COMBI

Calculating and Operationalising the Multiple Benefits of Energy Efficiency in Europe

Description of end-use energy efficiency improvement actions in the residential, tertiary, transport and industry sectors

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1 Selection criteria

This report gives a brief description of the 21 actions selected for the COMBI project.

1.1 Terminology

Actions to improve the energy efficiency of existing technologies, or to replace conventional technologies with new, more efficient ones, are often called "measures" in the literature. Regrettably, policy *instruments* (e.g. standards, taxes, subsidies, voluntary agreements, etc.) often also go by the name of (policy) "measures". COMBI therefore decided to refer to technical measures as "technical end-use energy efficiency improvement actions", often abbreviated to "energy efficiency improvements" (EEI), or "COMBI actions" for brevity.

At the kick-off meeting in March 2015 in Antwerp, the COMBI project team agreed on the following principles or criteria for selecting the end-use energy efficiency improvement actions that would be investigated in the COMBI project:

1. Use *energy services* as a starting point (i.e. not start from technical appliances, but from services such as "heating/cooling" or "mobility");
2. Use *existing EU energy scenarios* as a reference;
3. Focus on *technical* improvements;
4. Cover *80% of the EU end-use energy saving potential*.

We elaborate on these four principles below.

1.2 Energy services

The main *energy services* (e.g. space or process heating and cooling, ventilation, lighting, transport, (other) motor drive, etc.) of the different end-use sectors (households, tertiary sectors, industry and transport) serve as a point of departure for defining the different COMBI actions.

Ideally, COMBI relies on the "whole system approach", where an energy service is approached as one integrated system. For example, for space heating the entire system would consist of the location (climate zone) and orientation of the building, its compactness, the building shell (thermal insulation, airtightness), the heating, cooling and ventilation system, and the daylighting system. An interplay/combination of different behavioural actions ("best practices") and technical actions ("more efficient technologies") thus leads to an overall energy efficiency improvement of the system as a whole.

Furthermore, COMBI has to strike a balance between too much and too little detail. For example, improving the fuel efficiency of a conventional car would not only involve improving the energy efficiency of the engine and transmission (e.g. reducing friction, recovering heat from waste, improving combustion systems, etc.) but also vehicle design (e.g. reducing mass, rolling resistance and aerodynamic drag). To look at each of those possibilities in great detail would be beyond the scope of the COMBI project.

Therefore this report will give a *qualitative* description of the actions in more technical detail, whereas the adopted COMBI scenarios will remain at the more general level of *energy intensities* (energy consumed per unit of activity level) for the different energy systems.

1.3 Existing EU energy saving scenarios

COMBI distinguishes three main factors that determine energy consumption in the residential, tertiary, transport and industrial sectors, namely *activity levels*, *structural shifts*, and finally the actual *energy efficiency improvements*.

Activity levels may refer to e.g. number of dwellings for the residential sector, value added or square meter floor area in the tertiary sectors, vehicle-kilometres for transport, and physical outputs (e.g. ton of steel) in industry.

Structural determinants are related to e.g. shares of building types (single, multi-family, high-rise) in the residential sector; the activity shares of the different subsectors (offices, health care, education, etc.) in the tertiary sector; the share of private versus public transport, and / or the share of public road versus public rail transport; and the activity shares of energy-intensive versus non energy-intensive subsectors in industry.

Energy savings, the corresponding (energy) costs savings and other impacts from energy efficiency improvements must always be calculated against a "reference". In the reference case, COMBI assumes certain values for the activity levels, the structural factors and the energy efficiency levels. To isolate the effects of "end-use energy efficiency improvements" on changes in the overall energy consumption levels from the effects caused by the two other determinants, COMBI has to keep the values of the activity levels and structural determinants constant.

In COMBI, *existing EU energy efficiency scenarios* constitute a fixed reference for both activity levels (e.g. population and GDP growth) and structural factors (e.g. shares of single and multifamily dwellings in the residential sector, activity shares of the different subsectors in the tertiary and industrial sectors, or shares of transport modes).

Preferably, one should also consider the so-called "rebound effects", where changes in energy efficiency might lead to changes in activity levels and / or structural factors. However, in the course of the project, the COMBI team decided that explicitly considering rebound effects in great detail would be beyond the scope of COMBI. It is tacitly assumed that potential rebound effects are already incorporated in the existing EU energy saving scenarios.

1.4 Focus on technical improvements

Technical energy efficiency (EE) improvements are the focal point of COMBI, whereas behavioural and structural changes are assumed to be incorporated in the referenced EU scenarios (see item 2).

However, during the course of the project it soon became apparent that "modal shift" in transport would have to be included in the list of actions, given its prominence in realizing energy savings in that particular sector. Hence, different assumptions regarding the shares of non-motorized transport (walking, cycling) road and rail transport, inland navigation and aviation were taken into account.

We furthermore emphasize that technical improvements work on two levels:

1. Efficiency improvements of existing technologies;
2. A shift towards more efficient technologies.

A few examples will clarify this. For the residential and tertiary sectors, more in particular space heating, technical energy efficiency improvement actions of the heating systems consist of (combinations of):

- Energy efficiency improvements of conventional space heating technologies such as oil or natural gas boilers;
- A shift towards more energy efficient technologies such as heat pumps or solar heating.

For transport, possible actions relate to:

- Energy efficiency improvements of conventional drivetrains, such as internal combustion engines (ICE);
- A shift towards more energy efficient vehicles, such as hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) or battery electric vehicles (BEV),

Finally, for industry, more in particular low and medium temperature process heating, actions could refer to:

- Energy efficiency improvements of steam boilers;
- An increase in the share of combined heat and power (CHP) units or cogeneration, at the detriment of separate heat and power production (SHP).

The range of technical actions will be discussed in more detail in chapters two and following of this report.

1.5 Cover 80% of potential EU end-use energy savings

The COMBI actions should ideally cover approximately 80% of the energy efficiency potential in the EU. At the start of the COMBI project, the most recent and relatively most detailed final energy savings figures were only available from a Fraunhofer ISI research project (2009; 2012). This study estimated final energy savings potentials for the EU27 by 2030 (relative to a PRIMES final demand baseline scenario) for the households and tertiary sectors, transport and industry.

The results for the households and tertiary sector are as shown in table 1.

Table 1: Potential final energy savings in the residential and tertiary sectors

Energy service	Residential MTOE	Tertiary MTOE	Share %	Share %
Building envelope existing buildings	76	27	44.8%	40.3%
Building envelope + heating new buildings	27	10	15.9%	14.9%
Heating existing buildings	41	(a)	24.2%	
Heating and cooling existing buildings	(a)	16		23.9%
Fans	..	3		4.5%
Lighting	8	6	4.7%	9.0%
Street lighting	n.r.	2		3.0%
Green ICT (information, communication)	(b)	(b)		
Household appliances	5.6	-	3.3%	
Commercial refrigeration and freezing	-	2		3.0%
Sanitary hot water	12	..	7.1%	
Other motor appliances	..	1		1.5%
	169.6	**67**	**100%**	**100%**

(a): 57 Mtoe heating and cooling for existing buildings in both residential and tertiary sectors. COMBI assumed that space cooling in the residential sector is low for most EU member states.

(b): Energy savings largely compensated by increased use of ICT appliances.

For (residential and tertiary) buildings, one can easily obtain the 80% savings-coverage target by looking at the building envelope, space heating and cooling, ventilation, sanitary hot water and lighting. The COMBI project team decided to also include refrigeration and freezing (of products), as an example of how savings can be realized at the level of appliances.

The results for the transport sector are given in table 2.

Table 2: Potential final energy savings in the transport sector

Energy service	MTOE	Share
Improved efficiency of road vehicles	77	49.4%
Behavioural changes (a)	38	24.4%
e-mobility passenger transport (b)	1	0.6%
Modal shift in passenger transport	14	9.0%
Modal shift in freight transport	5	3.2%
Improved efficiency of trains	2	1.3%
Technical & operational Improvements in aviation	19	12.2 %
	156	**100.0%**

(a) Mainly eco-driving for passenger transport; and improved load factor for freight transport

(b) Diffusion of electric and (plug-in) hybrid vehicles

It is immediately apparent that behavioural changes and structural (modal) shifts play a very important role in the transport sector. However, given the focus of COMBI on technical improvements, a detailed analysis of behavioural changes was not included. It was also decided to concentrate on road and rail transport, due to budget and time constraints. As a consequence, the 80% savings potential target for transport was only attained under the assumption that behavioural changes should be excluded.

Finally, the aforementioned Fraunhofer study assessed the final energy savings potentials for industry, as shown in table 3.

Table 3: Potential final energy savings in the industrial sectors

Energy service	MTOE	Share
Process technologies, except pulp & paper (a)	18.00	28.7%
Pulp and paper	4.00	6.4%
Improvement of SHP and CHP (b)	10.00	15.9%
CHP diffusion	9.00	14.3%
Industrial space heating	20.00	31.9%
Pumps, fans and compressed air	0.80	1.3%
Industrial refrigeration	0.12	0.2%
Miscellaneous electric motor drives	0.80	1.3%
	62.72	**100.0%**

(a) Including iron and steel, non-ferrous metals, chemical, non-metallic minerals (mainly glass and cement)

(b) SHP = separate heat production; CHP combined heat and power or cogeneration

Process technologies in the energy-intensive subsectors (iron and steel, non-ferrous metals, chemical, non-metallic minerals and paper and pulp), low and medium temperature process heating as well as industrial space heating account for the bulk of potential energy savings in industry.

2 Selection of COMBI actions

2.1 COMBI actions for households and tertiary sectors

The energy services of the residential and tertiary sectors are very similar. The most relevant energy services are:

- Space heating;
- Space cooling, predominantly room air conditioning (RAC)for households; and central air-conditioning (CAC) in tertiary sectors;
- Ventilation ("fans"), often in combination with space cooling, esp. in the tertiary sectors;
- Water heating [domestic hot water (DHW) or sanitary hot water] for households; or process heat (domestic hot water, cleaning, sterilizing, etc.) in tertiary sectors;
- Lighting; including street lighting (tertiary);
- Cold appliances(refrigerators, freezers, refrigerator-freezers) for households; and commercial refrigeration and freezing (mainly retail sector);
- Wet appliances (washing machines, tumble driers and dishwashers)for households; and laundry (mainly hotels and health sector);
- Cooking appliances (hobs, ovens, microwave ovens, range hoods)for households; and cooking (mainly restaurants, hotels, large offices);
- Home equipment (TVs, set-top boxes, audio, mobile devices, ...) for households;
- Office equipment (broadband communication equipment, desktop and laptop computers, scanners, copiers, ...) for households; and ICT (office equipment and data centres);
- Other appliances for households; and elevators/lifts and miscellaneous building technologies for tertiary sectors.

