H-CHP Micro Combined Heat and Power System for Households

Northern Periphery and Arctic 2014-2020 program

Energy Action
THE WARM CHARITY

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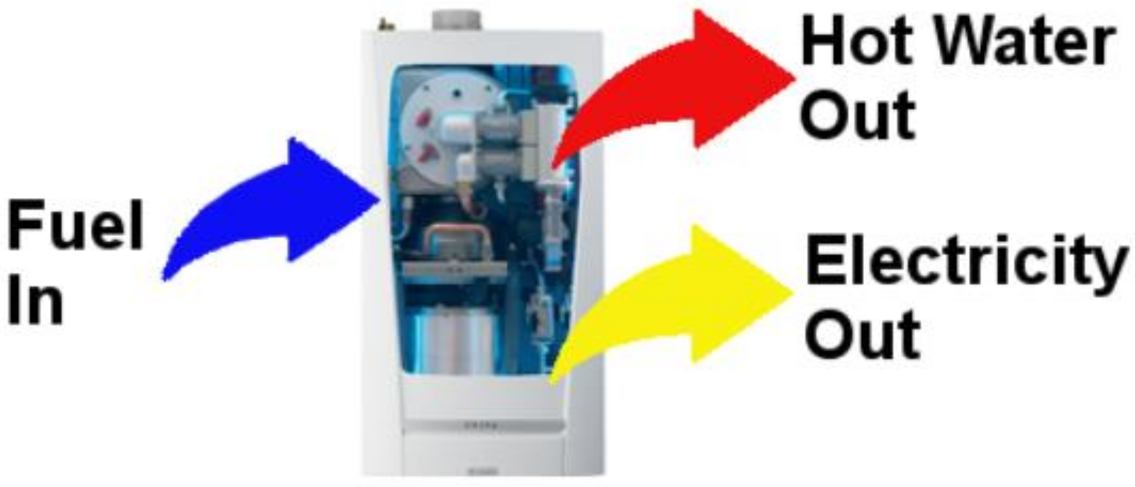
What is µCHP?



Source: https://www.renewableenergyhub.co.uk

- **Means the cogeneration of heat and electricity up to 50 kW**
  - Typical need for a detached house is less than 6 kW_e, the range we are targeting
- **A CHP system using renewable biomass converts about 10% of primary heat to electricity in average.**
  - Electrical efficiency poor with low power CHP plants.
  - Thus µCHP generator primarily follow heat demand, delivering electricity as the by-product.

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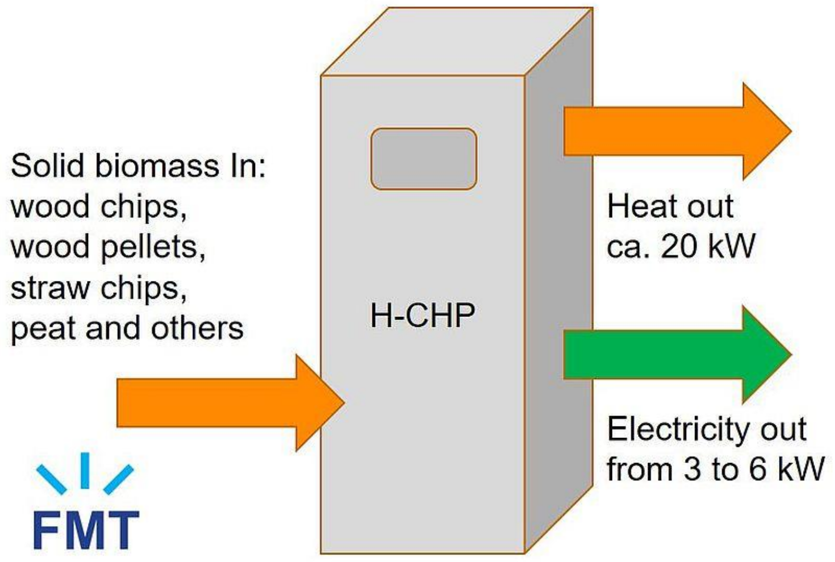
Why µCHP and is it worth to invest?

- **Desire to be self-sufficient in energy**.
- No worries about **power outages** in sparsely populated areas where repair could take weeks during winter storms.
- **But there are a few µCHP manufacturers** - if generators with an combustion engine won't count
  - So far commercial µCHPs are expensive, ie. unprofitable as an investment.
  - Payback time varies remarkably in different countries in the NPA due to different tariffs.
- Wood is commonly used for heating in remote areas in Sweden and Finland.
  - Some commercial solutions could be used for power generation by integrating them into an existing heating system (ie. Stirling, ORC).
  - The equipment should be nearly maintenance free, operation costs minimized and useful life should be 15-20 years.
- Some Solar Panel Suppliers promise up to 20 years warranty - what if the company no longer exists?



The aim of the H-CHP project is…

- **To establish H-CHP “Open Source” community to share**
  - ideas,
  - knowledge,
  - take responsibility of the further development of the project,
  - get µCHPs prices down to the consumer level
  - influence in political decisions…
  - Etc.
- **We, as the project actors, only do preliminary work**

Energy efficiency of a different size of CHP plants

- The larger the size of the plant, the better the efficiency of electricity production
- The power generation efficiency of µCHPs is generally around 10% and the overall efficiency (including heat generation) is typically about 80-85 %.

Table 1.1 CHP base technologies

CHP power generation technology	Power range (applied to CHP)	Power efficiency range (%)	CHP efficiency (peak) (%)
CCGT*	20 MW to 600 MW	30–55	85
Gas turbine	2 MW to 500 MW	20–45	80
Steam turbine	500 kW to 100 MW	15–40	75
Reciprocating engine	5 kW to 10 MW	25–40	95
Micro-turbine**	30 kW to 250 kW	25–30	75
Fuel cell	5 kW to 1 MW	30–40	75
Stirling engine	1 kW to 50 kW	10–25	80

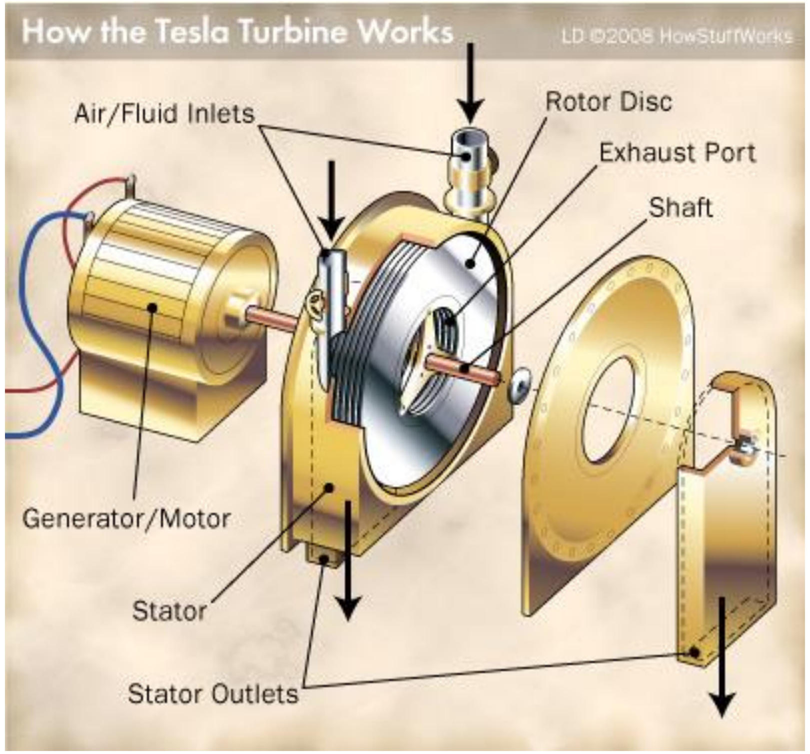
* Combined cycle gas and steam turbines
** Micro-turbines are small, radial flow gas turbines

Source: Woodhead Publishing Series in Energy: Number 18, 2011

CHP devices are based on

- ➢ Stirling engine
- ➢ Steam motor
- ➢ Organic Rankine Cycle - ORC
- ➢ Thermoelectric generator
- ➢ Gasifier + combustion engine
- ➢ Fuel cell
- ➢ Tesla turbine?

All of these require heating up / response time time.



Source:
https://newenergytreasure.com/2014/01/22/lenr-direct-electricity-production/

Source: Woodhead Publishing Series in Energy: Number 18, 2011

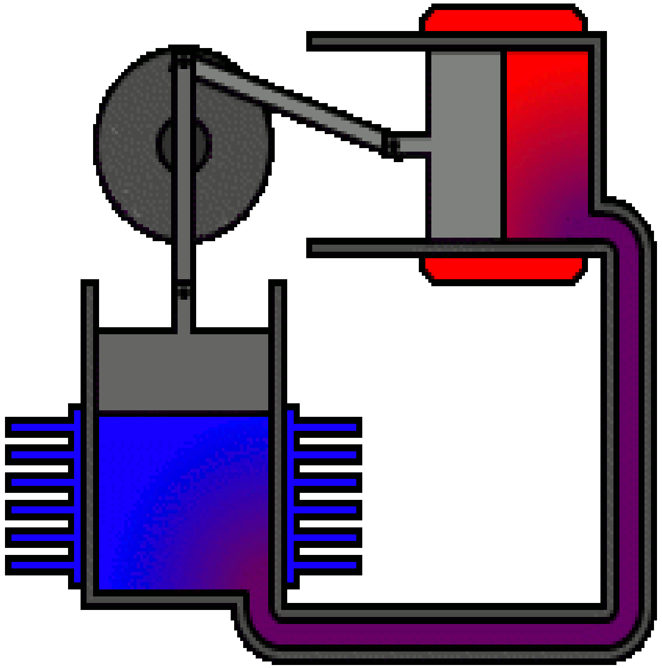
Stirling engine – Operating principle

The operating principle of Stirling engines is quite simple.

- The working gas between two pistons is alternately heated and cooled by changing the volume of the hot cylinder with a displacer piston.
- This causes the gas to expand and shrink, and thus periodical change at the gas pressure.
- Changes in the gas pressure moves the work piston back and forth at the cold cylinder.

Stirling engines can be powered by any heat source like solar or gas/wood flame.

- Therefore, they are most commonly used in µCHP applications.



