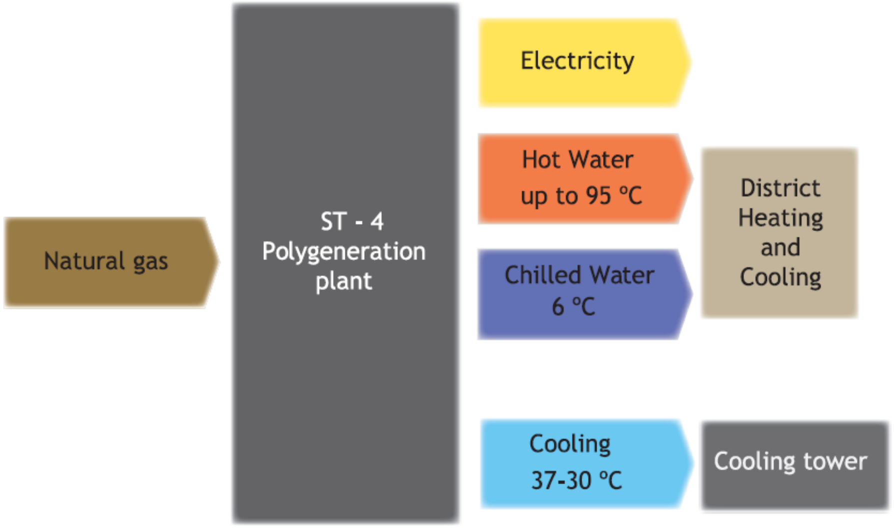


Implementation of Polygeneration Systems: The Polycity Project



The ST-4 Energy Plant produce electricity, hot water and chilled water. Currently there is only one consumer: the ALBA synchrotron light facility.

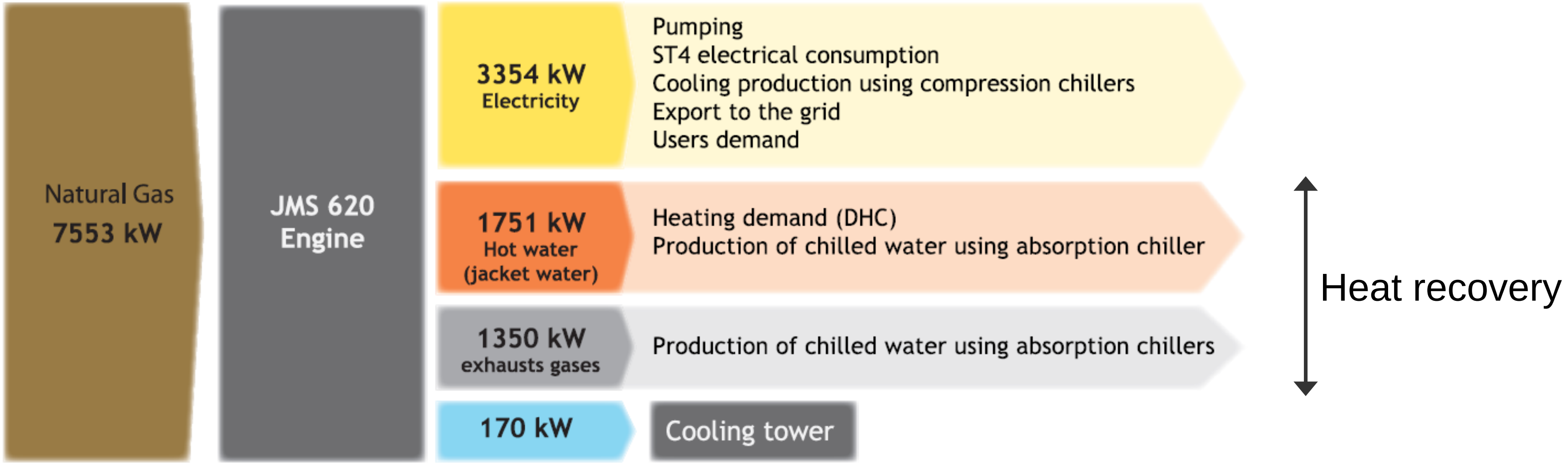
The heating and cooling demand of the synchrotron is supplied by means of a district heating and cooling network of four tubes.