In COMBI, energy efficiency improvement actions concerning the building shell, space heating and space cooling (air-conditioning) and/or ventilation, are lumped into one COMBI action. However, a clear distinction is made between existing (residential and non-residential) buildings on the one hand, and new buildings on the other hand. The *rationale* is that certain sub-actions, such as improvements of the buildings shell, are easier to accomplish for new constructions.

Although domestic hot water (DHW) is an important energy service, and in many cases directly related to space heating, it was decided during the COMBI project to not include actions related to DHW as a separate COMBI action, mainly because of severe data problems.

Actions concerning (artificial) lighting are important for both residential and non-residential buildings. Because of time and budget constraints street lighting was eliminated in the course of the project.

Appliances were omitted from the list of COMBI actions, with the exception of product cooling and/or freezing in both the residential and tertiary sectors.

Hence, the list of COMBI actions for the residential and non-residential sector is as follows:

- Action 1: residential refurbishment of the building shell + space heating + ventilation + space cooling (air-conditioning);
- Action 2: residential new dwellings;
- Action 3: residential lighting (all dwellings);

- Action 4: residential cold appliances (all dwellings);
- Action 5: non-residential refurbishment of building shell + space heating + ventilation + space cooling (air-conditioning);
- Action 6: non-residential new buildings;
- Action 7: non-residential lighting (all buildings);
- Action 8: non-residential product cooling (all buildings);

These actions are discussed in more detail in chapter 4.

2.2 COMBI actions for transport sector

Transport services in COMBI cover passenger and freight transport. For both types of services COMBI looks at modal shifts on the one hand, and technical energy efficiency improvements of a selected number of vehicle types (motorized two-wheeler, car, bus, light and heavy duty truck) on the other hand.

Allocating estimated energy savings per action varies largely between two quantification approaches: whether a) assuming first a modal shift and efficiency increases of the rolling stock afterwards or b) efficiency increases to the baseline stock and modal shift afterwards. In reality, both actions happen in parallel. But allocating the savings of increased efficiency of the baseline stock would be a severe overestimation of savings, given we assume modal shift to happen at the same time. The COMBI consortium decided thus to go for approach a).

The list of COMBI actions for the transport sector is thus as follows:

- Action 9: passenger transport – modal shift;
- Action 10: passenger transport – motorized two-wheelers;
- Action 11: passenger transport – car;
- Action 12: passenger transport – bus;
- Action 13: freight transport – modal shift;
- Action 14: freight transport – light duty truck (LDT);
- Action 15: freight transport – heavy duty truck (HDT).

These actions are discussed in more detail in chapter 5.

2.3 COMBI actions for industrial sectors

Industrial energy services consist of:

- process heating: high temperature process heat (mainly furnaces or ovens);
- process heating: medium and low temperature process heat (mainly boilers);
- process cooling and industrial refrigeration;
- machine drive (including pump, fan and compressor systems and other machine drive applications);
- electro-chemical processes;
- facilities (including heating, ventilation, air conditioning and lighting of industrial buildings);
- materials handling and onsite transportation;
- other process or non-process uses.

Materials handling and onsite transportation as well as other process or non-process uses are excluded in the COMBI analysis. Electrochemical processes are referred to as “specific process electricity”. Furthermore, the COMBI analysis is limited to seven (7) of the most energy-intensive industrial sectors, namely:

1. Iron and Steel;
2. Non-ferrous metals;
3. Chemical and Petrochemical;
4. Non-metallic minerals;
5. Paper, Pulp and Printing;
6. Food, Beverages and Tobacco;
7. Machinery and transport.

The list of COMBI actions for the industrial sector reduces to:

- Action 16: industry (7 sectors) - high temperature process heating;
- Action 17: industry (7 sectors) - low and medium temperature process heating;
- Action 18: industry (7 sectors) – process cooling;
- Action 19: industry (7 sectors) – specific process electricity;
- Action 20: industry (7 sectors) – motor drive;
- Action 21: industry (7 sectors) – HVAC in industrial buildings.

These actions are discussed in more detail in chapter 6.

2.4 Final list of COMBI actions: summary

Table 4 lists the end-use technical end-use energy efficiency improvement actions analysed in detail by the COMBI project.

Table 4: List of selected end-use technical energy efficiency improvement actions for the COMBI project

#	End-use energy efficiency action
Action 1	residential refurbishment of the building shell + space heating + ventilation + space cooling (air-conditioning)
Action 2	residential new dwellings
Action 3	residential lighting (all dwellings);
Action 4	residential cold appliances (all dwellings);
Action 5	non-residential refurbishment of building shell + space heating + ventilation + space cooling (air-conditioning)
Action 6	non-residential new buildings
Action 7	non-residential lighting (all buildings)
Action 8	non-residential product cooling (all buildings)
Action 9	passenger transport – modal shift
Action 10	passenger transport – motorized two-wheelers
Action 11	passenger transport – car
Action 12	passenger transport – bus
Action 13	freight transport – modal shift
Action 14	freight transport – light duty truck (LDT)
Action 15	freight transport – heavy duty truck (HDT)
Action 16	industry (7 sectors) - high temperature process heating
Action 17	industry (7 sectors) - low and medium temperature process heating
Action 18	industry (7 sectors) – process cooling
Action 19	industry (7 sectors) – specific process electricity
Action 20	industry (7 sectors) – motor drive
Action 21	industry (7 sectors) – HVAC in industrial buildings

3 Use of EU energy efficiency scenarios

3.1 The use of existing EU scenarios

The original idea was to use the results of existing scenario studies at the EU level, such as the ones derived from the PRIMES or JRC models, to assess the energy savings potentials as well as the direct costs of energy efficiency improvement actions, per individual COMBI action, for the EU as a whole and per individual EU Member State. Within the time and budget constraints of the COMBI project it would obviously have been impossible to 1) construct a completely new energy system model for all 28 EU member states; and 2) to built original scenarios which at any rate would also have to involve consulting a large group of stakeholders. Other complementary data would include information from relevant EU studies such as those on energy efficiency in buildings by ABUD or on energy savings potentials by Wuppertal Institute (WI). A significant amount of data was collected on the characteristics of energy efficiency technologies, including – amongst many others – applicability (e.g. country or region where it is utilised), development status, lifetime and construction time, energy consumption and energy intensity, energy efficiency, capacity, capital costs, maintenance and operating costs, pollution control and environmental loadings.

An energy accounting model in work package two (WP2) of the COMBI project would subsequently apply relatively minor variations in the results of existing EU scenarios by moderately changing a few "driver variables" over the planning horizon, such as e.g. percentage shares of particular energy saving technologies. In a bi-directional dataflow the other work packages would both deliver information to this energy accounting model and receive processed information based on the energy accounting model outputs.

During the initial and following stages of the COMBI project, the list of energy efficiency improvement actions was constructed, revised and fine tuned (see chapters 1 and 2), depending on the particular needs of the project partners and information availability.

The collection and processing of existing EU scenario results however was significantly delayed. The initial intent to use existing scenarios, more in particular either the PRIMES or the JRC scenarios for the EU, did not work out.

Deliberations among the COMBI partners in 2015 revealed that a huge amount of detail would be needed. Information would not only be required on energy savings and corresponding (investment) costs, but e.g. also on energy carrier mix and stocks of energy technologies. Additionally, this information had to be available per individual COMBI action and for all 28 individual EU member states. This amount of detail was not obtainable from reports available to the general public.

3.2 The use of original COMBI scenarios

The setback of not receiving the detailed results of existing EU scenarios (in particular those of PRIMES or JRC) meant that the partners responsible for the data analysis in work package two (WP2) within the COMBI project (UAntwerp), had to develop both a set of state-of-the-art energy system models as well as original scenarios, even though the latter would still be based – to the extent possible – on publicly available information from previous scenario analysis studies at the

EU level. Such a project would realistically require around 50 to 500 person-years (depending on the level of detail), whereas UAntwerp had less than 1 person-year available within the COMBI project, in other words, an impossible task. Thus, most of the work done by UAntwerp was extra-curricular and not entirely funded by the COMBI project.

Nonetheless, UAntwerp in an extremely short amount of time succeeded in constructing original and fully functional albeit by necessity somewhat rudimentary end-use energy models for the buildings sectors (residential and non-residential), the transport sectors (passenger and freight transport) and a substantial part of industry (the aforementioned seven energy-intensive industrial sectors).

Originally, work package two (WP2) would make use of an existing energy accounting model (LEAP). Given the unexpected unavailability of detailed information from existing EU energy scenario studies, a new set of energy system models was developed in MS Excel. These models had to include proper, detailed "stock analysis". This was a prerequisite as detailed information on stocks would be required by the COMBI partners as input for their work packages, more in particular work package four (resources) and five (building-related health and productivity impacts). Furthermore, the use of Visual Basic for Applications (VBA) in MS EXCEL added much needed flexibility in the actual modelling of the different energy systems. The use of stock analysis led to the added burden that scenarios had to be defined in terms of "percentage share of annual new sales for energy efficient technologies", rather than in terms of "market share of an energy efficient technology in a particular year". As this type of information is rarely available, if at all, a lot of original and very time-consuming work had to be done constructing the various COMBI scenarios.

The aforementioned COMBI models were consequently used to calculate "reference" and "energy efficiency" scenarios, for each of the COMBI actions and for each individual EU member state. The results were transferred to the other COMBI partners for evaluation and use in their respective models.

Detailed assumptions and results of the COMBI scenarios are available in separate Excel sheets.

4 COMBI actions in the residential and tertiary sectors

4.1 Actions 1 and 5: residential and non-residential refurbishment of the building shell + space heating + ventilation + space cooling (air-conditioning)

For both residential and commercial buildings the building envelope (a.k.a. building shell, fabric or enclosure) plays a key role in determining levels of heating, cooling, ventilation and natural lighting (Fraunhofer ISI 2009; 2012)

An optimum design of the building envelope, or an improved energy related performance of the existing building envelope can minimise potential heating, cooling, ventilation and (artificial) lighting requirements.