Source: Wikipedia.org / Stirling

Stirling engine – most commonly used working gases

- **Helium**
  - Has **low viscosity** and **high thermal conductivity** making it powerful working gas
  - On the other hand, helium is also most sensitive to escape through seals and is "expensive" at around 6 EUR / liter.
- **Nitrogen**
  - Like helium is inert non flammable gas.
  - Nitrogen binds less heat than helium and thus requires a larger heat transfer surface area, which also increases the structural size of the engine.
- **Air**
  - Contains 78% nitrogen and 21% oxygen.
  - Oxygen under pressure may cause a risk of explosion when mixed with e.g. flammable lubricant.
  - Oxygen can be removed from the air, whereby the “gas" is mainly nitrogen and about 1% argon.

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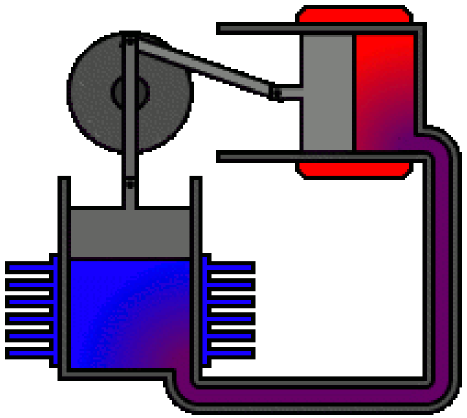
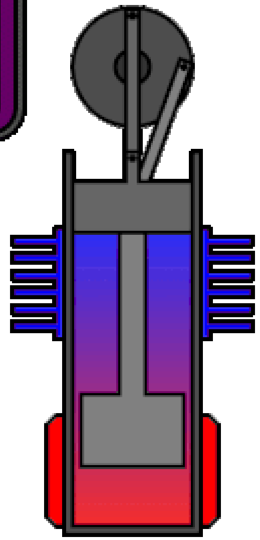
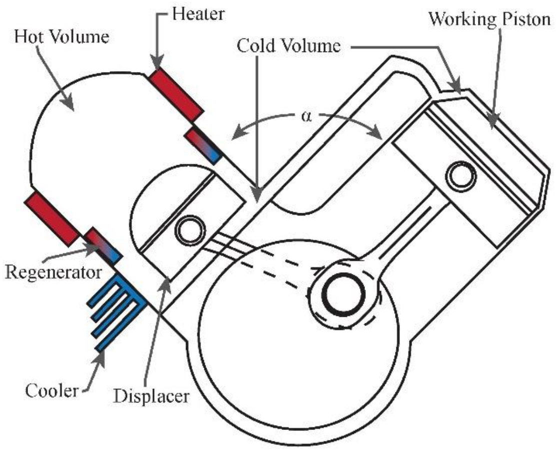
Stirling engine – most common





- An **alpha** Stirling contains *two work pistons* in separate cylinders, one hot and one cold.
  - The engine has a high power-to-volume ratio.
  - Durability of seals at the hot end might cause problems and thus the seals typically located far from the hot zone at the expense of some additional dead space.

- A **beta** type Stirling has *one cylinder* with cold and hot ends. Both pistons, displacer and work, are inside the cylinder.
  - The displacer piston is a loose fit and does not extract any power from the expanding / shrinking work gas.
  - Seals are located at the cold end of the cylinder, thus avoiding alpha-type heat resistance requirements.



- A **gamma** Stirling is simply a beta Stirling with a work piston mounted in a separate, cold cylinder.
  - The gas flows from the bottom of a hot cylinder to the top of a cold cylinder.

Sources: Wkipedia, https://doi.org/10.3390/en11112887

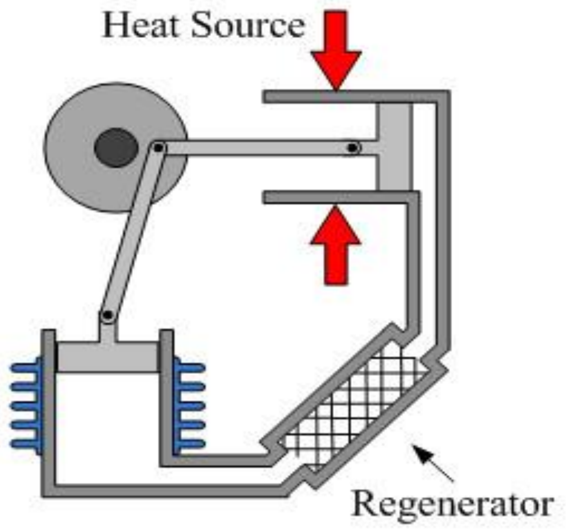
Stirling engine – Regenerator, work pressure

Regenerator improves thermal efficiency

- It is located in a gas flow channel between cold and hot cylinders (or ends).
- It can be as simple as a piece of metal mesh or foam.
- When a work gas flows thru it mesh binds and releases some of the heat energy of the gas (the gas cools and warms up again)

Pressurizing of a work gas improves the power.

- On the other hand cylinder walls might need to be designed thicker – which decreases ”rapid” heat transfer thru walls
- and increases the risk of escaping of the work gas thru sealings.



Sources: https://www.stirlingengine.com/regenerators/
Pixabay.com

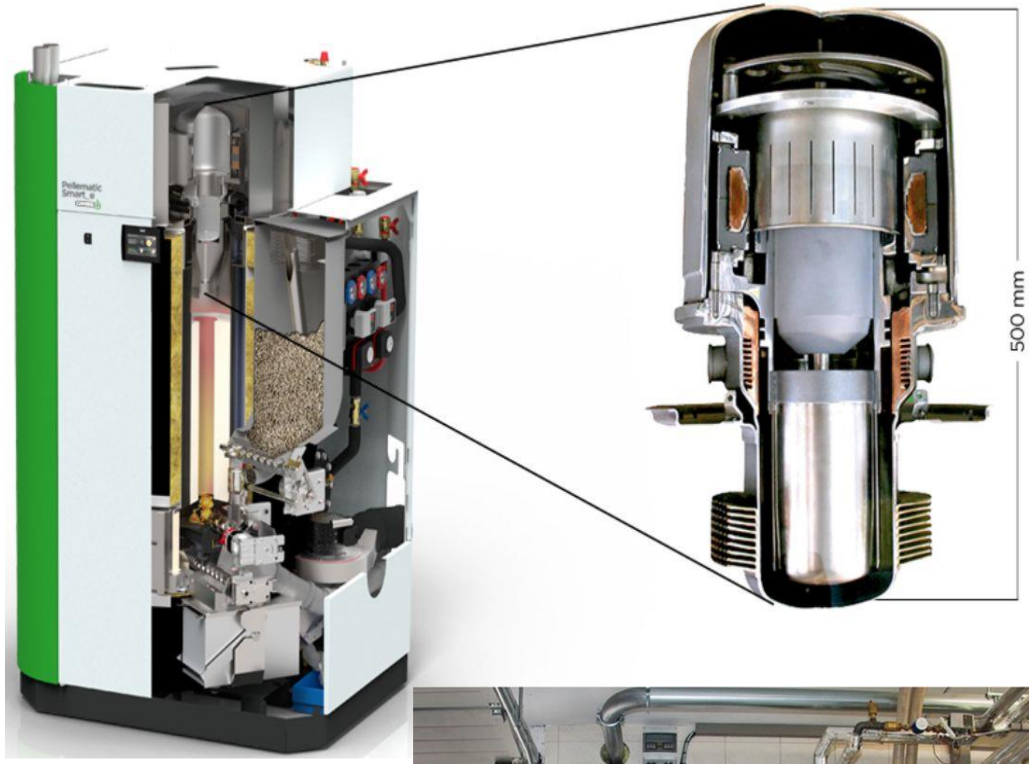
Stirling – Inresol Ab

Swedish company, in autumn 2018 went bankrupt

- Attempted to develop a consumer-grade µCHP with a gamma-type Stirling engine
  - Hot end temperature 600-1100 ° C
  - Nitrogen as a gas (N2)
  - Gas pressure "low"
  - The generator is connected directly to the crankshaft
  - Seals are self lubricating
  - Active Vibration Reduction
- The target was 5kWe and 15kW$_t$ – electricity generation efficiency would be as high as 25%
- The company invested heavily in marketing
- In particular, there were problems with the durability of crankshaft components
  - LTU offered help to solve the problem

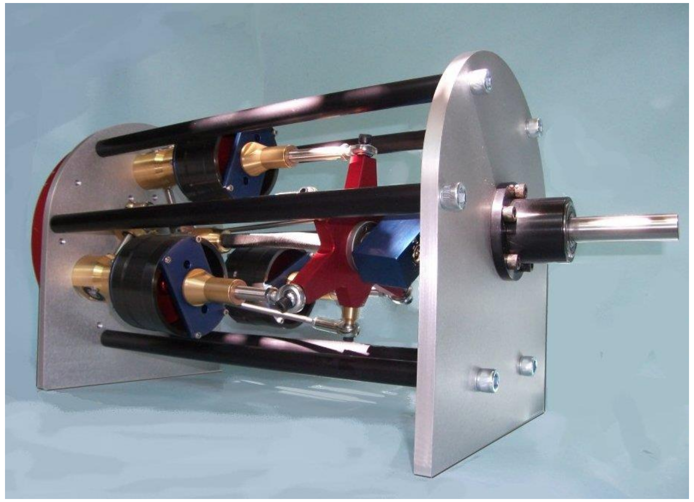
Stirling – Ökofen

- Beta-type stirling engine
  - Helium (He) as the work gas
  - The spring located to the bottom pushes the displaser piston back to up.
  - The work piston contains permanet magnets is surrounded by a fixed magnetic coil with copper windings, which means that an alternating current is generated.
  - The duty cycle is 50 Hz.
- The nominal power of the motor is 0.6-1 kWe when the boiler output is 9-16 kWt (corresponds to approximately 6% efficiency in generating electricity)
- The price of the whole system is about 20,000-25,000 EUR, the engine alone is over 10,000 EUR.
- The company is the only few suppliers of µCHPs, using renewable biomass, still in operation.
- They also offer a 5kW$_e$ version of the Stirling engine