Implementation of Polygeneration Systems: The Polycity Project

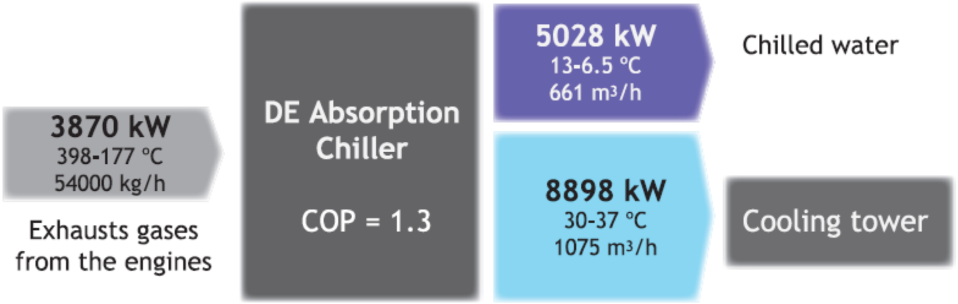
The ST-4 plant has three cogeneration engines Jenbacher JMS 620 with a nominal electrical capacity of 3.3 MW each engine.

The heat recovery of the engine is around 1.8 MW in the hot water circuit (jacket water) and 1.4 MW if the exhausts gases are cooled until 120 ºC



Implementation of Polygeneration Systems: The Polycity Project

Thermax ED 80C CX



The double effect absorption chiller is fired directly with the exhausts gases of the cogeneration engines.

At rated conditions the chilled water production is 5 MW with COP = 1.3

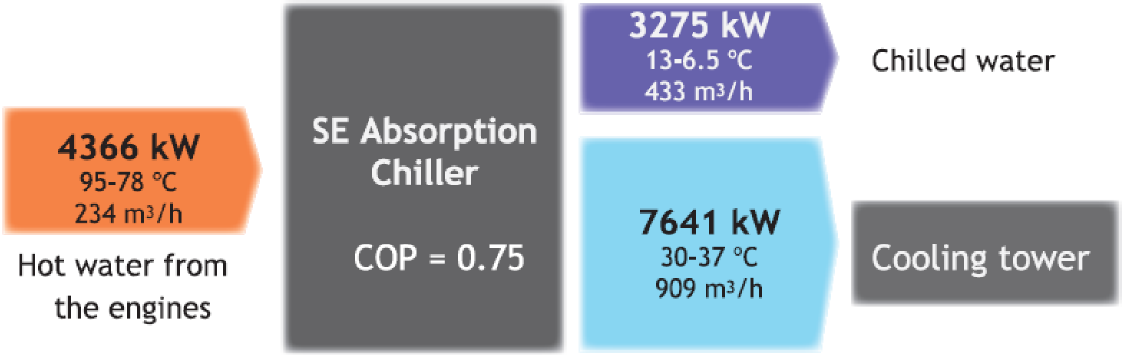
Damper that determines the amount of exhausts gases going into the chiller.

Implementation of Polygeneration Systems: The Polycity Project

The single effect absorption chiller is fired with the hot water produced in the jacket water circuit of the engines.