There are two perspectives on the relative importance of the building envelope and heating and cooling equipment (IEA, 2013b):

- The passive design approach. This approach promotes high levels of energy efficiency in building envelope components. Any remaining need for heating or cooling is met by basic, efficient mechanical equipment;
- The smart technology approach. This approach promotes high energy efficiency in mechanical equipment (space & water heating, heat storage, cooling and dehumidification), because it is routinely replaced and installing it is easier than retrofitting old, inefficient building envelopes.

The building envelope will be in place for many years, and the most energy efficient building envelopes may provide greater comfort.

Definitions of (very) high energy performance buildings tend to vary over Europe, but they define energy efficiency not only in terms of the building envelope, but also of the heating, cooling, ventilation, hot water and lighting systems. The space heating demand varies from 10 to 70 kWh/(m².a). The PassivHaus standard defines a maximum of 15 kWh/m².a for heating demand, whereas cooling demand should not exceed 15 kWh/(m².a) + 0.3 W/(m².a.K) x DDH, with DDH is dry degree hours.

Definitions of nearly Zero Energy Buildings (nZEBs) focus on a more or less equalized yearly energy balance between energy consumption and renewable energy generation.

4.1.1 Building shell improvements

For retrofits and new constructions improvements of the building envelope include:

- Compact shape, for new construction;
- A high level of insulation of the building envelope, in particular roof and walls for retrofits: typical U-values of ≤ 0.15 W/m².K in cold climates, and ≤ 0.35 W/m².K in hot climates. Insulation includes the use of:
  - typical materials such as mineral wool with glass padding or expanded polystyrene (EPS), with a thermal conductivity of 0.03 – 0.04 W/m.K;
  - advanced technologies such as aerogels (0.012 – 0.022 W/m.K) or vacuum insulated panels (VIPs) (0.004 W/m.K). These are used for very high performance buildings, e.g. nearly Zero Energy Buildings (nZEBs); or for space constrained applications.
- Energy efficient windows, including the use of:
  - Typical insulating windows with double low-e glazing and low conductive frames, with a whole window performance U-value ≤ 1.8 W/m².K;
  - Highly insulating windows (e.g. triple glazing, low-e and low conductive frames), with a whole window performance U-value of 0.6 – 1.1 W/m².K (windows with a U-value of 0.8 W/m².K or better meet the passive house standard);
  - Energy-plus windows, i.e. highly insulating windows with dynamic solar control and glass that optimises daylight. A whole window performance U-value ≤ 0.6 W/m².K in cold climates, and variable solar heat gain (SHG) coefficients of 0.08-0.65;
- Optimal fenestration for (passive) solar gains and daylighting, for new construction;
- Minimum thermal bridging. No (new construction) or reduced (retrofits) thermal bridges;

- High level of air tightness or air sealing. Restrict the (uncontrolled) passage of air through the building envelope, with air changes per hour (ACH) ≤ 3.0 for retrofits; and ≤ 0.5 with mechanical ventilation including efficient heat recovery for new construction.

4.1.2 Space heating

The interactions between the components of a heating, air-conditioning and/or ventilation (HVAC) system and the building envelope and lighting system, imply that energy savings in one area may increase or reduce savings in another. Architectural and engineering concerns should thus be integrated in the design process: efficient, properly-sized HVAC equipment in an energy-efficient building envelope, coupled with a state-of-the-art lighting system.

The true energy performance of a heating system is realized at the system level. The generation, storage, distribution, emission and control of heat should always be viewed as one system.

Preventive and regular maintenance of the different heating system components also improve the efficiency of the heating systems.

Heat generation systems

Starting from 26 September 2015 a mandatory European energy label grades space heaters' performance from A++ (most efficient) to G (least efficient). This likewise applies to 'combination heaters', i.e. space heaters designed to also provide heat to deliver (domestic) hot water (see also domestic hot water heating). A "space heater" is defined as a device that provides heat to a water based central heating system in order to reach and maintain at a desired level the indoor temperature. It is equipped with one or more heat generators, who generate the heat a) by the combustion of fossil fuels and/or biomass fuels, b) by use of the Joule effect in electric resistance heating elements, or c) by capturing ambient heat from an air source, water source or ground source, and/or waste heat.

The energy labelling for space heaters also applies to "heating packages", i.e. space heater or combination heater with temperature control and solar thermal.

One should in principle select a space heater with the 'most efficient' label, when available.

- **Boiler space heater**. Use a condensing boiler instead of a conventional boiler. Condensing boilers, typically fired with natural gas, have high(er) combustion efficiencies of 95%-96%, by extracting so much heat from the flue gases that the moisture in the gas condenses. Condensing boilers also operate more efficiently at part-load, and can be connected in modular installations (see heating controls);
- **Heat pump space heater**. Use a heat pump instead of a conventional or condensing boiler. Air-conditioning heat pumps extract heat from a conditioned space and reject it to a an-other space (e.g. outdoors) (see air-conditioning for the technical details). If the cycle is reversed, heat is moved from the outdoors to the conditioned space (indoors). There are two main types:
    - Air-source heat pumps. Heat is extracted from the outside air. Absorption heat pumps are air-source heat pumps powered by heat sources (rather than electrici-

ty), e.g. natural gas (gas-fired heat pumps), but also solar-heated water or geothermal-heated water;
  - o Ground-source or water-source heat pumps. Heat is extracted from the ground or an underground body of water.
- **Cogeneration space heater**. Use micro combined heat and power (mCHP) instead of boilers. A micro-CHP unit generates heat and power simultaneously, with a typical electrical power output of 1-5 kWe for residential and 5-50 kWe for commercial buildings. The main output is heat for water or space heating, with electricity as a by-product. The main technologies are:
  - o Internal combustion engine (ICE) mCHP. Total efficiency is 85-92%, electrical efficiency 20-30%;
  - o Stirling (a.k.a. "external combustion") engine mCHP. Total efficiency is in the low 80s, electrical efficiency 10-20%;
  - o Organic Rankine Cycle (ORC) mCHP. Total efficiency is 90+%, electrical efficiency ≈10%;
  - o Fuel cell mCHP. Total efficiency is 77-80%, electrical efficiency 30-35%;
  - o Micro-Turbine mCHP. Total efficiency is 80-92%, electrical efficiency mid 20's.
- **Connect to a district heating (DH) system**. District heating is not a generation technology in the strict sense, but provides the same function.

Heat distribution and emission

The efficiency of condensing boilers and heat pumps is higher when they supply heat at lower temperature.

The majority of existing heating systems in the EU run with high system temperatures, between 50°C and 80°C inlet temperatures. The energy efficiency of these heating systems can be improved by modernizing them into low temperature heating systems, between 35°C and 50°C inlet temperature. In principle, the lower the system temperature, the more efficient the heating system.

Low-temperature heating requires specific heat emitters.

- Modern radiators with low system temperatures feature a slim-line profile and minimal water content in combination with large heat-transfer surfaces. They not only save energy but also create a comfortable room climate;
- Surface heating (and cooling) systems circulate water in pipes permanently embedded in floors, walls or ceilings. Embedded heating systems operate at temperature levels very close to the desired room temperature.

Heating controls

HVAC systems are sized to meet heating and cooling loads that historically occur only 1% to 2.5% of the time. Controls have to ensure that the HVAC system performs properly, reliably and efficiently during those conditions that occur 97.5% to 99.0% of the time.

- "Right-size" the heating system to ensure efficient operation (avoid oversizing);

- Select heating systems that can operate efficiently at part load, e.g. variable capacity boiler systems:
    - Step-fired (hi/lo) boilers: the heat input to the boiler changes in steps, usually high/low/off;
    - Modulating flame boilers: the heat input to the boiler can be adjusted continually (modulated) up or down to match the heating load required;
    - Modular boiler systems: groups of smaller boilers are assembled into modular systems. As the heating load increases, a new boiler enters on-line. As the heating load decreases, the boilers are taken off-line one by one.
- Oxygen-trim boiler systems: the amount of combustion air is continuously adjusted to achieve high combustion efficiency. They are usually cost-effective for large boilers with modulating flame controls;
- For controlling heat pumps, see air-conditioning.

Modern control technologies based on micro-electronics efficiently control all the components of a central heating system, not only the burners but also the heat emitters. They also enable the integration of renewable energy sources in case of bivalent heating systems (i.e. heating systems that can be run with two energy sources at the same time). In combination with communication technologies they allow remote control of the heating systems (see ICT appliances).

4.1.3 Space cooling (air-conditioning)

Sensible cooling involves control of the air temperature. Latent cooling involves control of air humidity.

The first step is to avoid or reduce the need for air-conditioning (AC):

- Prevent heat from entering the building:
    - Shade windows by using deciduous trees or climbing foliage for south-facing windows to take advantage of low-angle sun in winter;
    - Improve insulation and air sealing and reduce thermal bridging (see space heating – building envelope);
    - Use architectural shading, exterior shades in the window plane, and reflective surfaces (see space cooling - building envelope);
    - Replace or discard energy inefficient appliances;
- "Cool" with air movement and ventilation. Fans cool people but don't actually reduce room temperature. Fans use less energy than air-conditioning and can be adequate for attaining he desired thermal comfort, by creating a low-level "wind chill" effect.

If "passive cooling" and fans are not sufficient, the second step is to select a (more) energy efficient air-conditioning system (or an alternative); or to improve the efficiency of the existing AC system.