Steam Engine

- **Is an old invention,**
  - the most famous in history in 1784 by James Watt
- **Steam turbines** are widely used in MW size power plants – too expensive to be used in µCHP applications
- Nowadays, **steam engines** are mainly familiar from jewelled-beauty nostalgic machines on boats,
- but there has been attempts to bring steam motors to µCHPs time to time.
- Piston type machines:
  - single cylinder,
  - double cylinder (compound) and
  - three-cylinder (Triple)
- Can be designed as double-acting - a piston is doing work on both directions



https://www.greensteamengine.com/

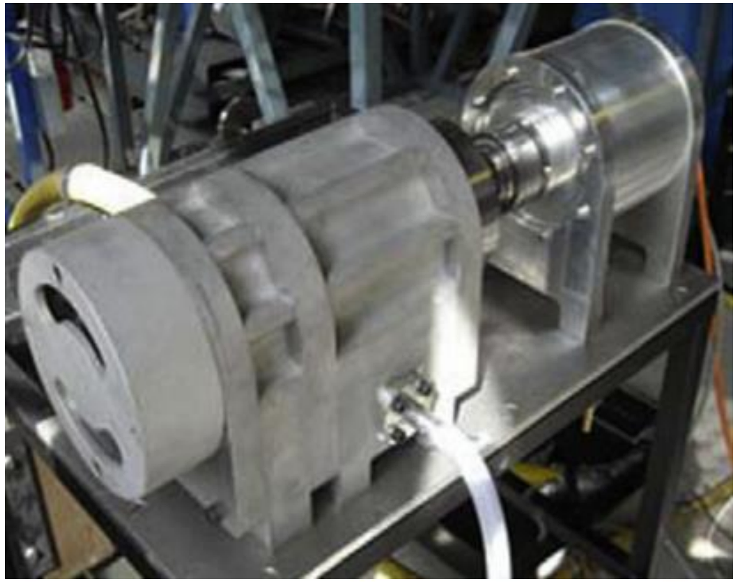
https://cyclonepower.com

Rotary Steam Engine – Novoro Oy 2006

Aalto University — Rotary steam engine (RSE)-I

© Aalto University, Dept. of Energy Technology

- Developed by Novoro Inc. in collaboration with Aalto University since 2006
- Operational principle:
  - Rankine cycle
- Characteristics:
  - Utilize 150...200 ºC vapor (5-15 bar)
  - Oil free, noiseless, 1000-2000 RPM
  - Compact size, power/weight ratio
  - Connection to generator without gearing
  - Versatile sources of heat (e.g. biofuels or solar energy)
  - Estimated installed cost of a similar magnitude as for micro-CHP plants based on internal combustion engines



- ➢ Boiler 25 kW
- ➢ Electrical efficiency of 9%, thermal efficiency of 77%
- ➢ An overall cogeneration efficiency of 86%

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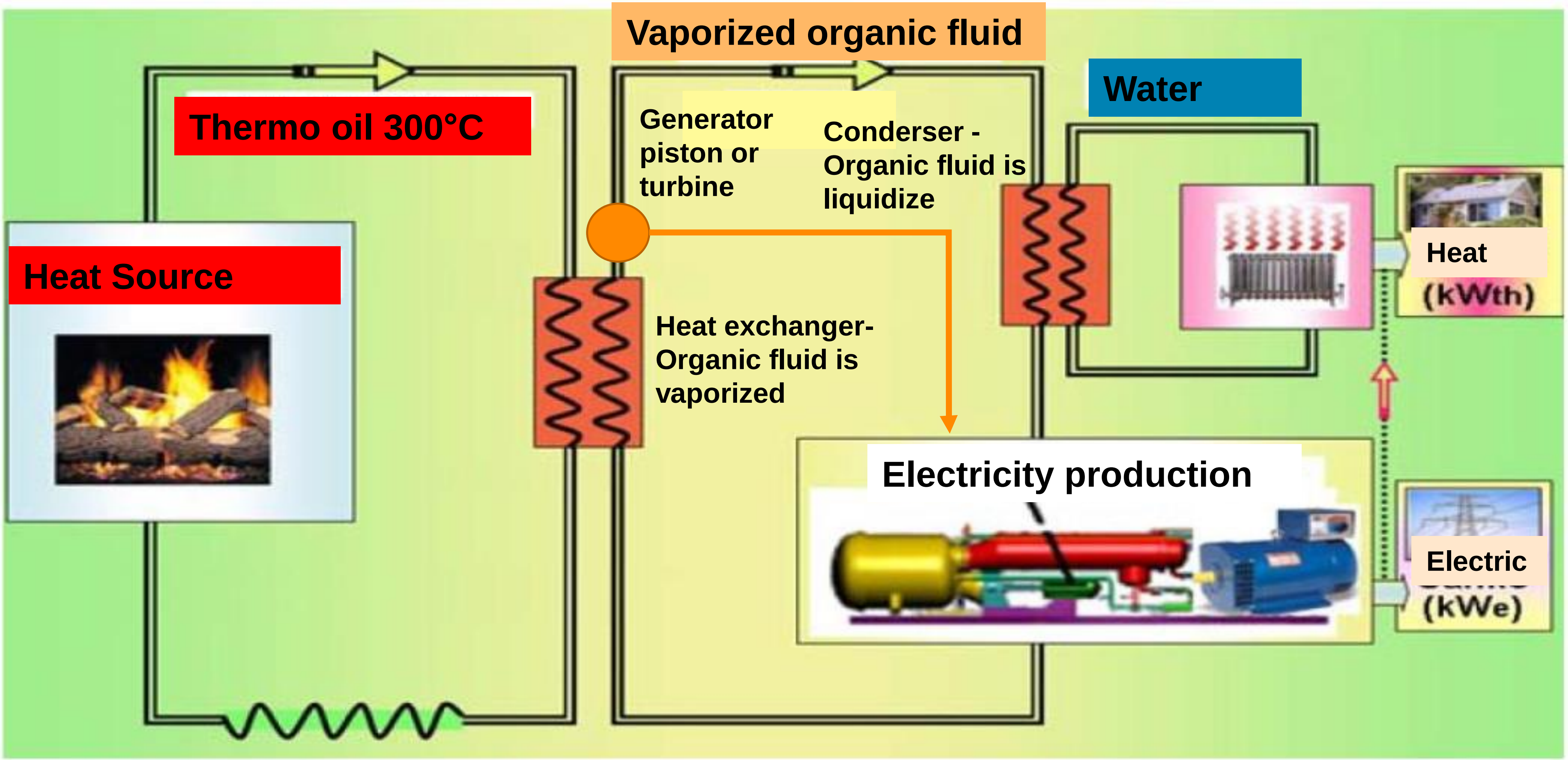
Organic Rankine Cycle - ORG



Source: Granö, U-P. 2010. Hajautettu energiantuotanto. Biomassan kaasutus. http://www.scribd.com/doc/49586467/Hajautettu-energiantuotanto-2010-FI-Ulf-Peter-Grano.

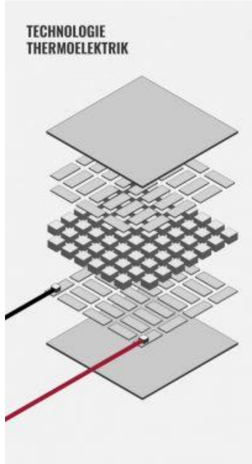
ORG – Keymacor, Italy

Thermal input	45 kW
Thermal output at 50	37
Net electrical output	4kW
Eta orc	10%
Eta chp	90%
Energy label	A+

- Based on the technology familiar from air-source heat pumps but works the other way round
- Built from commercially available components
- Commercialization is just beginning

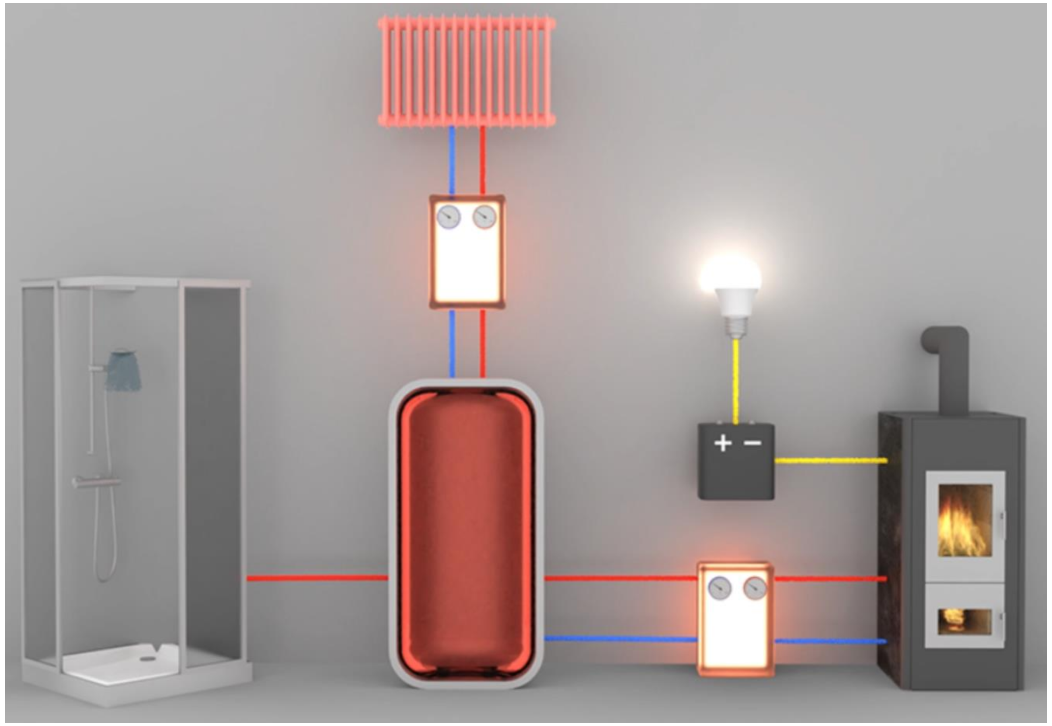
https://www.kaymacor.com/en/

Thermoelectric µCHP



- Based on so called ”Peltier” – element but works the other way round

- **Seebeck 250W$_e$**
  - 10-20 kW for heating and service water with highly efficient wood-nano-cogeneration unit
  - Wood (logs) with a size of 33-40 cm
  - Various e-stove coverings
  - Made in Germany by Thermoelectric GmbH
- So far efficiency of producing electricity with thermo-electric systems has been poor, about 6%.