At rated conditions the chilled water production is 3 MW with COP = 0.75

Thermax LT105T

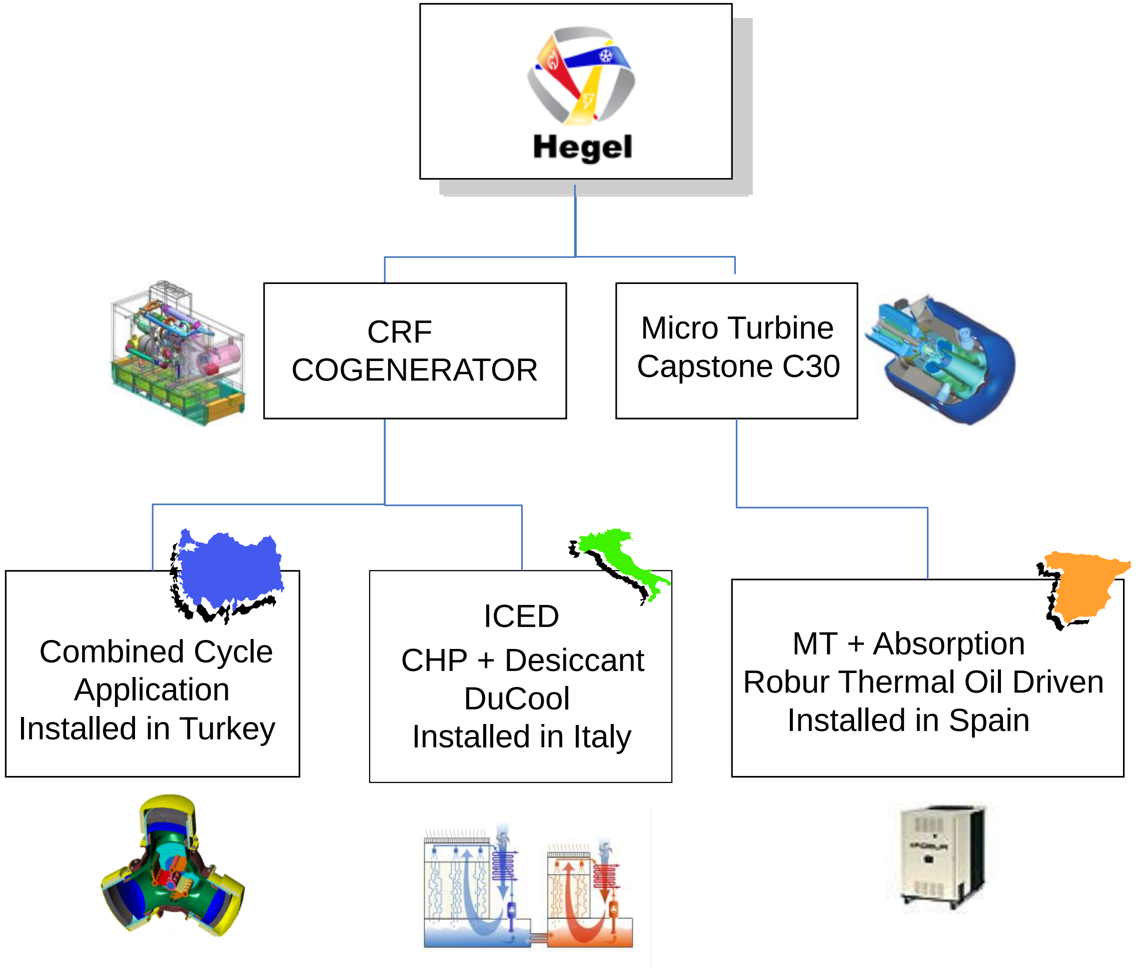


Implementation of Polygeneration Systems: The Polycity Project

ST-4 Polygeneration Plant
in Cerdanyola del Vallès
(Barcelona, Spain)

Implementation of Polygeneration Systems: The HEGEL Project

HEGEL was a project aimed to develop, demonstrate and compare high efficiency applications of micro-polygeneration systems.



<u>Three demonstration plants</u> were tested:

•"<u>ICE-Desiccant</u>"

A trigeneration plant in Politecnico di Torino (Italy)

• "<u>Combi System</u>"