Building envelope improvements

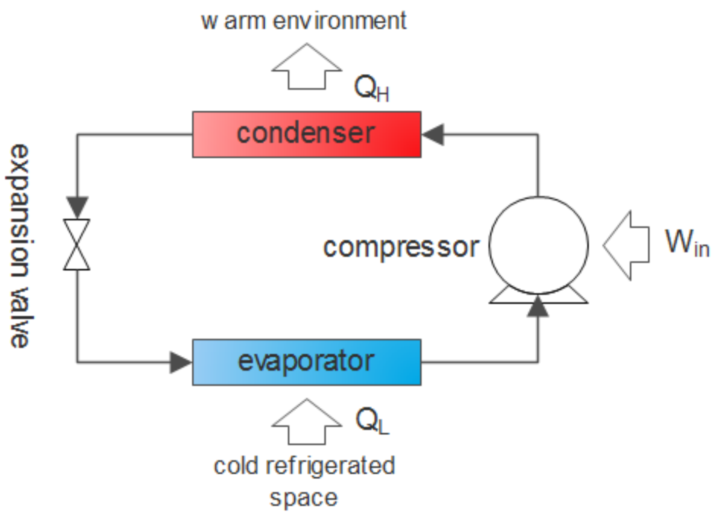
The same technologies apply as for space heating. Additional technologies include:

- Architectural shading. Structural changes to the building design (mostly new buildings) provide exterior shading. The shading devices are either attached to the building skin (e.g. overhangs, fins or light shelves), or they are an extension of the skin itself (e.g. windows set back in a deeper wall section);
- Exterior shades in the window plane. The shading devices are industrially manufactured systems, e.g. exterior shade screens, roller shades or reflective retrofit films. Manufacturers also offer (fixed or adjustable) shading systems between glazing layers. Exterior shades are able to reduce solar heat gain to zero, but preferred options would have daylight features;
- Low SHGC windows;
- Reflective (exterior) surfaces. Use reflective roof and wall coatings or materials in hot climates or dense urban areas, with a long-lasting solar reflectance (SR) of ≥ 0.75 for white surfaces; and SR ≥ 0.40 for "cool-coloured" surfaces;

Air-Conditioning (AC) systems

Most vapour-compression air-conditioning (and refrigeration) systems have an evaporator, a compressor, a condenser and an expansion valve. Indoor air is cooled by blowing it over the evaporator. The evaporator contains a working fluid called "refrigerant". The refrigerant changes from a liquid to a gas as it absorbs heat from the air. The compressor moves ("pumps") the refrigerant between the evaporator and the condenser, and compresses the gas to a state of higher pressure and higher temperature. The working fluid thus enters the compressor as a low temperature, low pressure gas, and leaves the compressor as a hot, high pressure gas. A condenser fan blows outside air over the refrigerant. The ambient air absorbs heat from the refrigerant, which condenses from a high temperature, high pressure gas to a high pressure, high temperature liquid. The expansion valve regulates the flow of refrigerant into the evaporator. The expansion valve causes a pressure drop of the refrigerant. The working fluid "expands" and cools, and flows to the evaporator where the cycle starts all over again. Energy is required for driving the motor of the compressor, and also for the motors of the evaporator and condenser fans.

Figure 1: Vapour-compression refrigeration cycle



Air conditioners transfer ("move") heat from the space being cooled (e.g. a room) to another environment (usually outside). Residential air-conditioning technologies consist mainly of "room air conditioners" (RACs), whereas tertiary sector air-conditioning technologies mostly involve "central air conditioners" (CACs).

Single and double duct air-conditioners have a relative low energy efficiency ratio (EER). EER is the ratio of output cooling energy to electrical input energy. They consist of a single unit placed freely in the room, where for single duct systems the condenser is cooled with air taken from the room and the air is expelled through a duct; whereas double duct systems have separate ducts for air intake and exhaust.

More energy efficient space cooling technologies include:

- Ductless Split or Multi-Split Air-Conditioners [aka "room air conditioners"] with a high EER, instead of less efficient single or double duct AC. Each space (room) to be cooled has its own (dedicated) air handler, connected to an outside compressor/condenser unit via a conduit carrying the power, refrigerant and condensate lines. They make it easier to meet the varying comfort needs of different rooms; and by avoiding the use of ductwork, they also avoid energy losses. The most efficient RACs are fixed split air conditioners with a variable speed compressor and a permanent-magnet motor (inverter technology); with an EER of 5 to 6 and a COP of 5 to 6;
- Heat pumps Heat pumps refer to easily reversible vapour-compression air-conditioning systems, optimized for high efficiency in both directions of heat transfer (see also space heating systems);
- Evaporative coolers (a.k.a. "swamp coolers"). The outside air – in dry areas – is pulled through moist pads where the air is cooled by evaporation. Direct evaporative coolers add moisture to the building; indirect evaporative coolers do not add moisture to the building;

The tertiary sector often uses "chillers". Chillers produce cool water, which is pumped to air handling units to cool the air. Mechanical refrigeration chillers use one or more compressors powered by electric motors, fossil fuel engines or turbines. Absorption chillers produce chilled water via an absorption cycle.

Energy efficiency improvements for chillers include:

- Improved controls for chillers in general:
    - Variable Speed Drives (VSD) that vary the speed of the compressor by matching the motor output to the chiller load;
    - Multiple compressor chillers: sequence multiple compressors by bringing compressors on or off line, to achieve a closer match to the load;
    - Water temperature reset controls: raise the water temperature as the demand decreases;
- Improved controls for chillers with water-cooled condensers, where the water is cooled indirectly via a cooling tower (i.e. a rooftop cooling tower rejecting heat in the outside air):
    - Variable speed or multiple speed cooling tower fans;
    - Wet-bulb reset strategies: the temperature of the cooling water is adjusted according to the temperature and humidity of outside air (instead of keeping it constant);

- Waterside economizer: a waterside economizer consists of controls and a heat exchanger installed between the chilled water loop and the cooling tower water loop. When the wet-bulb temperature is low (i.e. the outdoor air temperature is low and/or the air is very dry), the temperature of the cooling tower water may be low enough to directly cool the chilled water loop without use of the chiller;
- Integrated chiller plant controls use monitoring and computational strategies to yield minimum energy consumption for chillers, cooling towers, fans and pumps;
- Thermal storage: Thermal storage is a system in which an ice storage tank allows ice to accumulate during one period, and thaw it for use in another. Thermal storage allows smaller chillers. Thermal storage systems are mainly used for buildings with a large cooling load during daytime and little or no cooling at night.

4.1.4 Domestic Hot Water (DHW)

Domestic hot water (DHW) systems or 'water heaters' deliver a minimum requested amount of hot water with a minimum temperature. They are differentiated into two general principles: "on-demand water heaters" (a.k.a. "tankless", "instantaneous" or "point-of-use" water heaters) (water is heated instantly as it flows through the appliance) and "storage (tank) water heaters" (the hot water is stored in a tank).

Starting from 26 September 2015 a mandatory European energy label grades water heaters' performance from A to G.

In very high energy performance buildings where space heating is primarily accomplished through high levels of insulation and passive solar gains, the energy consumption for (domestic hot) water heating can be higher than for space heating.

The first step is to reduce hot water demand. The next step is to eliminate water heating system inefficiencies, which include how the water is heated (e.g. combustion efficiency, standby losses) and distributed (primarily heat loss from pipes).

Reduce hot water demand

- Reduce hot water use. Take a shower instead of a bath and use water-efficient or low flow showerheads; use tap aerators in the kitchen and bathroom; turn the hot water down or off while you shave or wash dishes; fix hot water leaks; turn off the water heater when the building is unoccupied for an extended period;

Efficient hot water generation

- [combination heater] Use an efficient combination space-water heating system, e.g. a condensing combi (combination) boiler (see space heating);
- [conventional water heater] Use an efficient conventional water heating system: …
- [solar water heater]Use a solar domestic hot water (SDHW) heating system. A solar water heating system uses solar panels (collectors) which collect heat from the sun and use it to heat up water which is stored in a hot water storage tank. There may also be circulating pump(s) in the collector loop. A conventional water heater or back-up immersion heater

can be used the heat the water further or to provide hot water when solar energy is unavailable. Larger solar panels could in principle contribute to space heating (see 'packages');

- [heat pump water heater] Use an efficient heat pump water heater (HPWH);
- Maintain a moderate tank temperature;
- Install a drain water heat recovery (DWHR) device to reduce the water heating load. DWHR pipes take advantage of the warm water flowing down the drains to preheat the water going into the hot water tank.

Reduce hot water distribution losses

- Eliminate distribution losses: Insulate the hot-water pipes; optimize the pipe diameter and the distance between the water heater and the tap. The smaller the pipe, the more quickly hot water reaches the tap. Larger-diameter pipes also waste heat because more hot water remains in the pipe after the tap is turned off.

4.2 Actions 2 and 6: residential and non-residential new buildings

The actions are basically the same as for actions 1 and 5. The main difference is that many actions, certainly those relating to the building shell, can already be implemented at the design stage. Standards can also be set at a higher level for new buildings, because they in general less costly than retrofits.

4.3 Actions 3 and 7: residential and non-residential lighting

Artificial lighting systems are related with the architecture of the building (e.g. shape and orientation of the building influence the daylight distribution) and the heating, cooling and ventilation systems (e.g. light can be a large source of internal heat gain).

There are two ways to reduce energy use for artificial lighting:

- Minimize the amount of time that lights are in use (e.g. via building design, behavioural change, and automation);
- Reduce the amount of energy used to light a given space, in general by using a more efficient lighting technology.

4.3.1 Minimize the amount of time lights are in use

- Maximize the use of natural day lighting by implementing a daylighting system. Daylighting involves decisions about the building siting, form, components (e.g. windows, skylights) and artificial lighting system;
- Behavioural changes, e.g. turn off the lights in unoccupied rooms or when there is adequate natural light; use task lighting (e.g. desk lamp); or use dimmers to use lights at maximum capacity when necessary and at low capacity when less light is need (e.g. safety lighting);
- Automated control of lighting:
  - o Programmable timers (switch lights off after a certain time has passed) and clocks (switch light on and off at predetermined times);

    - Presence detection. Occupancy sensors (e.g. infrared sensors or sound sensors) ensure that lights are on only when people are present;
    - Daylight responsive dimming. Light-responsive sensors adjust the level of output in response to daylight (indoor use only near windows).

4.3.2 Reduce the energy amount used to light a given space

An artificial lighting system is based on lamps, ballasts (in case of fluorescent lamps), luminaires and controls. A lighting design or upgrade identifies the appropriate quantity and quality of light for various areas, selects the combination of light sources, luminaires and controls that maximizes energy efficiency while balancing the considerations of lighting quantity and quality; and includes provisions for lighting maintenance.

Incandescent lamps (including halogen lamps), linear or tubular fluorescent lamps (TLs) and compact fluorescent lamps (CFLs) are commonly used in residential and tertiary buildings. High-Intensity discharge (HID) lamps are typically used when high levels of light over large areas are required. Solid state lighting (LEDs, OLEDs) is increasingly being used for architectural lighting in buildings.