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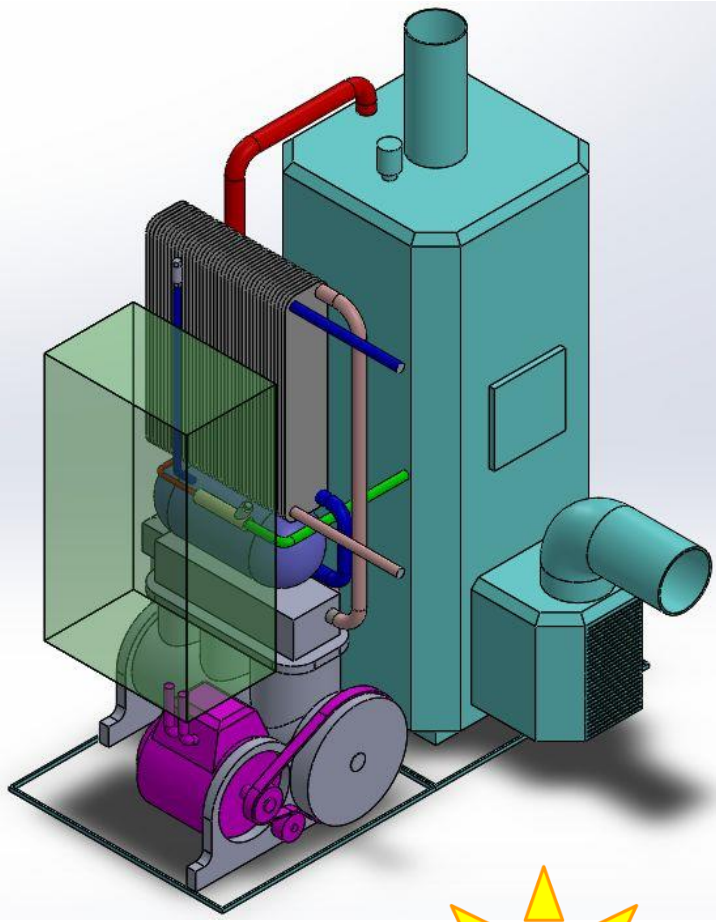
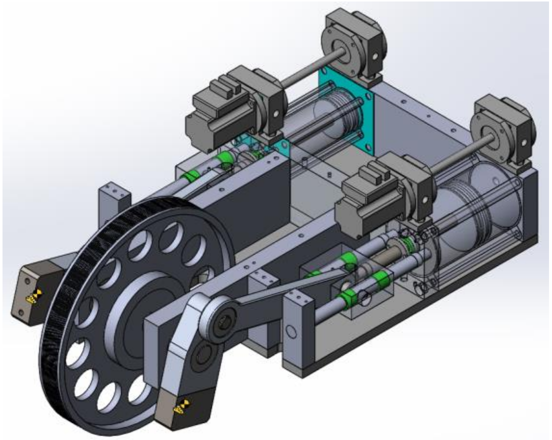
Design of µCHP based on steam engine

- **Generally, the design can be divided into 4 design entities**
  1. Boiler
  2. Steam Engine
  3. Power Electronics
  4. Control
     - so-called smart energy management control
     - tracks consumption, adaptability
- **The system produces 3-6 kWe 20-40 kWt**
- **Fits in two 600x600x1800mm modules (cabinet size)**



Steam engine – design basics



- Type: Double acting compound (piston doing work on both side)
- Rotation speed 600 rpm
- Stroke 125mm
- **High pressure piston** dia. selected as 63mm (calculated 59,2 mm)
- **Low pressure piston (LP)** dia. selected as 100mm (calculated 96,3 mm)

  -> According the closest standard size of cylinders and seals

- Valve: rotary type
  - HP valve is kept open 39,8% of stroke then closed and let the steam expand
  - LP valve 46,9% of stroke
- Receiver volume 0,515 liter (including hoses + receiver)

Steam engine dimensioning…

High pressure cylinder (HP)	p_1 =	14	bar(a)
	p_2 =	5,87	bar(a)
	V_1 =	0,000137	m^3
	V_2 =	0,000344	m^3

$$p_2 = \frac{V_1 \times p_1}{V_4} + \Delta p_{vs}$$

$$V_2 = \frac{V_4}{r}$$

HP cylinder diameter	$Ø_{HP}$ =	0,0592	m
		59,2	**mm**

$$Ø_{HP} = 2 \times \sqrt{\frac{V_2}{l_{Stroke} \times \pi}}$$

Receiver pressure loss	Δp_{res} =	0,30	bar(a)
Receiver	p_{res} =	4,48	bar(a)
	V_{res} =	0,000515	m^3

$$p_{res} = p_3$$

$$V_{res} = 1{,}5 \times V_2$$

Low pressure cylinder (LP)	p_3 =	4,48	bar(a)
	p_4 =	2,10	bar(a)
	V_3 =	0,000427	m^3
	V_4 =	0,000911	m^3

$$p_3 = \frac{p_1 - \Delta p_{res} + (p_b \times r)}{(r+1)}$$

$$p_4 = \frac{V_1 \times p_1}{V_4}$$

$$V_3 = \frac{V_1 \times p_1}{p_3}$$

$$V_4 = R \times V_1$$

LP cylinder diameter	$Ø_{LP}$ =	0,0963	m
		96,3	**mm**

$$Ø_{LP} = 2 \times \sqrt{\frac{V_4}{l_{Stroke} \times \pi}}$$

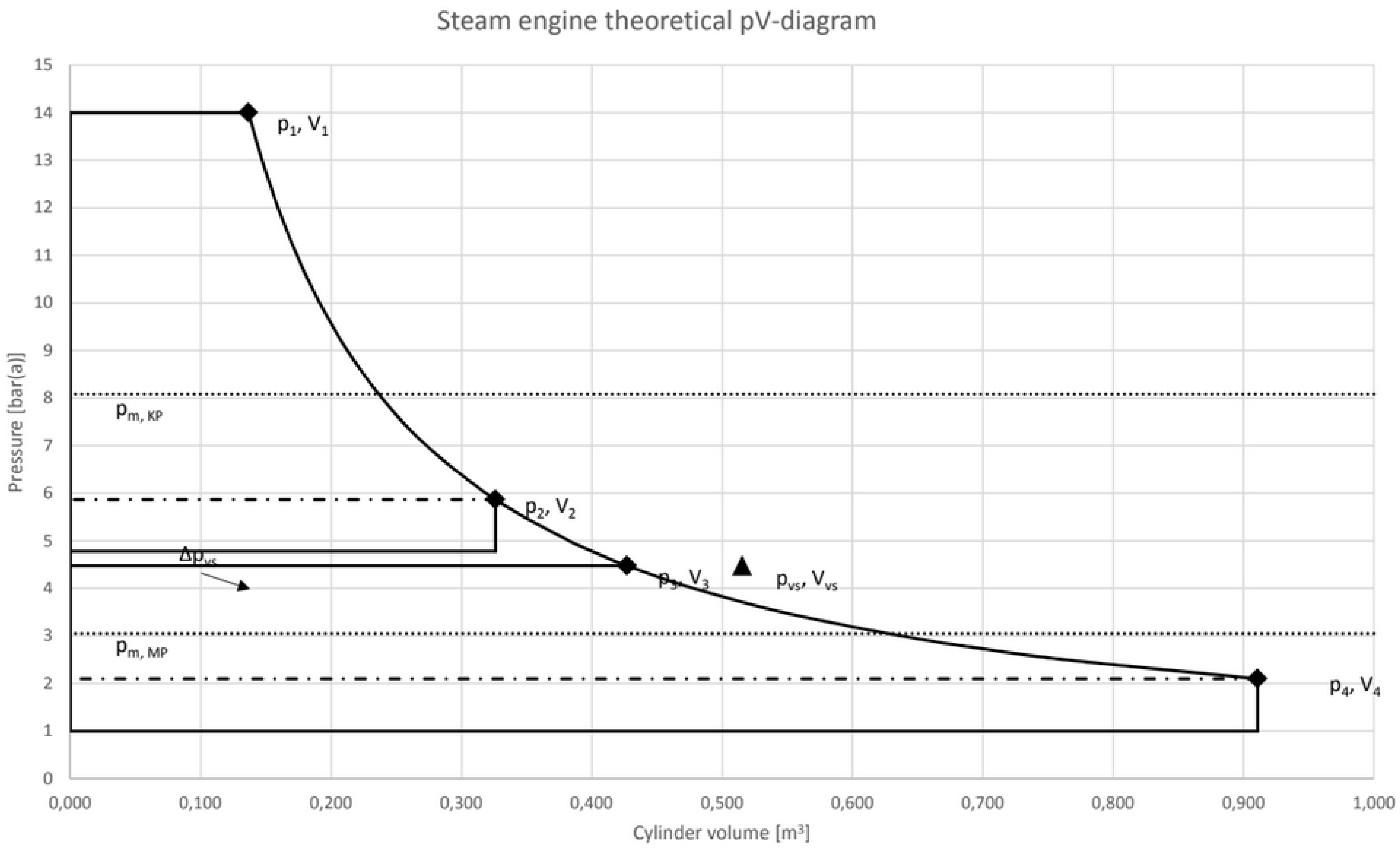
Condenser pressure	p_b =	1	bar(a)