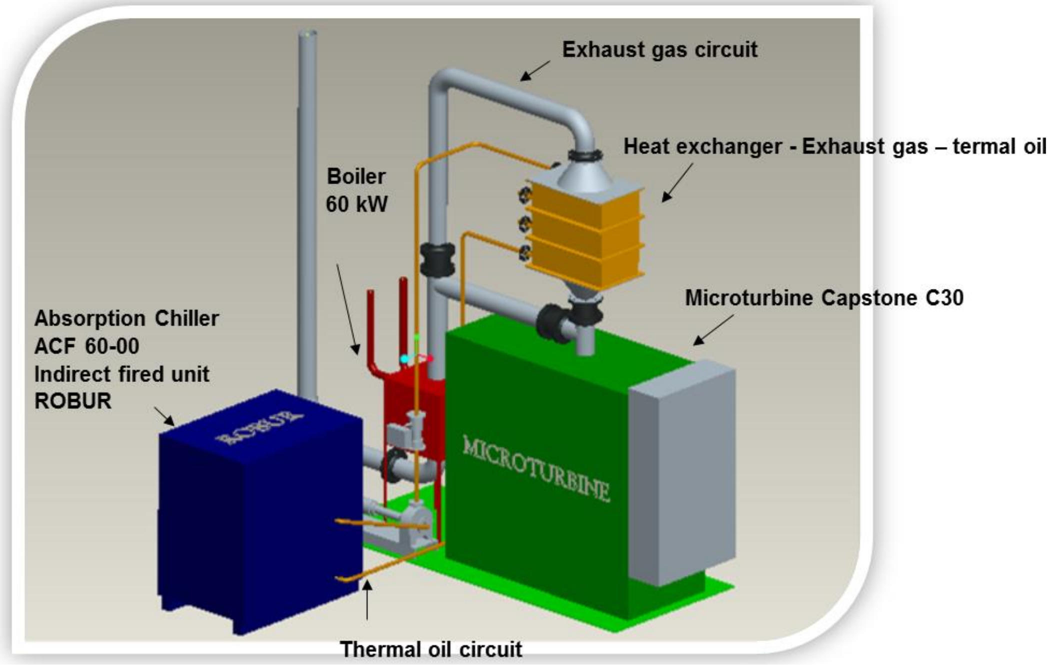
A small-size combined-cycle in Middle Technical University, in Ankara (Turkey)

•"<u>MT-Absorption</u>"

A trigeneration plant in a Districlima in Barcelona (Spain).

Implementation of Polygeneration Systems: The HEGEL Project

Characterisation and Integration of a microgasturbine for microtrigeneration applications.



Characterization of the Absorption Chiller and the Microtrigeneration System in a Multifunctional Test Bench

CLIMATIZATION ROOM

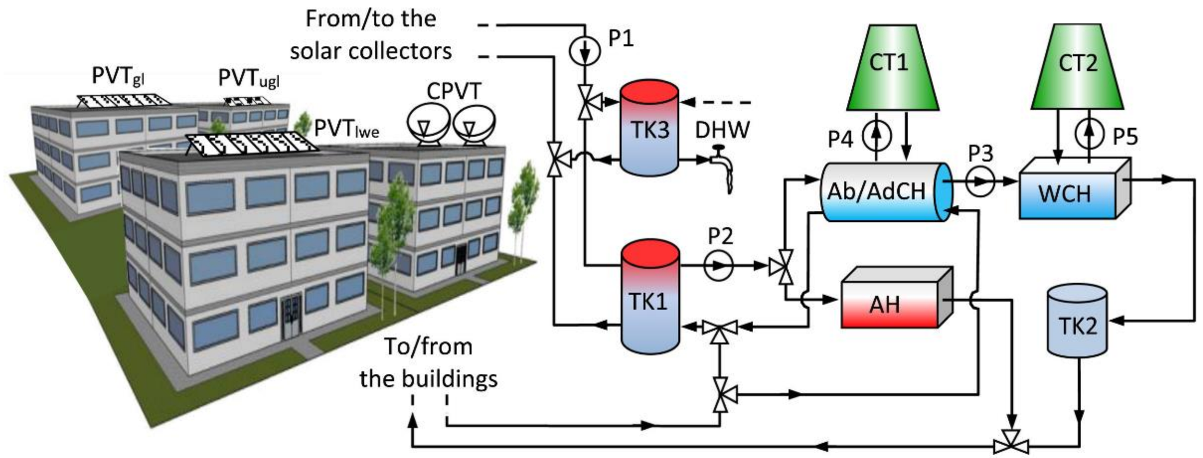
Implementation of Polygeneration Systems: The HEGEL Project