Actions include:

- Use Compact Fluorescent Lamps (CFLs) instead of incandescent lamps or halogen lamps;
- Use Solid State Lighting (SSL) instead of CFLs. SSL uses semi-conducting materials to convert electricity into light.
    - Light Emitting Diodes (LEDs);
    - Organic Light-Emitting Diodes (OLEDs);
    - Light-Emitting Polymers (LEPs);
- Use more efficient “tubes” (linear fluorescent lamps), e.g. use T8 tubes with electronic ballasts instead of T12 tubes; or better still use T5 tubes with electronic ballasts instead of T12 or T8 tubes (this may require replacing existing luminaires);
- Use electronic ballasts instead of electromagnetic ballasts. They are available for linear fluorescent lamps (“tubes”), low pressure sodium vapour (LPSV) lamps and high pressure sodium vapour (HPSV) lamps;
- Use High-Pressure Sodium Vapour (HPSV) High-Intensity Discharge (HID) lamps instead of Mercury Vapour HIDs, (outdoor) when colour rendering is not critical. Use Metal Halide (MH) HIDs instead of mercury / sodium HIDS, when colour rendering is critical;
- De-lamping. Improve (existing) luminaires by adding (better) reflectors and lenses. This – possibly in combination with reducing the height - allows de-lamping, a reduction in the number of lamps per luminaire with little loss in illuminance;
- Lighting maintenance. Light levels decrease by more than 50% due to aging lamps, dirt on the lamps, luminaires and room surfaces.

4.4 Action 4 residential cold appliances and action 8 non-residential product cooling

Almost all residential “cold appliances” (refrigerators/freezers) use the vapour compression cycle (see air-conditioning), with a single compressor and condenser and one or two evaporators operating in series in a single cooling circuit. Most European residential refrigerators / freezers use natural convective cooling to transfer heat to the evaporator and from the condenser; rather than forced convection (electrically powered fans) aka "no frost system". Natural convective cooling is efficient, but in high humidity and beyond a certain volume and height a fan might become necessary.

Manufacturers can e.g. improve the quality of the insulation, the efficiency of the compressor and of the heat exchangers, and the quality of the control system.

End-user actions include:

- Do not keep the refrigerator or freezer too cold; do not leave the door open longer than necessary; avoid putting warm food in the freezer; cover foods stored in the refrigerator to prevent the release of moisture; regularly defrost manual-defrost refrigerators and freezers (frost build-up decreases energy efficiency);
- Use efficient cold appliances. Energy efficiency class A+++ (EU energy label) and a maximum annual energy consumption of 200 kWh, according to the EU energy label.

For commercial refrigeration and freezing units (tertiary sector) similar strategies apply:

- Reduce heat loads on the system:
  - Reduce air infiltration, e.g. improve door management; or use night blinds or strip curtains;
  - Control lights. Switch the lights off in the cooled room when the unit is not in use or outside trading hours;
  - Keep the refrigeration units far away from any sources of heat (including sunlight) and draught ;
  - Make sure the product loaded in display cabinets or cold rooms hasn't warmed up by being left in an ambient temperature area;
  - Temperature management. Only cool to the temperature needed;
  - Allow cool air to circulate.
  - Do not overfill retail display cabinets;
  - Do not allow products to block the grilles at the front of a retail display cabinet; or to obstruct the airflow to and from the coolers in cold rooms;
- Use "free cooling" for larger cooling units, i.e. raise process temperatures and improve control of auxiliary equipment such as pumps and fans (see also space cooling);
- Maintenance. Regularly service the units. Clean condensers and evaporators, etc.

5 COMBI actions in the transport sectors

The transport system energy efficiency can be expressed as the optimization of the (spatial) interactions between (residential, commercial and industrial) "land use" and the "transport services", so as to:

- Provide optimal access and choice ("accessibility");
- Maximize the energy efficiency of travel activity by combinations of modal share, energy intensity and fuel type ("activities").

ASI (Avoid, Shift, Improve) is a policy strategy that comprises the following components:

- **AVOID**. Avoid or reduce the need to travel (less trips); and reduce trip lengths;
- **SHIFT**. The shift approach focuses on shifting travel to more efficient or "sustainable" modes;
- **IMPROVE**. Reduce fuel consumption and emissions through:
    - behavioural changes, e.g. eco-driving or increased occupancy levels or load factors;
    - improving fuel efficiency and vehicle technology efficiency;

ASI can be extended with a "Go green" (alternative fuels) component, namely:

- **GO GREEN**. Reduce emissions through the use of so-called alternative "clean" or "green" fuels, such as biofuels / biogas, renewable electricity, or possibly even hydrogen produced by renewable energy sources.

The COMBI project team decided that actions in the transport sectors should comprise modal shifts, as well as technical energy efficiency improvements. Although alternative (or "green") fuels are not so much related to energy efficiency as they are to climate change and environmental strategies, they were also included in the COMBI scenarios, mainly because of their effect on emissions.

5.1 Actions 9 and 10: modal shift in passenger and freight transport

Model shifts involve:

- [urban passenger transport] a shift to public transport (PT), including high capacity "Mass Rapid Transit" (MRT) systems such as metro rail or "Light Rail Transit" (LRT), or medium capacity MRT systems such as "Bus Rapid Transit" (BRT) systems; and to non-motorized transport (NMT) such as non-motorized vehicle transport (NMVT), (e.g. cycling) or walking;
- [interurban passenger transport] a shift from aviation and road transport to rail and public transport (such as long distance buses);
- [interurban or long distance freight transport] a shift from road freight transport (trucks) to rail or waterborne transport (inland navigation or short-sea shipping). Supply and demand limiting factors are that modes other than road freight transport need transhipment terminals near the origin and destination regions; the additional transhipment costs need to be compensated by lower transport costs, which is only possible for certain minimum distances (50 km for inland navigation, 250 km for rail, and 350 km for short sea); value density needs to be lower than 6000 euro per m³ and package density lower than 15 packages per m³; the size of the shipment has to be above 1 tonne; and shipment speed should be 2 days or more. Another important factor is whether there is enough capacity in the other modes of transport.

5.2 Actions 10, 11, 12, 14 and 15: road transport (motorized two wheelers, car, bus, light duty truck and heavy duty truck)

5.2.1 Technical improvements

In conventional gasoline powered vehicles, 68%-72% of the energy is "wasted" in the engine: 58%-62% as waste heat through the radiator and exhaust; 3% through combustion inefficiency, 4% through pumping air into and out of the engine; and 3% through engine friction. Energy "lost" in the transmission and other drivetrain losses account for 5%-6%. Parasitic losses refer to energy generated by the engine and consumed by power steering, the water pump, and other accessories. Power-to-wheel losses refer to braking (5%-7%), air resistance (9-12%), and rolling resistance (5%-7%). Heat is lost through friction at the brakes. Air resistance (aka aerodynamic drag) is a frictional force that acts upon objects as they travel through the air. Rolling resistance is the force required to maintain the forward movement of a loaded pneumatic tire an a straight line at a constant speed. It is caused by the natural viscoelastic properties of rubber along with the tire's internal components constantly bending, stretching and recovering.

Manufacturers of cars [passenger road transport], and light and heavy duty vehicles [freight road transport] can improve:

- The engine.
  - Reduce internal friction losses, to limit fuel consumption during idling and breaking periods;
  - Use direct fuel injection for a more compete combustion;
  - Use cylinder shutoff during low load conditions (cylinder deactivation);
  - Use variable valve timing and lift (VVT&L);
  - Combine direct fuel injection and turbocharging for diesel engines, allowing more air and fuel to be injected into the cylinders (smaller engine, same performance);
- The drivetrain.
  - Use automated manual transmission (AMT);
  - Use double-clutch, lock-up transmission;
  - Use continuously variable transmission (CVT);
- The body.
  - Use a light weight vehicle body. Weight can be reduced by using lightweight materials and lighter-weight technologies;
  - Improve the aerodynamic efficiency of the body;
  - Use low rolling resistance tyres;
- The accessories.
  - Use very efficient accessories, e.g. alternator, power steering pump or oil and water pump;
  - Reduce energy consumption for cooling, by using advanced air conditioning systems (electrical heat pumps), improved roof insulation; and specially tinted glass as a barrier to infrared radiation.

5.2.2 The GO GREEN approach

End-users can either use alternative fuels, such as compressed natural gas (CNG), liquefied petroleum gas (LPG), hydrogen (H2), biofuels or biogas in modified conventional internal combustion engines (ICEs); or they can use alternative drivetrains allowing the use of renewable energy source (RES) based electricity.

Use alternative fuels in conventional drive trains

- Use compressed natural gas (CNG) or liquefied petroleum gas (LPG). CNG/LPG vehicles have some emissions benefits compared to conventional gasoline and diesel vehicles. Dedicated natural gas vehicles (NGVs) are designed to run only on natural gas; bi-fuel NGV have two separate fuelling systems that enable them to run on either gas or gasoline; dual-fuel NGV (limited to Heavy Duty Trucks) have fuel systems that run on natural gas, and use diesel fuel for ignition assistance. Dedicated NGVs have better performance and lower emission levels than bi-fuel vehicles. Furthermore, dedicated NGVs only have one fuel tank (less weight);
- Use hydrogen gas (H2) in a modified ICE. The combustion process is very efficient, but the storage of hydrogen requires high pressures or very low temperatures. Leaking of hydrogen in the fuel tank is another issue;
- Use biofuels or biogas, which do not require significant modifications to the conventional ICE. A blend of biodiesel and regular diesel (e.g. 20/80%) can be used in many diesel vehicles without engine modification;

Use alternative drive trains

- Use hybrid electric vehicles (HEV). A HEV combines the power of a conventional ICE with an electric motor. In parallel hybrids, the ICE and the electric motor can turn the transmission at the same time. In series hybrids, the ICE turns a generator, and the generator either charges the batteries or powers an electric motor that drives the transmission. HEVs use a smaller ICE, sized for running at average and not peak power, because HEVs can draw extra power from the batteries and the electric motor (see also electric motor drive/assist). The HEVs are more efficient than comparable conventional vehicles, especially in stop-and-go driving, due to the use of a number of technologies:
    - HEVs, as well as plug-in hybrids and battery electric vehicles, use regenerative braking. Advanced electronics allow the electric motor to act as either a motor or a generator. The electric motor applies resistance to the drivetrain causing the wheels to slow down. In return, the energy from the wheels turns the motor, which functions as a generator, converting energy normally wasted during coasting and braking into electricity;
    - HEVs use electric motor drive/assist. The electric motor provides additional power to assist the engine in accelerating, passing, or climbing hills;
    - HEVs use integrated starter/generator (ISG) systems (automatic start/shutoff). These systems eliminate idling by turning the engine off when the vehicle comes to a stop and restarting it when the accelerator is pressed;
- [passenger road transport]Use grid-connected vehicles, such as battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV). These electric vehicles can also provide their battery capacity for short term electricity storage during peak renewable energy sources (RES) power production.
    - Plug-in hybrid electric vehicles (PHEVs). PHEVs are HEVs that are additionally equipped with a power connection enabling battery charging by the motor as well as by the power grid;

  - Battery-electric vehicles (BEVs). BEVs aka "All-Electric Vehicles" (EVs) are solely driven by the electric motor. BEV batteries need to be charged by an external source (the power grid);
- Use fuel cell electric vehicles (FCEVs). Hydrogen gas stored directly on the vehicle is transformed to electricity by means of a fuel cell. The hydrogen supply is provided by a public supply grid. FCEVs are more efficient than conventional ICEs and only emit water vapour and warm air.