Steam engine dimensioning…

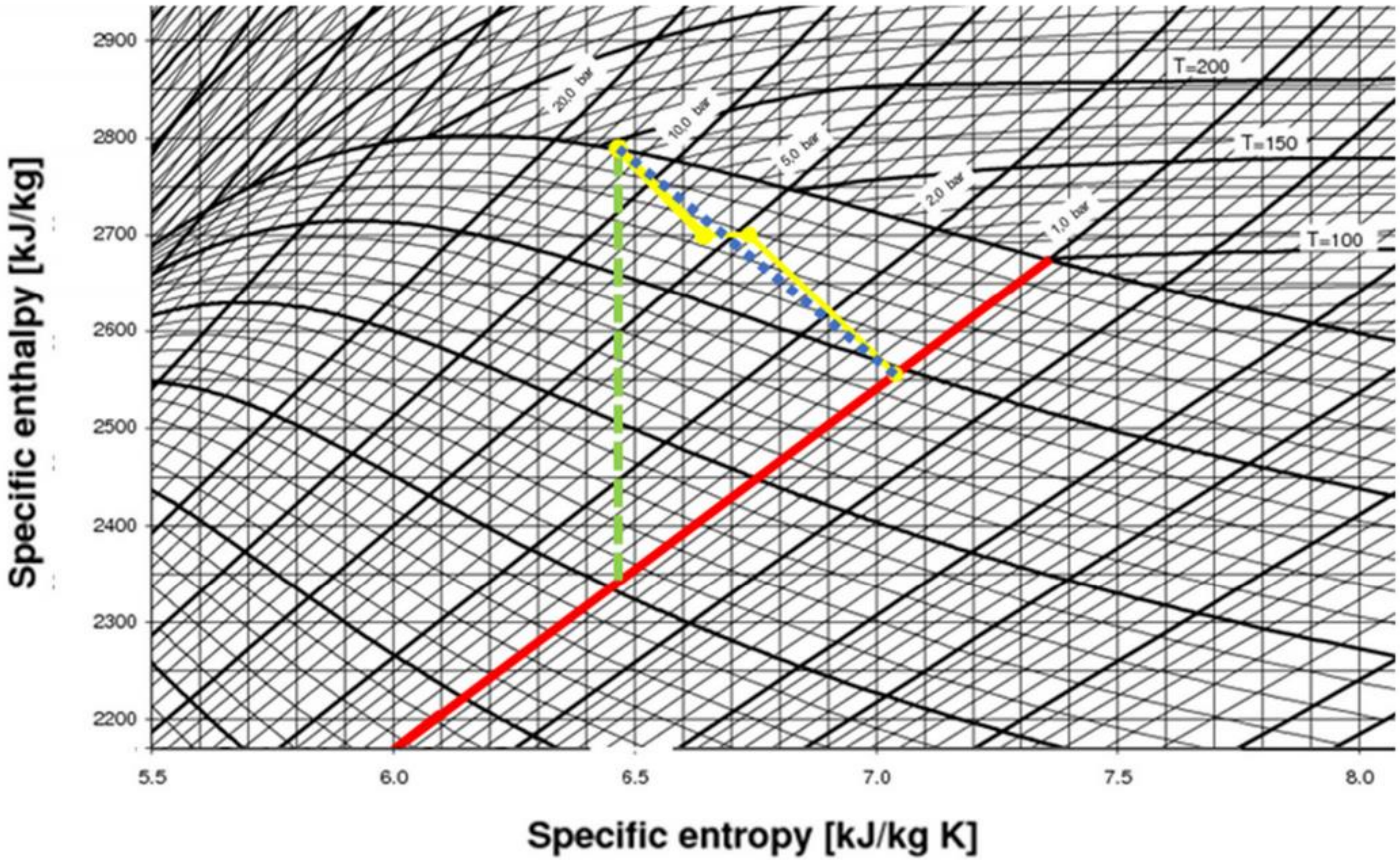
Steam engine sizing

Wanted power	P =	5	kW	
Ratio of expansion, whole engine	1 / R =	0,15		$\frac{1}{R} = \frac{V_1}{V_4} = \frac{p_4}{p_1}$
	R =	6,67		$R = \frac{V_4}{V_1}$
Cylinden volume ratio	r =	2,65		$r = \frac{V_4}{V_2}$; *One piston expansion ratio* $r_{1,HP} = \frac{V_2}{V_1} = 2{,}52$ $r_{2,LP} = \frac{V_4}{V_3} = 2{,}13$
Overall diagram factor	f =	0,6		The actual indicator area
Mechanical efficiency	η_{Mech} =	0,9		Steam engine mechanical parts
Total efficiency	η_{Tot} =	0,54		$\eta_{Tot} = f \times \eta_{Mech}$
Rotation speed of engine	rpm =	600	r/min	$N = \frac{rpm}{60\ ^{s}/_{min}}$
	N =	10	r/s	
Piston speed	v_m =	2,50	m/s	Speed should be <5 m/s
Piston stroke length	l_{stroke} =	0,125	m	$l_{stroke} = \frac{v_m}{2 \times N}$
	l_{stroke} =	125	mm	
HP cut-off volume	V_1 =	0,000137	m^3	$V_1 = \frac{P_{engine}}{\langle 100 \times 2 \times f \times N \rangle \times \langle [p_1 \times (1 + lnR)] - (p_b \times R) \rangle \times \eta_{Mech}}$
	V_1 =	0,13660	dm^3	
	V_1 =	136,60	cm^3	
Steam amount	V_{Steam} =	0,002732	m^3/s	10 strokes/s * 2 sides of piston
	ρ_{Steam} =	7,1028	kg/m^3	Saturated steam 14 bar(a)
	m_{Steam} =	**0,019404**	**kg/s**	
Mean effective pressure	$p_{m,LP}$ =	3,05	bar(a)	$p_{m,LP} = f \times \left\{\left[\frac{p_1}{R} \times (1 + lnR)\right] - p_b\right\}$
	$p_{m,HP}$ =	8,08	bar(a)	$p_{m,HP} = r \times p_{m,LP}$

Steam engine dimensioning…

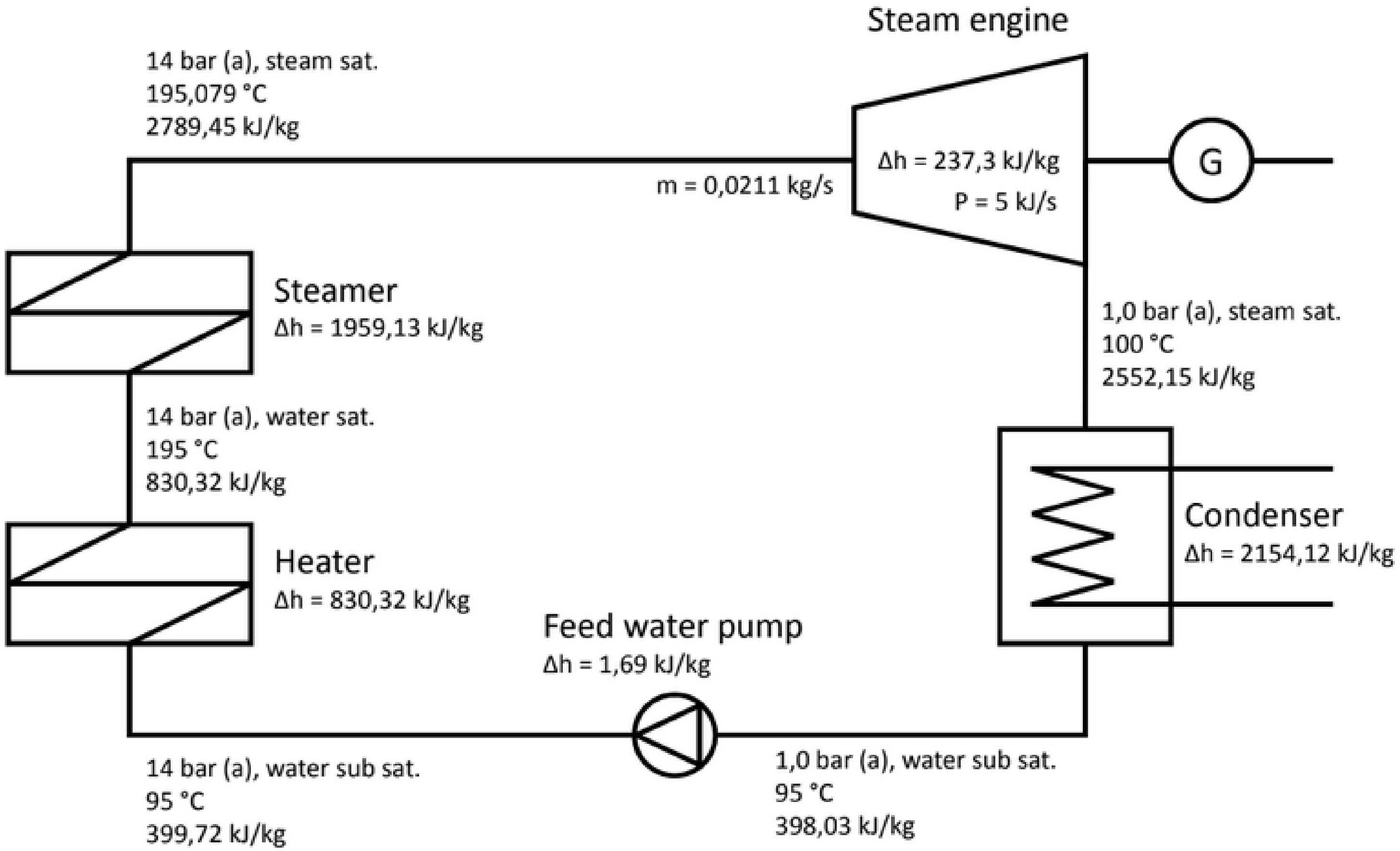


Steam engine dimensioning…



Steam engine’s theoretical power efficiency

	Δh [kJ/kg]	Φ [kW]	
Boiler process	2 389,7	50,35	94 %
Boiler losses	71,7	1,5	3 %
Flue gas losses	71,7	1,5	3 %
Total	**2 533,1**	**53,4**	**100 %**
Steam engine	**237,3**	**5,0**	**9,9 %**
Condenser	**2 154,1**	**45,4**	**90,1 %**



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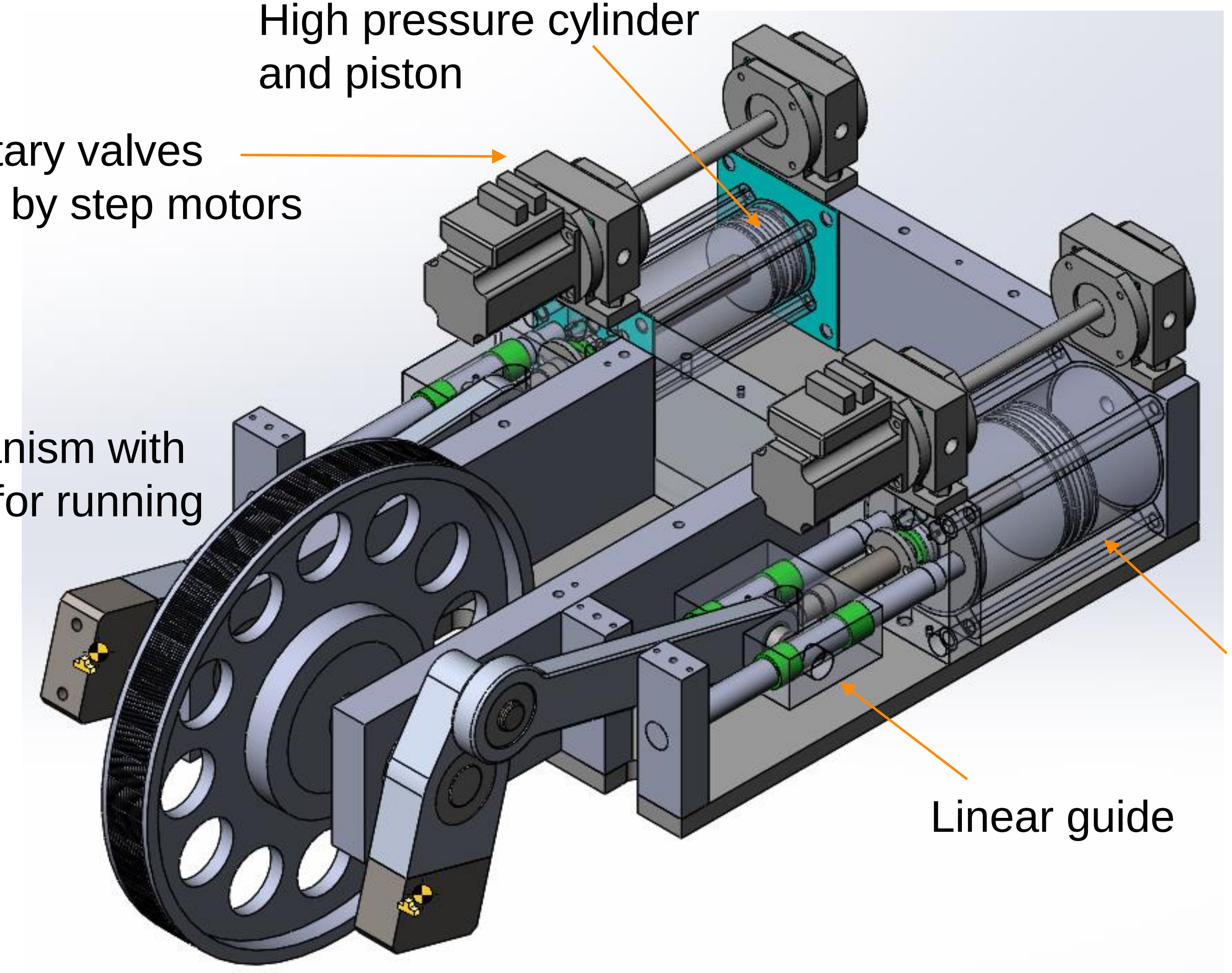
3D-model of proto steam engine