Installation of the microtrigeneration system in Districlima (Barcelona)

Emerging Technologies for Polygeneration

New polygeneration Technologies: Concentrating PV/T collectors, Gasifiers, Fuel Cells, Electrolizers, methanation reactors, High Temperature Heat Pumps, Absorption Heat Exchangers, Heat Transformers,…..etc

Solar heating and cooling systems by absorption and adsorption chillers driven by stationary and concentrating photovoltaic/thermal solar collectors



Ab/AdCH: Absorption/Adsorption CHiller
AH: Auxiliary gas-fired Heater
CPVT: Concentrating PhotoVoltaic/Thermal solar collector
CT: Cooling Tower
DHW: Domestic Hot Water
P: Pump

PVT_{gl}: simple glass flat-plate PhotoVoltaic/Thermal collector
PVT_{lwe}: low-e glass flat-plate PhotoVoltaic/Thermal collector
PV_{ugl}: unglazed flat-plate PhotoVoltaic/Thermal collector
TK: storage TanK
WCH: Water-to-water electric CHiller

Source: Buonomano A et al.;. Renewable and Sustainable Energy Reviews (2018) Vol. 82, Pa; rt 2, 874-1908;

Cold recovery from LNG-regasification for polygeneration applications

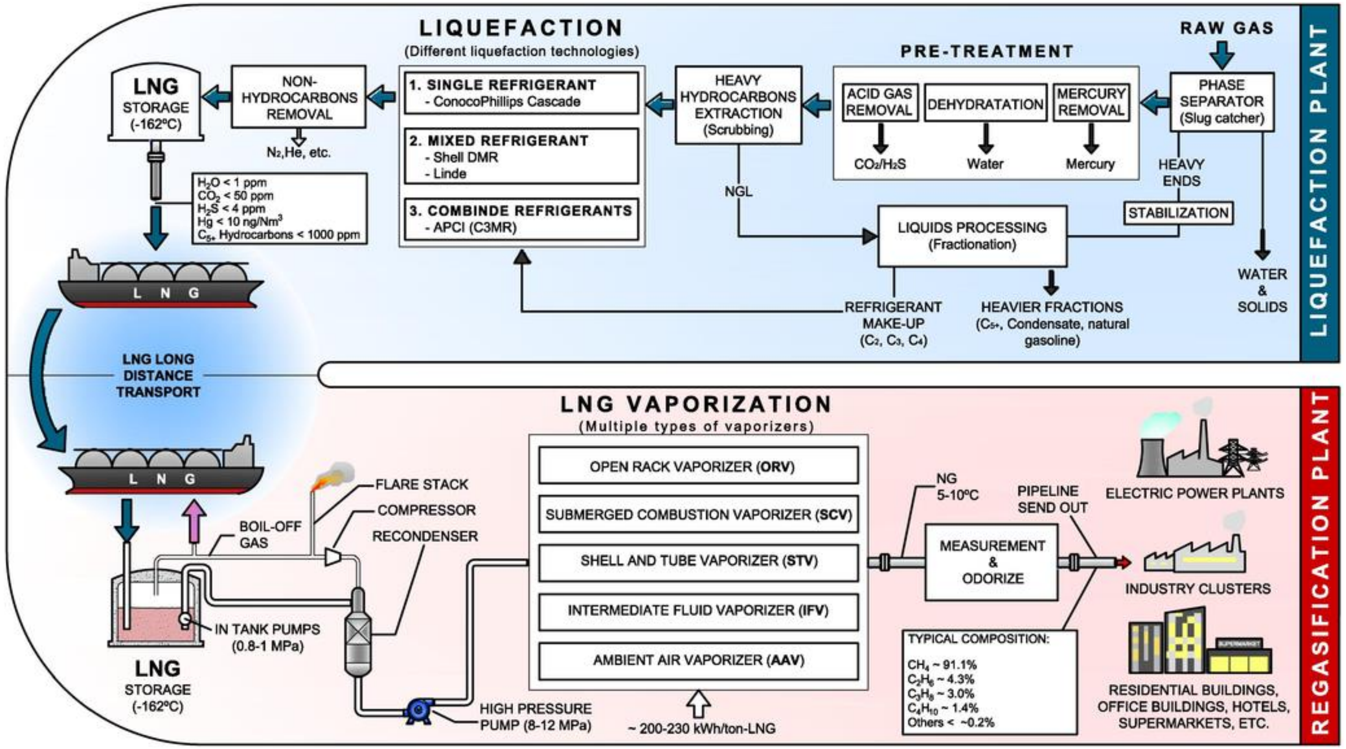
LNG supply chain: Regasification as cold recovery opportunity