6 COMBI actions in industry

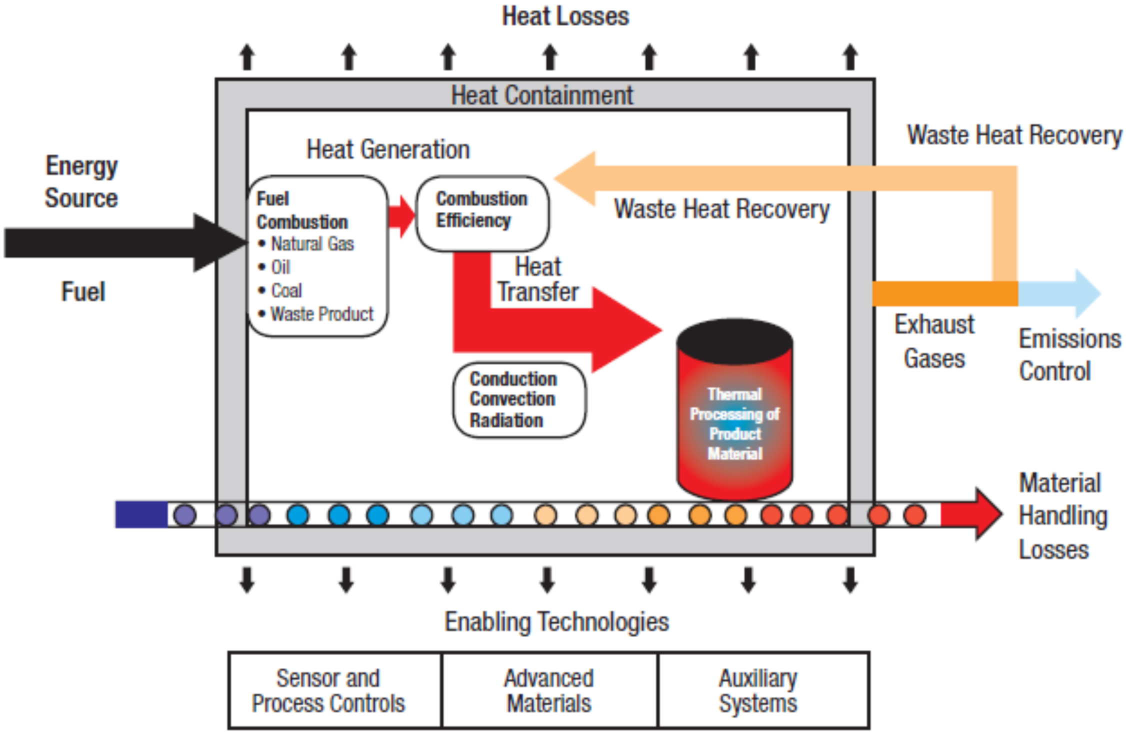
An industrial process is a complex system of different processing units that are connected and work together during operation. Process integration (PI) is a holistic (whole system) approach to process design and operation, which emphasizes the unity of the process, and may be defined as "all improvements made to process systems, their constituent unit operations, and their interactions to maximize the effective use of energy, water and raw materials". The most widely used PI methodology is "pinch analysis". The fundamental principle is to match a suitable supply (source) with a suitable demand (sink). The target is the minimum theoretical requirement in a process. For example, energy pinch technology provides guidelines to set energy targets for an industrial process, i.e. the minimum amount of heat that must be added and removed (cooled) in a process, as well as the maximum amount of heat that can be recovered internally through heat exchanging.

6.1 Action 16: high temperature process heat

6.1.1 High temperature process heating equipment

High temperature process heating equipment includes various types of furnaces, ovens, kilns, Lehrs, dryers, heaters, reactors, or thermal oxidizers. In standard English furnace is part of the names denoting many types of metallurgical furnaces, e.g. blast furnaces used for the extraction of metal from ore. The term oven usually refers to a furnace-like chamber or enclosed compartment used mainly for drying, curing or baking. A 'kiln' is a type of oven, mostly used for the production of ceramics, lime and cement. Chemical reactors where heating is not the main function are often not considered being furnaces or ovens.

Figure 2: A fuel-based process heating system and opportunities for improvement (LBNL, 2008b)



In this report we use furnace or oven interchangeably to denote all kinds of high temperature process heating equipment. Steam and hot water generators (boilers) are considered a category of their own (see medium and low process heat). High temperature electrolytic processes are discussed separately (see electrochemical processes).

A furnace is by definition a class of equipment where high-temperature heat is generated and transferred directly or indirectly to matter (material) for the purpose of effecting a physical or chemical change. Direct methods generate heat within the material itself (e.g. induction). Indirect methods transfer energy from a heat source to the material by convection, conduction and/or radiation. Furnace key components are material handling equipment, a device that generates and supplies heat, heat transfer devices, a "heat containment" enclosure, heat recovery (thermal processing of material) or heat recycling/recovery devices, process control systems (including sensors), safety equipment and emissions controls.

The high temperature process heat can be supplied by e.g. fuel combustion, electricity [either through resistance heating (resistance furnace), arc heating (arc furnace) or induction heating (induction furnace), or solar power (solar furnace)]. Combustion furnaces or ovens can be fired by gaseous fuels (natural gas), liquid fuels (oil, ethanol), solid fuels (coal, biomass) or by-products.

Many processes that are carried out in furnaces involve chemical reactions that are exothermic. The chemical reaction heat is either supplementary to the main heat input; or sufficient for the process so that additional heat need only be supplied at start up. In some processes more heat is generated than is needed and needs to be removed to avoid damage to the furnace (e.g. blast furnace).

The thermal efficiency of furnaces and ovens is the ratio of heat delivered to a material ['heat to load' or useful output] and heat supplied to the heating equipment. The efficiency of a furnace can be as low as 7%.

Heat losses include waste gas (aka flue gas or stack) loss; stored heat in the metal structure of the equipment; losses from the equipment's outside walls; heat transported out the furnace or oven by material handling equipment such as load conveyors, fixtures, trays, etc.; heat losses via cooling components and cooling media (air or water); radiation losses from openings; losses from cold air infiltration into the furnace or oven; and heat carried by the excess air used in the burners.

For most fuel-fired heating systems the exhaust gas heat losses are the single most important source of waste heat.

6.1.2 Energy efficiency improvements of furnaces in general

The thermal efficiency can be improved as follows:

- Improve scheduling and loading. "Load" is the amount of material processed in the furnace or oven in a given period of time. Operating schedules and load sizes should be selected to keep the furnace operating as near to 100% design capacity as possible;
- Reduce the moisture of the load before processing. A significant amount of heat is required to remove product moisture within a process heater;
- Reduce the exhaust gas heat losses, by minimizing exhaust gas temperature and mass or volume of the exhaust gases.
    - Optimize heat transfer within the furnace or oven;
    - Avoid overloading;
    - Optimize the fuel-air ratio;
    - Use oxygen enriched combustion air; …
- Reduce other heat losses, e.g.:
    - Reduce wall and cooling media losses by adequate insulation;
    - educe material handling losses, e.g. by reducing the weight of the fixtures or by re-placing fixtures with lower thermal mass materials;
    - Reduce air infiltration losses by maintaining a slightly positive furnace or oven pressure;
    - Reduce heat storage losses and radiation losses from openings;
- Waste heat recovery. Recover part of the exhaust gas heat and recycle it to the process or use it in lower-temperature processes. Alternatives include:
    - Direct heat recovery to the load: the load ('feedstock') is preheated by exhaust gases;
    - Recuperators: gas-to-gas heat exchangers on the stack transfer heat from the outgoing exhaust gas to the incoming combustion air;
    - Regenerators: A regenerator is an insulated container filled with metal or ceramic shapes that can absorb and store large amounts of thermal energy. They are also used to preheat the cold combustion air;
    - Use of a waste heat boiler.

6.1.3 Energy efficiency improvements of furnaces in different industrial sectors

Large and even many mid-size furnaces and ovens are custom designed, either by furnace / oven manufacturers, furnace design consultants or by the users themselves.