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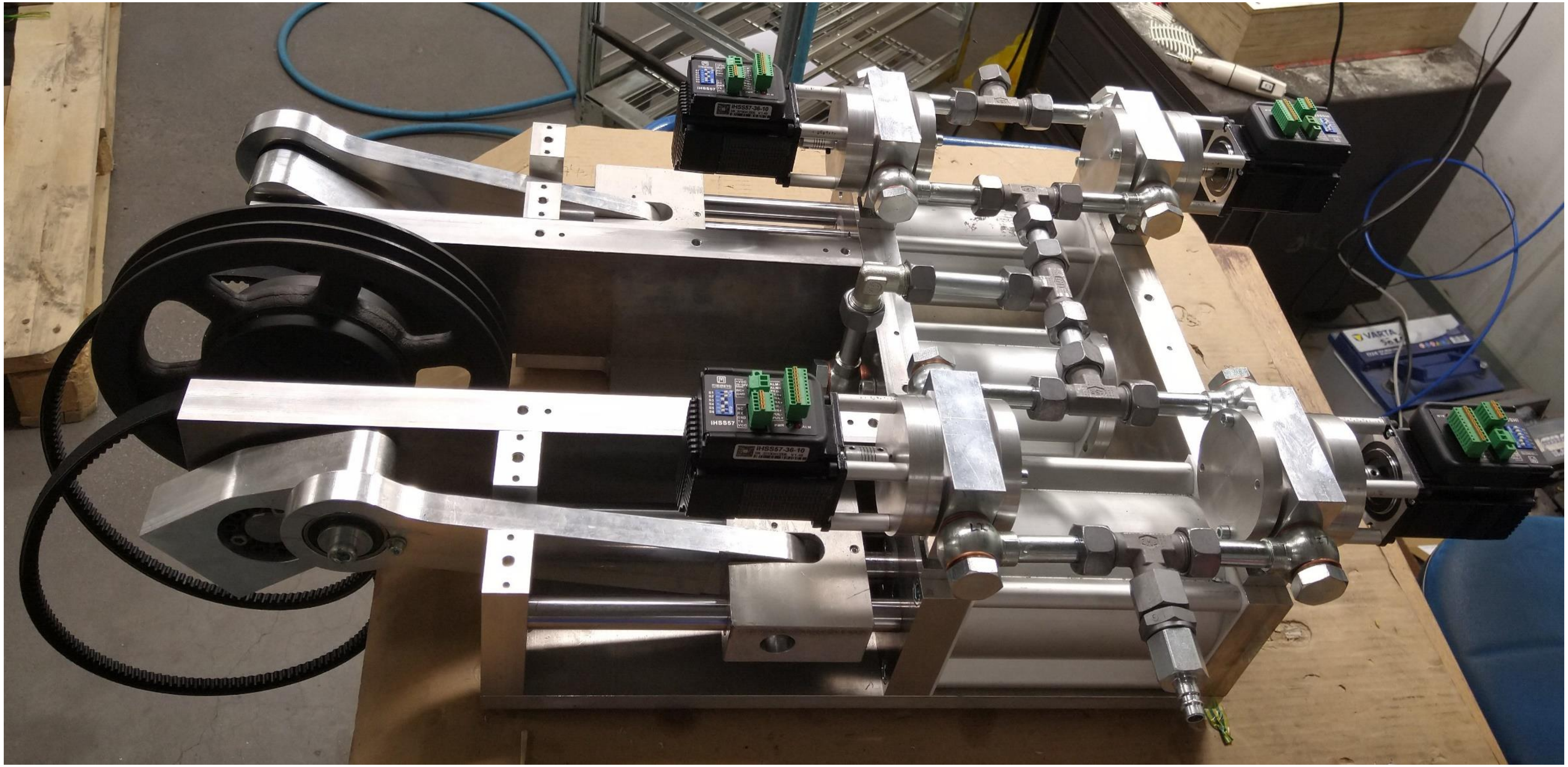
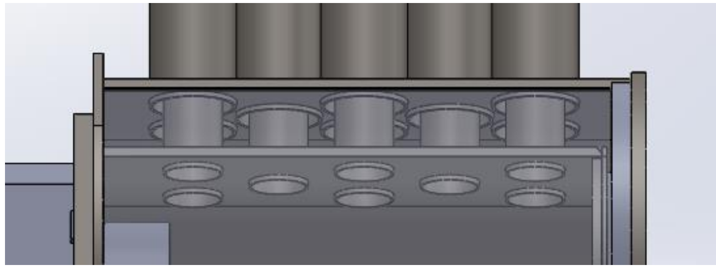
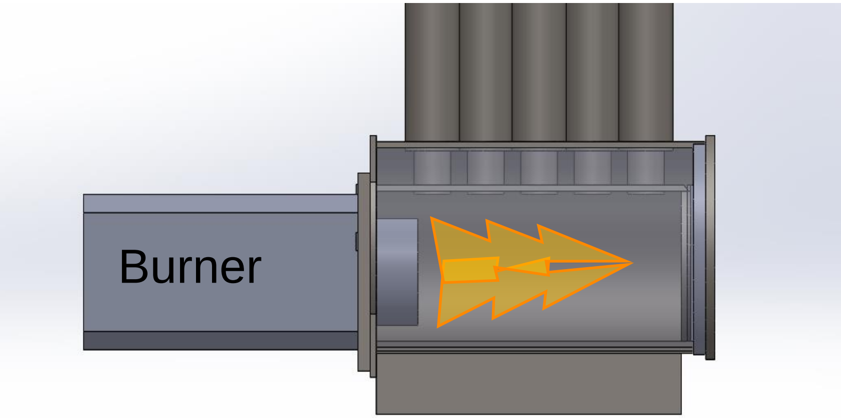
The proto steam engine

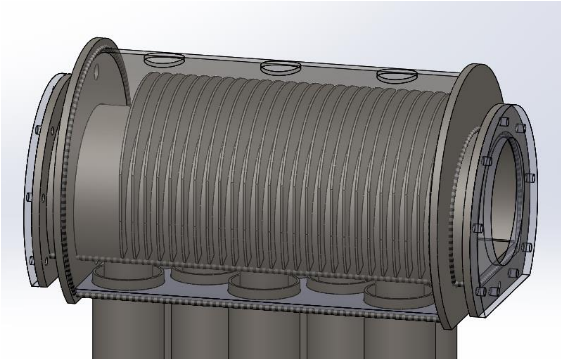


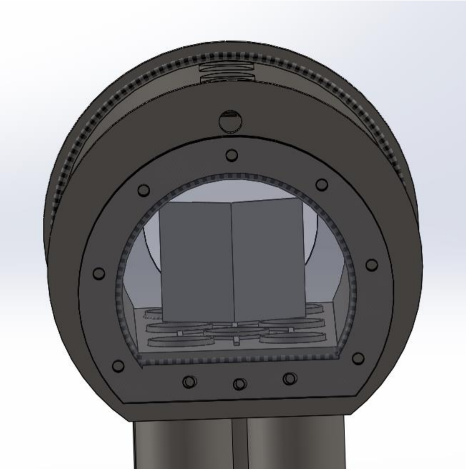
Boiler (1st version)

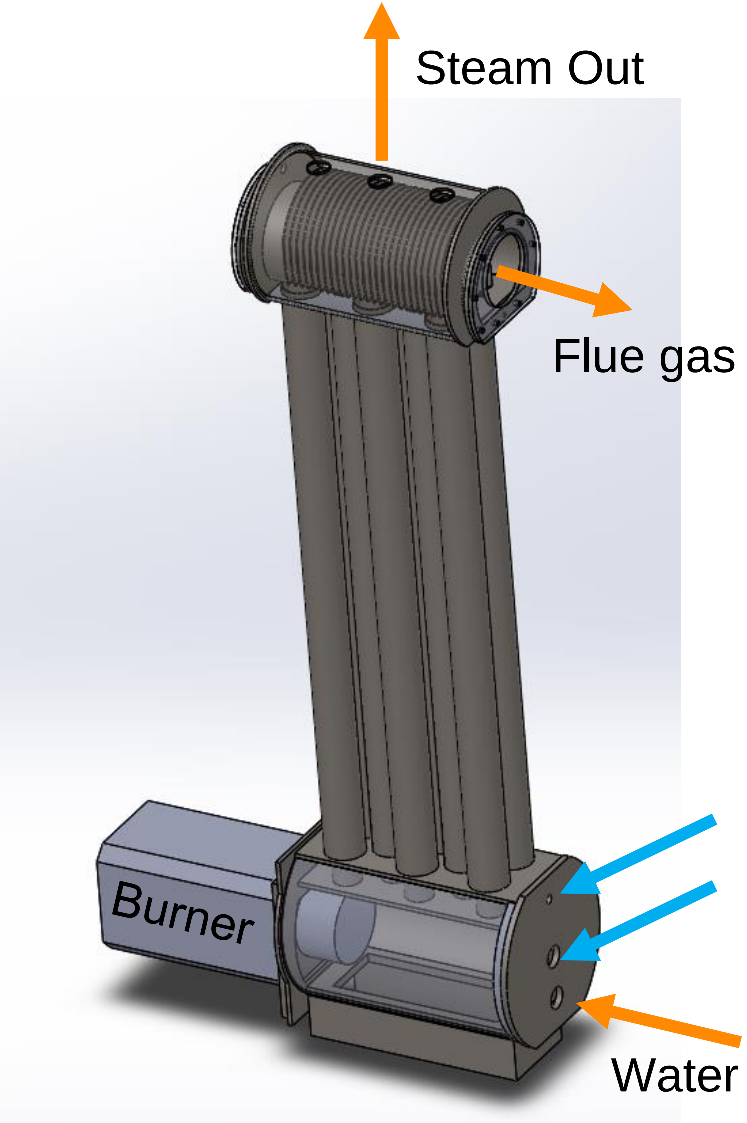
Combine of fire-tube and water-tube boiler