The regasification is only one of the multiple stages of Natural Gas supply chain.

The natural gas liquefaction is a process that requires an important amount of energy (300–850kWh/ton-LNG)

At the end of the liquefaction process, the temp. is −162 °C with a density of 450 kg/m^3 and its physical volume is around 1/600 the volume of Natural Gas.

LNG is transported over long distances in carriers of auto-refrigerated LNG tankers with a storage capacity up to 266,000m3 of LNG

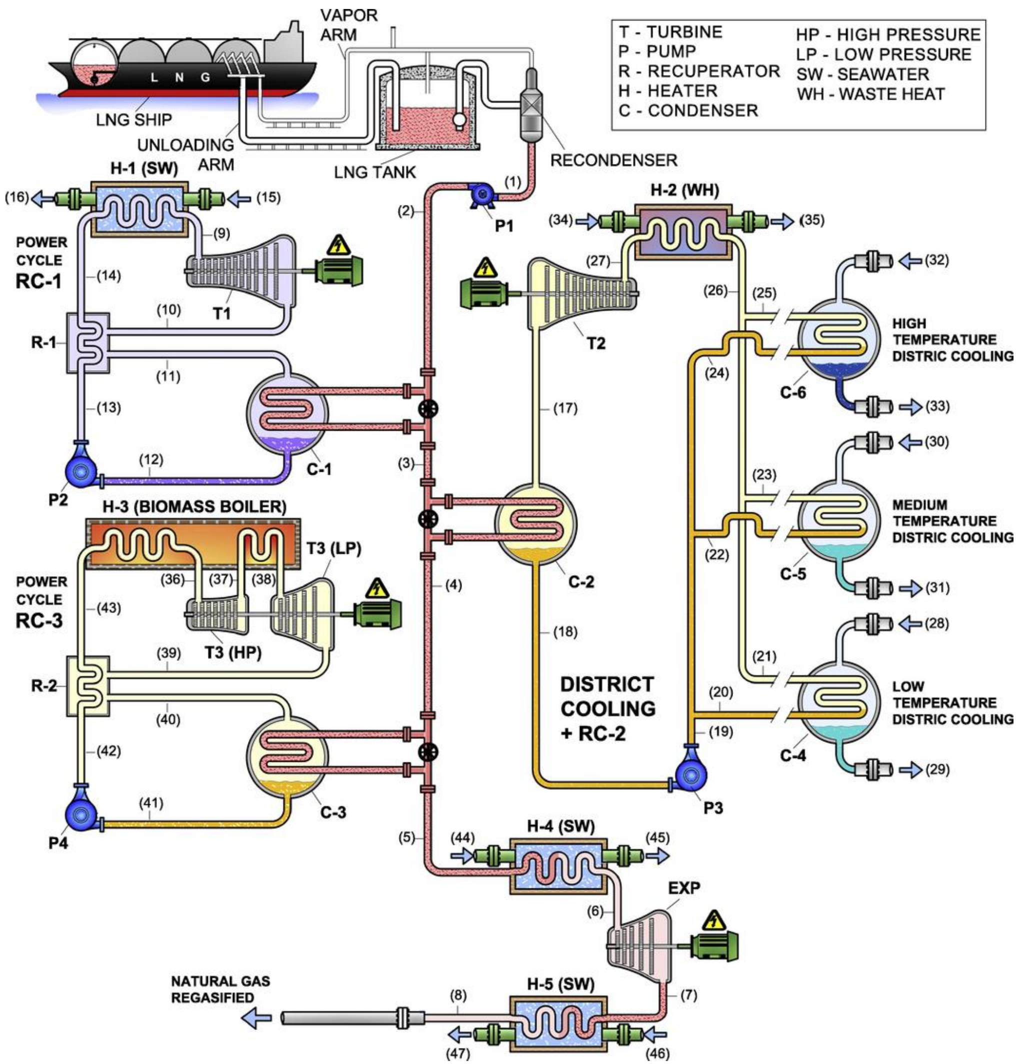


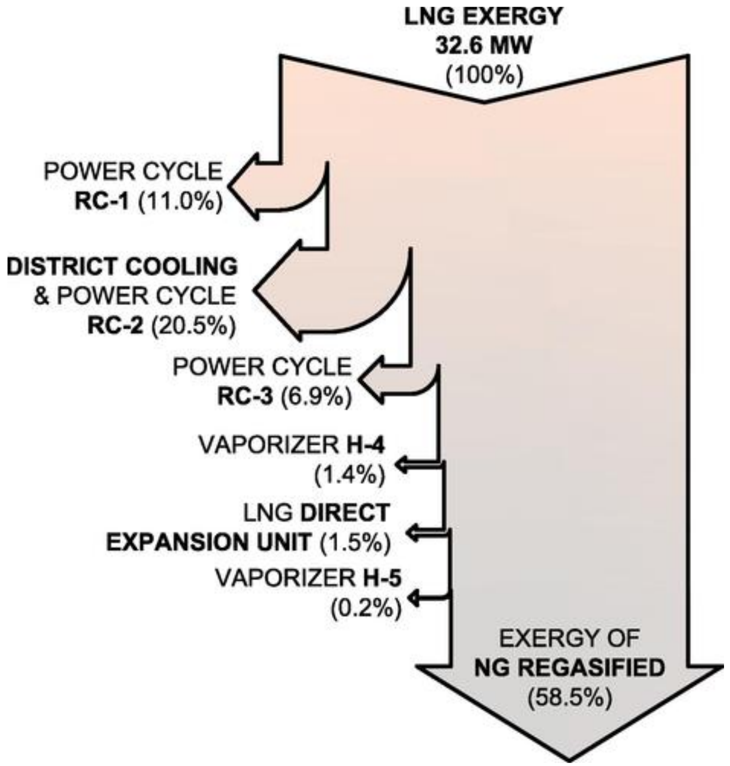
Cold recovery from LNG-regasification for polygeneration applications

- Although in the conventional regasification process the LNG cold is not recovered, **the high exergy content of LNG is very attractive** to be exploited in multiple industrial activities and low temperature processes.
- The temperature level of several low-temperature applications that are suitable for exploiting LNG exergy is shown in the Figure .
- Some of most studied applications of LNG exergy are: **cryogenic power generation, air separation process, CO_2 capture or seawater desalinization** .
- Others less explored applications are light and heavy hydrocarbon separation, cold storage , etc.

Cold recovery from LNG-regasification for polygeneration applications

Scheme of the polygeneration plant for cold recovery from LNG-regasification





LNG exergy flow diagram for the polygeneration plant. Percentages are based on the LNG exergy at the exit of the pump P1

Concluding remarks

- **Polygeneration systems** for single buildings or integrated into District Heating and Cooling networks or industrial application **can yield significant energy saving** together with Greenhouse gases (GHG) emission mitigation with respect to a conventional systems.
- Among the variety of polygeneration technologies and systems available, the appropriate system must be selected taking into account the type of application and the local resources.
- Polygeneration is a viable option to implement sustainable heat and power when polygeneration is powered by renewables.

Thank you for your attention

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