Potential improvements of large furnaces and ovens in industry include:

- Iron and steel.
  - Use an Advanced Blast Furnace (BF). Hot air injected in the blast furnace is replaced by pure oxygen, the top gas is recycled into the furnace, and CO2 from the furnace top gas is captured and stored. This process reduces fuel consumption (-20%), but increases electricity consumption (+600%);
  - Apply other improvements to blast furnace (BF), e.g. process control, improved heat recovery, increased injection of alternative fuels;
  - Use Basic oxygen furnace gas recovery. Increased use of the gas that is produced in the basic oxygen furnace (BOF) that converts pig iron into primary steel;
  - Use Direct Reduced Iron (DRI). Iron is reduced to metallic iron in the solid state using a reduction agent such as a gas. DRI bypasses the need for coke production;
  - Use more efficient Electric Arc Furnaces. In the primary metals industry electric-arc furnaces (EAF) are mainly used to refine scrap steel. Efficient technologies are DC arc furnaces with scrap pre-heating, oxy-fuel burners, foamy slags and process control.
- Non-ferrous metals.
  - Primary aluminium. See electrochemical processes;
  - Zinc. See electrochemical processes;
  - Copper. Either retrofitting plants that use the pyro-metallurgical route with state-of-the art technology, or building new plants using the hydrometallurgical route.
- Non-metallic minerals - Cement.
  - Use a more efficient kiln. Fuel consumption for clinker making ranges from 3 to 6.5 GJ/t clinker, depending on process and kiln type. The average consumption in the EU in 2009 is 3.7 GJ per tonne of clinker. Efficient pre-calcining, six-step pre-heater kilns use 2.9 – 3.1 GJ/t clinker;
  - Apply small improvements to kilns. Installation of combustion controls, reduction of kiln shell heat loss and improved operation of the clinker cooler;
  - Switch to waste fuels.
  - Reduce the cement clinker ratio. Use secondary products with similar properties to clinker (e.g. fly-ash, blast-furnace slag or natural pozzolana) as substitutes.
- Manufacture of glass.
  - Use a more efficient (BAT) glass furnace. The most efficient type of glass furnace depends on type of glass: container glass or flat glass;
  - Use a preheater for container glass production. Use residual heat of the waste gases to preheat the raw materials and cullet. ...
- Manufacture of ceramics.
  - Use more efficient (BAT) kilns. The energy intensity of best available technology kilns for the production of bricks and roof tiles is 1.7 GJ/t product;

  - Switch fuels. This mainly reduces CO2 emissions. Changes in specific energy consumption are small.
- Manufacture of olefins (ethyl, propylene, and by-products).
  - Use more efficient (steam) cracker furnaces.
- Manufacture of paper.
  - Use more efficient rotary drum driers. Note however that driers for drying paper are usually not regarded as being furnaces or ovens.

Large energy consumption reductions are achievable in the EU, eventually by replacing the large number of old, inefficient furnaces and ovens by modern efficient designs.

There are a few caveats (Goodman et al, 2012):

- Many furnaces and ovens in industry have a relatively long lifetimes of 20 – 30 years, but sometimes even 100 years (e.g. coke ovens in industry);
- Industrial furnaces and ovens are commonly custom-designed for specific processes, all of which have particular requirements, limitations and constraints. This means that the maximum energy efficiency that is achievable is very varied. For example, not all designs can use heat recovery options, due to technical constraints.
- Large scale users already tend to install the most energy-efficient designs, because energy costs are a large part of production costs. For example, many energy efficiency improvements such as heat waste recovery are already implemented.

6.2 Action 17: medium and low temperature process heating

6.2.1 Industrial heating systems

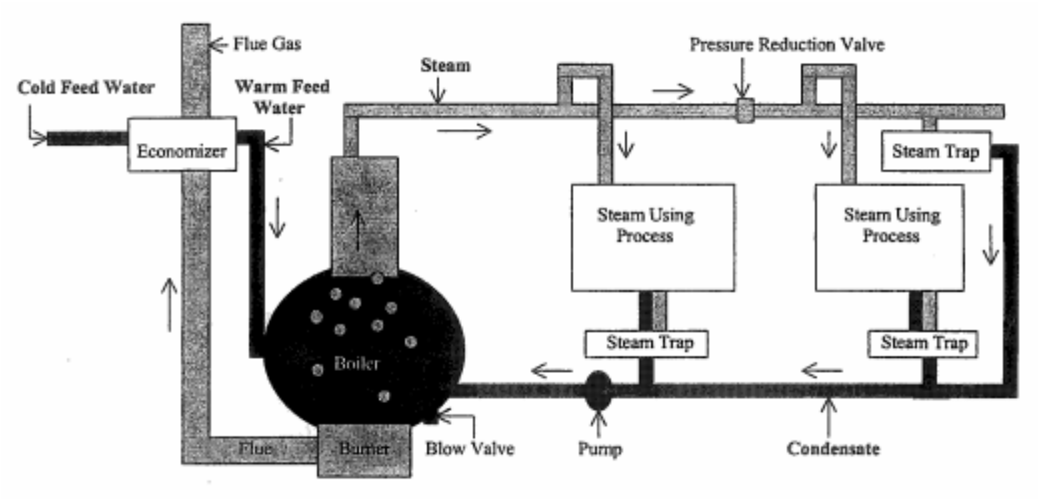
Industrial heating systems typically use water and steam as heat carriers. Hot water and steam with temperatures below 100°C are mainly used for space and water heating, whereas temperatures between 100°C and 500°C are used for many different industrial processes. Typical boilers in industry work in a power range of 100 kW – 50 MW and are fired by hard coal, lignite, oil, natural gas (mixed with biogas) or biomass. The choice of boiler type depends on the process requirements

For some process heating applications, thermal oil (a special oil-based fluid) instead of hot water or steam is used as the heat transfer media. The type of thermal oil heater depends on the specific requirements.

A modern steam system features four distinct elements:

- Steam generation (heat water to its boiling point): fuel supply, combustion burner area, boiler and combustion exhaust stack;
- Steam distribution (carry the steam to the point of use): piping, valves, regulators, steam separators and accumulators, steam traps and flow meters;
- Steam end use: heat exchangers, condensers, turbines, fractionating columns, chemical reaction vessels dryers, evaporators, etc.;
- Condensate recovery (transfer cooled condensate back to the boiler): steam traps, piping, tanks, pumps and condensate treatment equipment.

Figure 3: Schematic presentation of a steam system (Einstein et al, 2009, p. 537).



6.2.2 Efficiency improvements of industrial heating systems

Efficiency improvements of steam systems should optimize the whole system (and not the boiler alone):

- Reduce generation losses: boiler maintenance (e.g. clean boiler heat transfer surfaces, add or restore boiler refractory); replace burners; improve boiler insulation; improve water treatment to minimize boiler blowdown losses; boiler process control; minimize excess air, optimize the deaerator vent rate; consider high-pressure boilers with a backpressure turbine generators;
- Reduce distribution losses: implement a steam trap improvement, maintenance and monitoring program; repair steam leaks; improve and maintain insulation of piping, valves, fittings and vessels; minimize vented steam; steam distribution controls; isolate steam from unused lines; use backpressure turbines instead of pressure-reducing valves;
- Heat recovery. Optimize condensate recovery; use high-pressure condensate to make low-pressure steam; install heat recovery equipment such as feedwater and condensing economizers; recover energy from boiler blowdown and from wastewater streams.

The energy efficiency improvement alternatives are:

- Improve the energy efficiency of steam systems. See above. Modern systems already have high efficiency levels;
- Replace separate heat and power (SHP) generation systems with energy efficient cogeneration or Combined Heat and Power (CHP) generation systems, where possible. CHP systems can be used instead of steam boilers to provide steam for processes up to 500°C. CHP technologies include;
    - o Steam-back pressure turbine;
    - o Steam condensing turbine;
    - o Gas turbine;
    - o Combined Cycle Gas Turbine;
    - o Fuel cells;
    - o Internal combustion engine;

- Use solid oxide fuel cell (SOFC) CHP technologies, for temperatures in the 500°C-900°C range.

6.3 Action 18: Industry – Process cooling and industrial refrigeration

Electric motor-driven compression refrigeration systems account for 4% of total industrial electricity demand (Fraunhofer ISI, 2012).

To improve the energy efficiency of industrial process cooling, one has to look at the whole system, namely the design of the refrigeration system and the refrigerant used, the condition of the equipment, the control strategy, and the load profile of the system (deviation of the operating cooling loads from the design loads).

Refrigeration controls improvements include:

- Use floating head pressure control. The control allows the head pressure to drop with decreasing outside air temperature. A lower head pressure at the compressor, and consequently a lower condensing operating temperatures at the condenser, allow the compressor to operate at less power; at the expense of a slight increase in the evaporative condenser fan power consumption. Energy savings depend on the compressor's efficiency at part-load operation, the condenser fan control, and what determines the change in head pressure;
- Use compressor sequencing. Compressors should be sized to match the loads as closely as possible. It is good practice to include different sized compressors and sequence them to keep them as fully loaded as possible;
- Use a completely integrated automation system. An automated system can e.g. automate temperature controls and defrost cycles, based on constant calculations and adjustments, without being prone to human error.

Energy efficiency improvement retrofits include:

- Apply Variable Frequency Drive (VFD) for screw compressors. This improves the part-load efficiency of the compressor;
- Apply an oversized evaporative condenser. An oversized evaporative condenser usually results in an optimum head pressure that depends on outdoor air temperature, but a larger condenser implies more fan power. One has to balance between condenser size and condenser fan power;
- Apply Variable Frequency Drive (VFD) for condenser fans. This improves the efficiency of systems with variable loads, as it reduces fan speeds based on the heat rejection load (see also floating head pressure control);
- Apply Variable Frequency Drive (VFD) for evaporator fans. This reduces fan speed based on refrigeration load;
- Recover heat. The refrigeration process includes a heat rejection stage, at the condenser, where there may be opportunities to recover and re-use that heat for space heating or hot water. The two types of heat recovery are:
  - High grade heat recovery. A 'de-superheater" (a heat exchanger) between the compressor and the condenser de-superheats the refrigerant. The recovered heat

can be between 60°C and 90°C. This also reduces the cooling water or air needed by the condenser;
  - Low grade heat recovery. The low grade comes from the refrigerant being cooled. The heat is between 20° and 40°C (typical UK values).

6.4 Action 19: Industry – specific process electricity

Industrial electrochemical or electrolytic processes include electrowinning and refining, the production of electrochemicals, and electroplating (and anodizing). Electrowinning and refining refer to obtaining metals (e.g. copper, nickel, zinc, magnesium, …) from their ores (winning) or from impure stock (refining). The most important electrowinning process is the electrolytic refining of aluminium. Two common electrochemicals are chlorine and sodium hydroxide. Electroplating is the electrodeposition of an adherent coating upon a base metal. Anodizing coats a metal (especially aluminium) with a protective oxide layer.

Electrolysis refers to the decomposition of a substance by an electric current. Electrolysis cells consist of a container (the cell body), two electrodes (anode and cathode) where the electrochemical reactions occur, and an electrolyte. Some cells have a diaphragm or membrane between the anode and cathode compartments to separate the anodic and cathodic products.