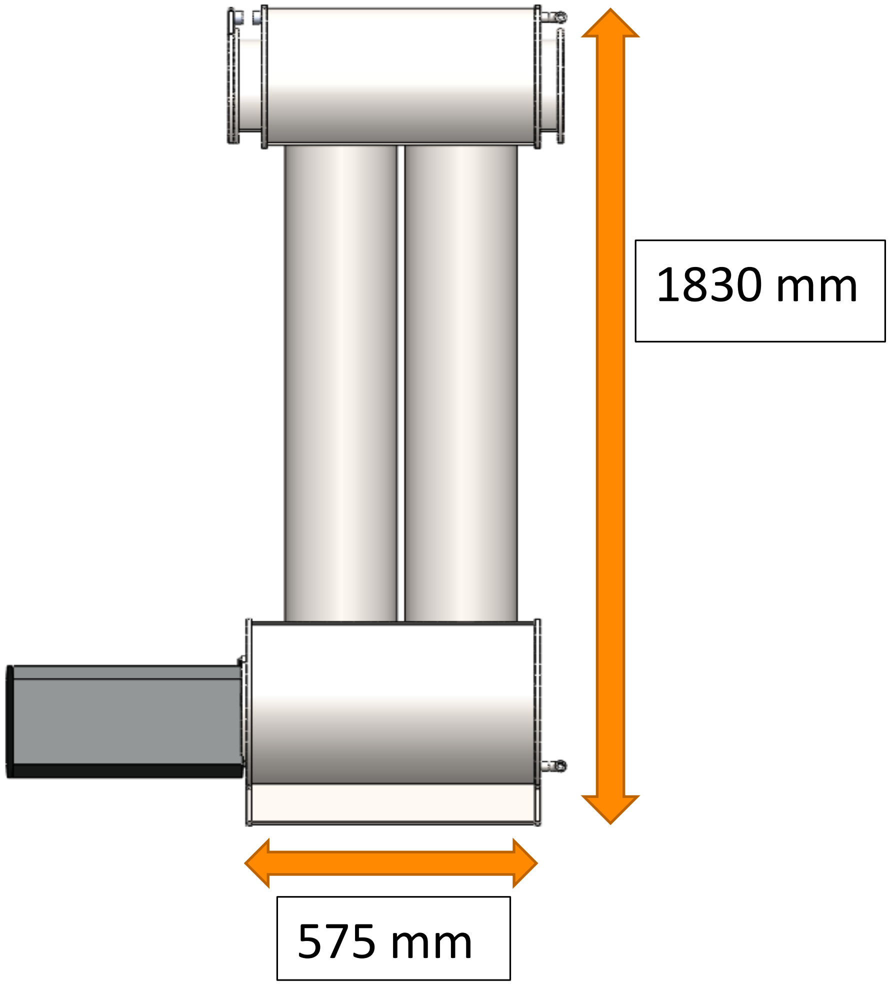


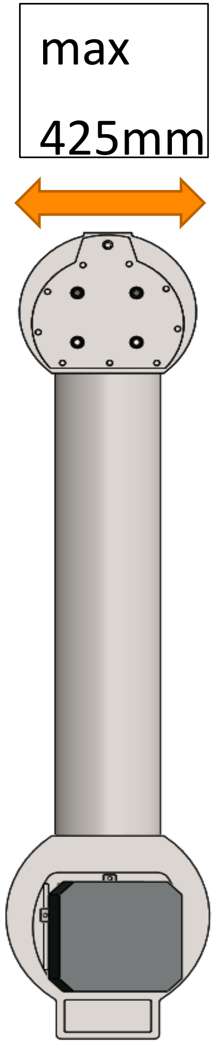






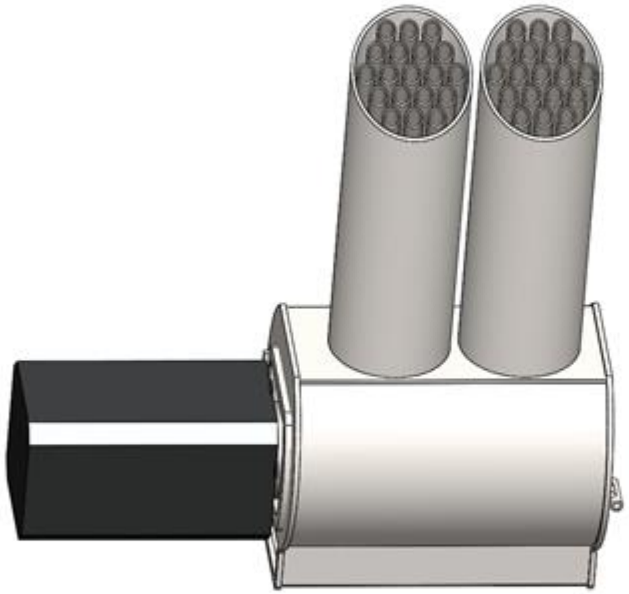
Boiler proto





"Fire-tube" construction

- 19+19 "fire tubes",
  - Ø 33,7 x 3,2 mm
- 2 "water tubes"
  - Ø 219,1 x 6,3 mm
- Weight: ca. 400 kg



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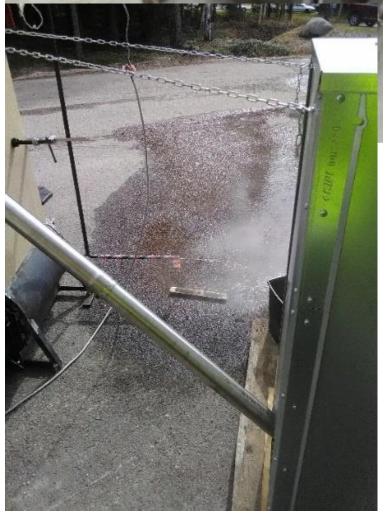
The Boiler proto

Manufactured and some test implemented…

- Pressure tested up to 16 bar – no leaks
- Capable of producing steam from 4 °C water at the mass rate of 2,5 kg/min at full power (50 kW)
  - Requirement is 1,2 kg/min
  - Actual temp. of return water in run is approx. 90 °C

-> The capacity of producing steam is enough.



Boiler proto - Challenges

- P355GH heat resistant, pressure vessel steel grade
  - Difficult to purchase in small patches, now enough for three protos
- Weight of the boiler is quite high due to material wall thicknesses
- Industrial components are very expensive e.g.
  - **Float** for adjusting water level from one supplier: 514€ + VAT

    Material: Stainless steel
    Pressure: 16,0
    Test pressure: 24,0
    Fluid density: 1000
    Temperature, fluid, max.: 300
    Temperature, fluid, min.: 0

  -> We made the float ourselves and used neodymium magnet -> costs < 50€
- Fact: below requirements of 16 bar and 200°C – components are much cheaper - components are available in “the consumer class”.
- Pressure vessel regulation
  - If water volume is max. 50l and pressure max. 10 bar (500 bar liter)
    - -> Boiler does not need to register as a pressure vessel
- The height of the water in the boiler should also be visually detectable.

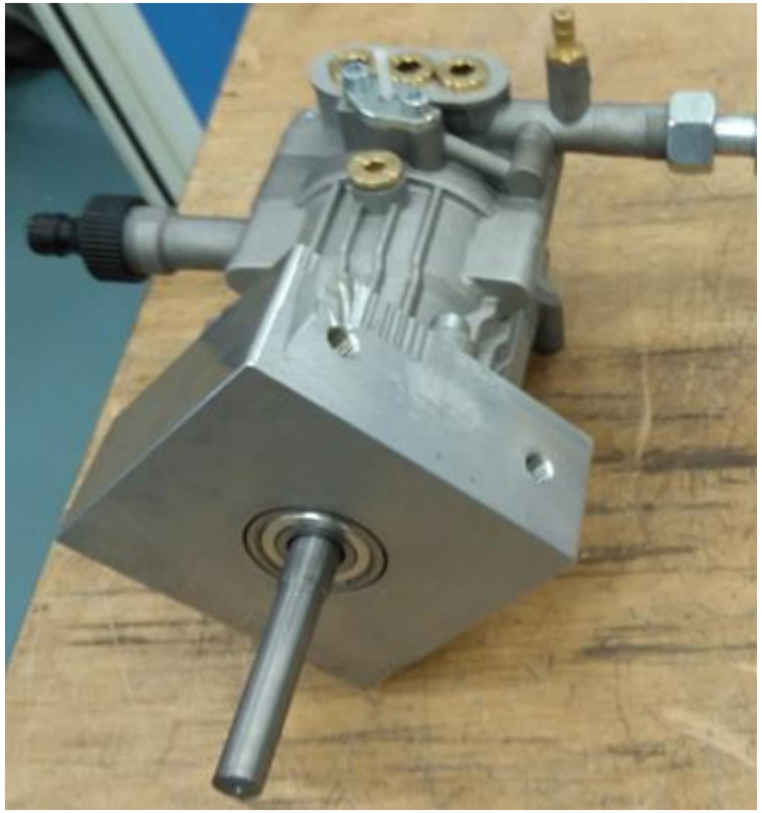
FMT

A cheap water pump ”solution”

Pressure washer pump as spare part

- Tested up to 40 bar -> Pressure sensor “explode”

- Capacity ok (>8 l/min, requirement is 4 l/min)



FMT

Power electronics

Main components:

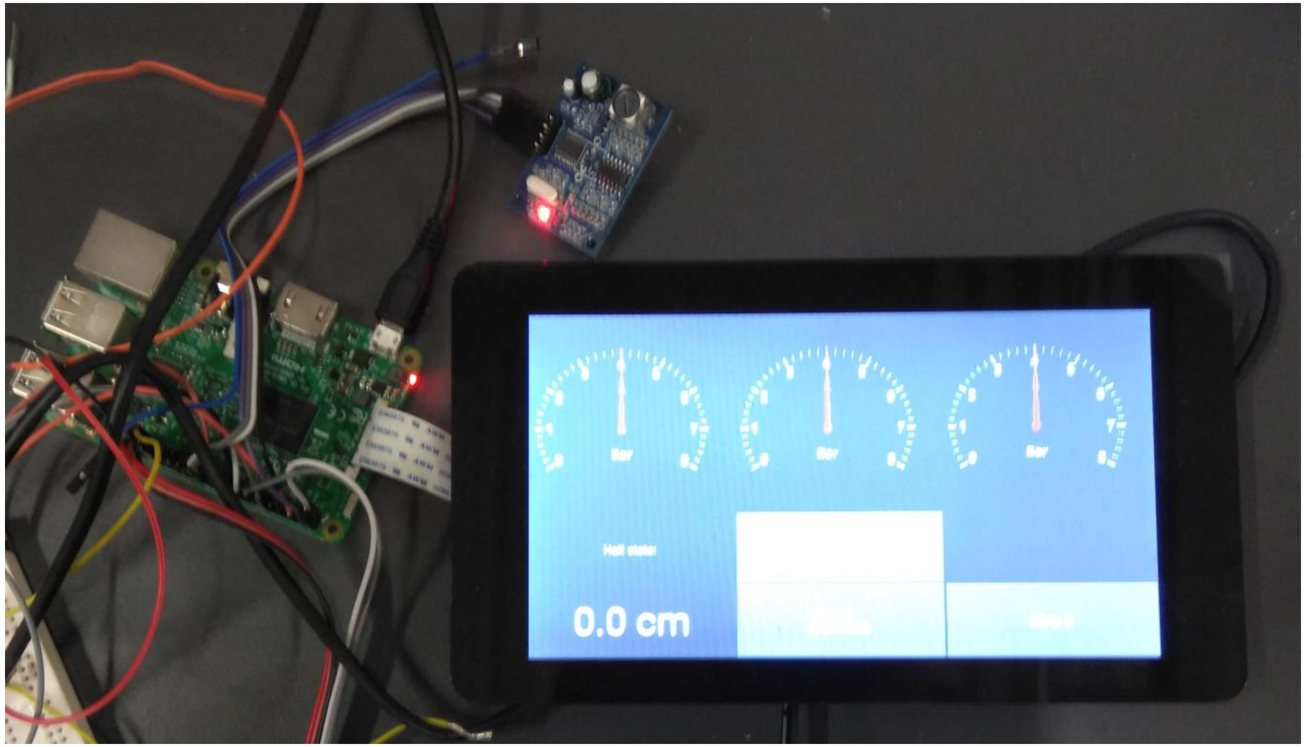
1. Generator,
2. Inverter and
3. Battery

- ➢ Inverter could be used on- and off-grid
- ➢ We did not manage the Inverter (Victron Quattro) to charge the Lithium-ion battery pack (LG Resu)
  - ➢ -> bought common lead-acid batteries

FMT

Smart energy management system
(System control)

- Virtual system tests implemented – everything should be ok
- Tested with boiler (temp. & pressure)
- Next: fine adjustment within 1st CHP proto



Unit costs of the prototype
(approx. without steam engine)

▪ Battery pack (LG CHEM RESU 3,3 Li-io 3,3 kWh)	2500€
▪ Stepper motor for rotary valve	200€
▪ Generator (Sincro 6 kVA, 230 V, 50 Hz, 3000 rpm)	600€
▪ Inverter (Victron quattro 48/8000/110)	2700€
▪ Power electronics accessories	1000€
▪ Burner (KIPI Rot Power 50kW)	2600€
▪ Safety valves	550
▪ Steel plates	3200€ (for all three protos)
▪ Steel pipes	800€
▪ Accessories	approx. 500€
▪ Total without steam engine	12 500€

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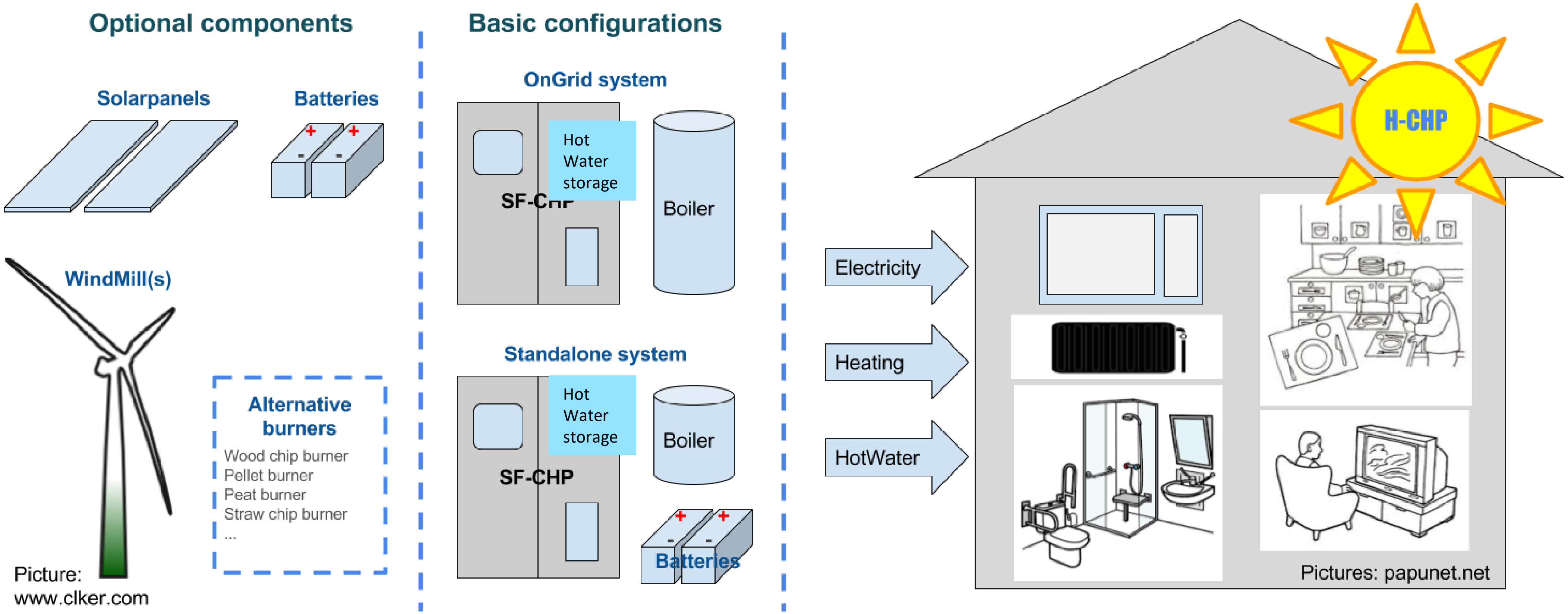
Output 3.

Increased use of renewable energy in housing...

– ...in the remote and sparsely populated areas

- Basic CHP system on-grid or standalone system
- Optional components – many alternative configurations



Smart energy management solution – takes advantages of daily peak loads

What in the near future?

- The aim is for interested parties to join the H-CHP community and continue developing equipment after the project.
- We publish all documents, templates and drawings created in the project.
- Link to project website: www.h-chp.eu

Public events…

Publications

Household Energy Survey

Location

This section is intended to gather data on the gene
identify any specific property.

Country of residence

- Faroe Islands
- Finland
- Greenland
- Iceland
- Northern Ireland
- Norway
- Republic of Ireland
- Scotland
- Sweden

Postal code

1. Introduction

Combined Heat and Power (CHP) device uses the principle of co-generation – simultaneous generation of electrical and heat power. The aim of combining these two processes together is a more efficient extraction of the energy from the fuel.

According to thermodynamics laws and energy conversion principles there always will be some heat energy losses during the heat-to-electricity transformation process (Shavit, 1995). The waste heat can be captured and used for other needs, increasing the overall efficiency of the cycle.

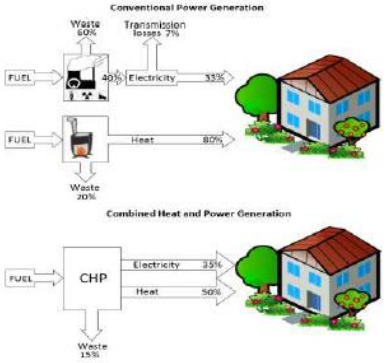


Fig 1. CHP Efficiency.

The well-known applications of the CHP are:

- Combined Heat and Power District Heating (CHPDH)

Popular solution in northern countries, when waste heat from power plants is used for heating the buildings in nearby areas.

- Local CHP and Distributed Generation

This type of systems can be used to produce the power for individual projects: it can be either industrial applications (when heat is used for heating the premises and electricity for manufacturing processes), or domestic applications (Micro-CHP). Excess power from individual CHP units can be stored or exported to the grid.

- Automotive

Even the cars employ the principle of cogeneration. Excess heat from internal combustion engines is used for cabin heating.

The fast expansion of renewable energy market and development of new technologies (such as

- **Household Energy Survey Tool (website)**
  - Questionaire Website, documentation and results (heat map)
  - Domestic energy consumption in the NPA region - the balance between heat and electricity use
- **Micro-CHP: 'National and EU Regulations'**
- **CHP fuels in the NPA region**
- **Optimal micro-CHP configuration of the region**
  - Overview of the Micro-CHP Technologies
  - Funding, subsidies and cost of CHP in all NPA regions with a comparison of payback times
- **Eight thesis (by students in OUAS, in Finnish)**

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For achievíng goals … multinational co-operation is needed

UNIVERSITY OF ICELAND

Alternative fuels and Gasification

WP T3

UNIVERSITY OF OULU

Project coordinator
Design and manufacturing up to 10 SF-CHPs

WP M, WP T2 Conceptual planning and implementation

OAMK OULU UNIVERSITY OF APPLIED SCIENCES

Energy technology
Laboratory testing

WP T5 Evaluation

POINT AND SANDWICK TRUST
COIMHEARSNACHDAN COMHLA

LULEÅ UNIVERSITY OF TECHNOLOGY

Manufacturing methods
Laser welding – Hybrid welding
Additive Manufacturing
DFMA

H-CHP Consortium member roles and responsibilities

Energy Action
THE WARM CHARITY

End user point of view
Dissemination and Exploitation of results

WP TC Communication

WOODLAND TRUST

Omakotiliitto

HARVIA
Sauna & Spa

FMT

TIGHEAN INNSE GALL

WP T4 Piloting

End user point of view
Organizing of field test arrangements
Dissemination and Exploitation of results

University of the Highlands and Islands | Oilthigh na Gàidhealtachd agus nan Eilean
Lews Castle College | Colaisde a' Chaisteil

Energy technology - Fuels
Laboratory testing

WP T1 Assessment

Thank you for your kind attention!

Northern Periphery and Arctic Programme
2014–2020

EUROPEAN UNION
Investing in your future
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