Electrolysis cells are custom designed for a particular process.

6.4.1 Chlor-alkali

The chlor-alkali industry produces chlorine (Cl_2) and alkali [sodium hydroxide (NaOH) or potassium hydroxide (KOH)], by electrolysis of a salt solution ('brine'). The anode reaction is given by 2Na+ + 2Cl- Cl_2 + 2Na+ + 2e-; the cathode reaction by $2H_2O$ + 2e- H_2 + 2 OH-. The anode and cathode compartments have to be physically separated, because chlorine reacts with both OH- and H_2.There are three processes to produce chlorine and alkali:

- Diaphragm cell. A permeable diaphragm, i.e. a porous asbestos mat, separates the anode and cathode compartments;
- Mercury-cell. The cathode is liquid mercury, where sodium forms an amalgam with the mercury. The amalgam reacts with water in a separate reactor ("decomposer), where hydrogen gas and a 50% caustic soda solution are formed. The mercury cell process produces a product of higher purity than the diaphragm cell, but uses more electricity;
- Membrane cell. An ion-exchange membrane allows only sodium ions (and a little water) to pass between the anode and cathode compartments. The membrane cell process produces a product of higher purity than the diaphragm cell process, uses less energy than the mercury cell process, and eliminates environmental concerns about asbestos and mercury.

The electrolysis cells of the membrane process use 2650 kWh/tonne ECU, compared to 2720 kWh/tonne ECU for the diaphragm process and 3360 kWh/tonne ECU for the mercury process. ECU is electrochemical unit, the fixed product ratio of 1.1 tone of caustic soda and 0.02 tonne of hydrogen per tonne of chlorine. Total energy consumption, including power and steam consumption, is 2970 kWh/tonne ECU for the membrane; 3580 kWh/tonne ECU for the diaphragm; and 3560 kWh/tonne ECU for the mercury process.

In Europe, in 2014, membrane cell capacity accounted for 60% of total installed chlorine production capacity. In the EU producers should either voluntarily convert mercury-cell processes to membrane cell processes by 2020; or shut down technically obsolete processes by December 2017.

6.4.2 Primary Aluminium

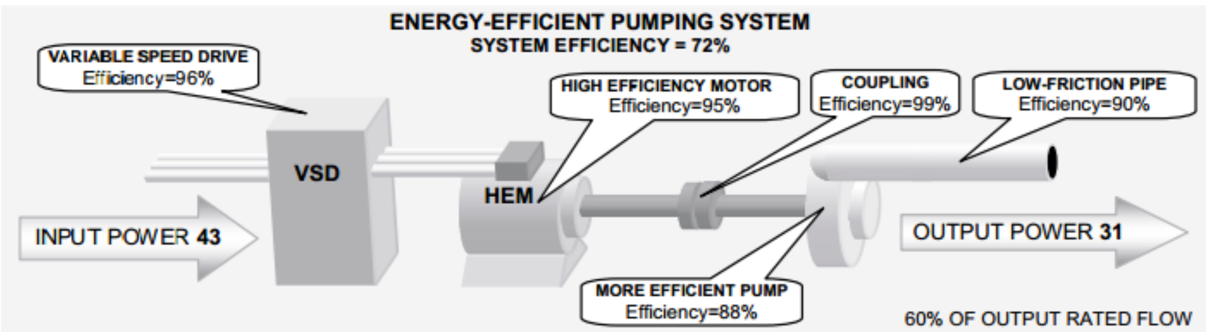
The production of primary aluminium consumes more electricity than any other electrochemical process. Bauxite has to be processed into “alumina” (pure aluminium oxide) before it can be converted to aluminium by the Hall-Héroult electrolytic reduction process. Approximately 4.2 tonnes of bauxite are required to produce ±2 tonnes of alumina, which in turn produces one tonne of aluminium. The reduction of alumina into liquid aluminium takes place in electrolytic cells called “pots”. Alumina is dissolved in a molten cryolite bath within a carbon-lined steel pot. The pot itself acts as the cathode. Carbon anodes are held at the top of the pot. The process is operated at around 950°C under high intensity electrical current. The carbon anodes are consumed during the process when they react with the oxygen coming from the alumina. The net reaction is $2Al_2O_3 + 3C$ $4Al + 3CO_2$. At regular intervals molten aluminium at the bottom is tapped from the pots.

The theoretical minimum electricity requirement for the electrolysis cell is 6.3 kWh/kg Al. The best smelters use 13 kWh per kg of aluminium or under; the worldwide average is 15 kWh/kg Al. The target for the next generation of electrolysis cells is 11 kWh/kg Al. The efficiency of the process is influenced by temperature, spacing between the electrodes, electrode material, electrolyte consumption, cell size, source of the raw material, and production rate. Research efforts to improve the efficiency focus – amongst others – on electrode materials (e.g. the use of “inert” anodes made of ceramics, metals or composites of ceramics and metals) that allow lower cell voltages; and process sensors.

6.5 Action 20: Industry – motor drive

Electric motor-driven fan (11%), pump (12%) and compressed air (9%) systems account for 32% of total industrial electricity demand combined (Fraunhofer ISI, s.d.).

Figure 4: Energy-efficient pumping system (De Keulenaer et al, 2004, p. 3)



Modern motor systems are comprised of a number of sub-systems, namely (optional) a variable speed drive (VSD), the fully functioning high-efficiency motor itself, the driven equipment (e.g. fan, pump or compressor), the transmission and coupling (e.g. gear or belt), the ducting or piping system and all possible end-use equipment.

For motor-driven systems, one should focus on the entire powertrain system, and not on a motor upgrade alone. The efficiencies of electric motors are already very high (up to 90-95%). The development toward more efficient electric motors is nevertheless still in progress. In 2014 the International Electrotechnical Commission (IEC) published a standard defining the 'super premium' IE4 motor efficiency levels. Some motor manufacturers have already announced IE5 motors.

The energy efficiency improvement of machine drive systems not only involves technical improvements, but also behavioural and organisational aspects.

6.5.1 Fan and pump systems

Energy efficiency improvements include:

- Maintenance and monitoring, e.g. inspection and replacement of packing seals and mechanical seals; replacement of worn impellers and wear rings; inspection and repair of bearings; replacement of bearing lubrication; alignment checks of pump/motor; etc.;
- Reduce demand. For pumps systems demand can be reduced by e.g. using holding tanks; eliminating bypass loops and other unnecessary flows; or by reducing total head requirements;
- Replace inefficient pumps and fans with efficient ones;.
- Avoid oversizing. Fans and pumps have a range of optimal operating characteristics that must be matched to the actual process flow and pressure requirements;
- Modify the fan or pump. For example, trim the pump impeller to reduce the impeller's tip speed; or substitute the fan impeller; improve the sealing;
- Use demand-related controls.
    - Use Variable Speed Drives (VSD). VSDs automatically adapt the pump or fan speed to the load requirements. Use VSD only in situations with varying load. Avoid throttling valves or remove them if possible;
    - Stage multiple fans or pumps for highly varying loads;
- Replace belt drives. Replace belts with a direct driven system; or replace standard V-belts with cog belts;
- Reduce friction losses .This applies only to dynamic systems.
    - Optimize pipe diameters. Optimize the pipe diameters (at the design stage) to reduce losses due to friction;
    - Reduce surface roughness. Use precision castings, surface coatings or polishing. …

6.5.2 Compressed air systems

A compressor is a machine that is used to increase the pressure of a gas. A compressed air system is composed of sever major sub-systems, including the compressor itself, the prime mover (usually but not necessarily an electric motor), the controls, the air treatment equipment, and the distribution system.

Basically, there are two ways to improve the energy efficiency of compressed air systems: produce less compressed air, and produce the compressed air more efficiently.

Energy efficiency improvements include:

- Maintenance and monitoring: clean radiators, inspect and clean inlet filters; drain traps; maintain lubricant levels; check water cooling systems, etc.;
- Produce less compressed air:
  - Avoid inappropriate uses. Compressed air is often used for applications where alternative energy sources are more economical (e.g. blowing compressed air on a motor to cool it);
  - Detect and repair compressed air system leaks. Leaks can come from any part of the system, but mainly couplings, pressure regulators, open condensate traps, shut-off valves and pipe joints.
  - Reduce "artificial demand". Artificial demand is consumption of air by end-users because the system pressure is higher than the user needs. One can incrementally lower the average system operating pressure, albeit making sure that pressure at point-of-use do not fall below minimum requirements;
- Replace or improve inefficient compressors with more efficient ones.
  - Use multi-stage compressors (the final discharge pressure is generated over several steps). They save energy by cooling the air between the stages;
  - Use the most efficient (electric) motor available, use flange mounting or direct coupling (instead of a V-belt), ensure proper alignment;
- Use demand-related controls. Compressed air system controls match the compressed air supply with system demand. All units should operate at full load, except one unit for trimming.
  - Individual compressor control. Load/unload control can improve the efficiency at part-load operation if there is enough storage capacity; variable speed drive (VSD) control can be very efficient to provide "trim duty" (see next);
  - Multiple compressor control. Follow a base-load/trim strategy. Some compressors are fully loaded to meet the base-load demand. The compressor(s) with the highest part-load efficiency is placed in trim service to handle variations in load;
- Minimize pressure drop. Any type of obstruction, restriction or roughness in the system causes pressure drop. Therefore:
  - Select air treatment components with the lowest possible pressure drop at specified maximum operating conditions;
  - Reduce the distance air travels through the distribution system;
  - Specify pressure regulators, lubricators, hoses and connections having the best performance characteristics at the lowest pressure differential;
- Use compressed air storage. Storage can be used to control demand events (peak demand), to protect critical pressure applications from other events in the system; or to control the rate of pressure drop to end-users;
- Use outside air intake when outside air is cooler than inside air. Cooler air is denser and provides more mass for each compression cycle with no additional power use;
- Recover waste heat. The waste heat of the compressor can be recovered and used for supplemental space heating, water heating, makeup air heating, boiler makeup water preheating, and industrial process heating.

6.6 Action 21/ Industry – HVAC in industrial buildings

Industrial facilities refer to buildings on industrial sites. Relevant energy service systems are heating, cooling (air-conditioning), ventilation (HVAC) and lighting of buildings at the site, as well as outdoor lighting. We refer to the descriptions given for the residential and tertiary sectors.

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