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BACKGROUND AND SUMMARY OF COMMERCIAL ORC DEVELOPMENT AND EXPLOITATION

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Background of commercial ORC

- The principle of Organic Rankine Cycles have been already known for decades
- The first ORC power plants were built in the beginning of 1960-decade
- Only a few commercial (over 50 kW) ORC power plants were realized since 1980s
- The main two companies making ORC-plants during 1980-decade are still nowadays the largest ORC manufacturers worldwide
- If excluding cloro-fluoro-carbons, the most popular working fluids at that time were clorobenzenes, fluorinol 85 and toluene.

Background of commercial ORC

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- Most likely Ormat was the pioner in ORC-technology; they started the making of micro sized (0.2 – 3 kW) ORC-units for remote tele stations already durind 1960-decade. Making of bigger ORC plants (50-600 kW) Ormat started 1980-1983
- Turboden made their first ORC plants (16 - 100 kW) 1982 - 1984
- Lappeenranta University (LUT) made their first ORC-plant based on high speed technology 1984. This was the backgroung of commercial plants developed later by Tri-O-Gen in co-operation with LUT
- During 1980-decade several companies in Japan (IHI, Mitsui, Mitsubishi), some companies in U.S.A. (Sundstrand, Baber-Nickhols) and several companies in Europe (Kali-chemie, Gemmindustria, Franco-Tosi, Betin et Cie) made ORC-plants, but are not any more active in this field.

* Reference: Larjola J. "Organic Rankine cycle (ORC) based waste heat / waste fuel recovery systems for small CHP applications". Chapter 9 in: Small- and micro-combined heat and power (CHP) systems, Advanced design, performance, materials and applications. Editor: Robert Beith, 528 p. Woodhead Publishing Limited, Oxford 2011

Early ORC-plants: large number of micro-size ORC-plants was built by Ormat already during 1970 and 1980 decades

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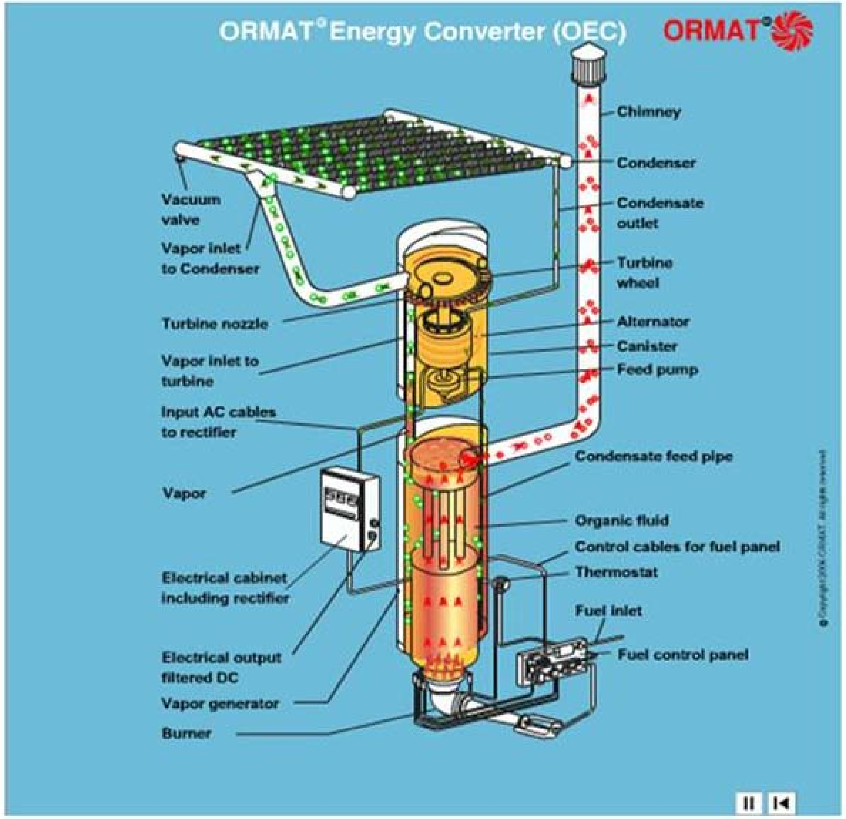
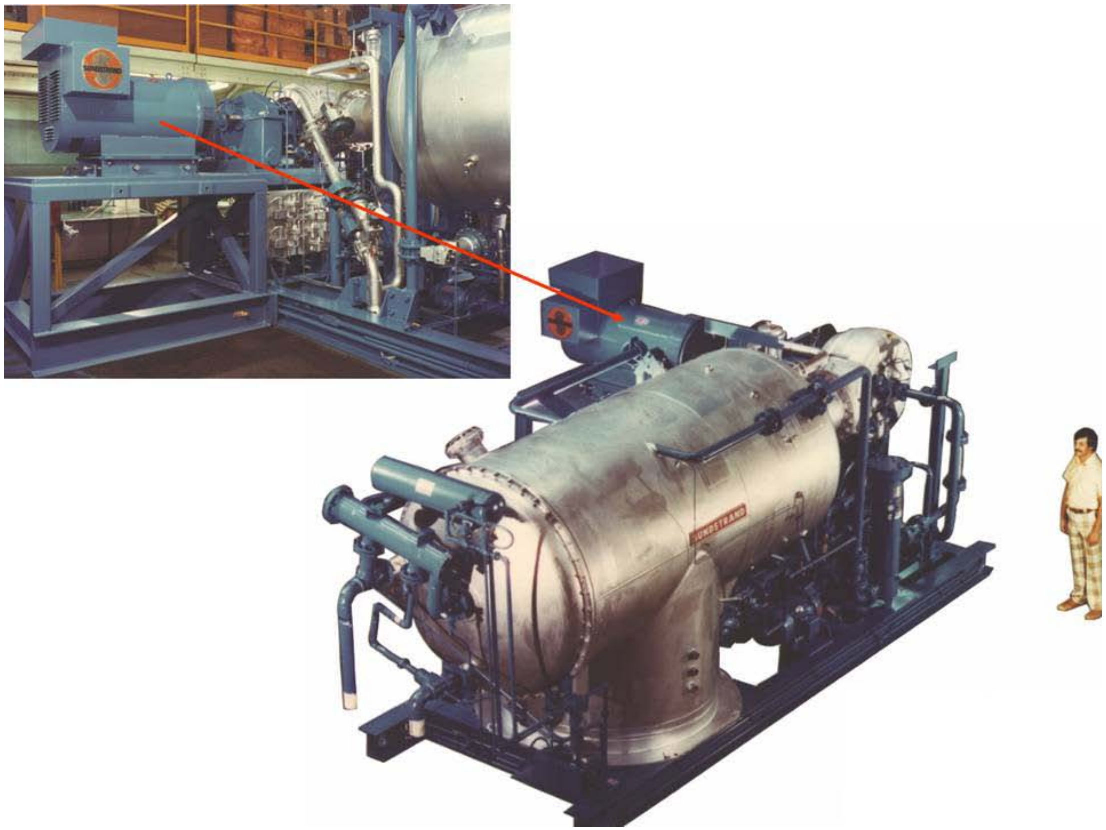


Principle of micro-ORC plant for special applications, and two example plants: Pipeline gate valve station in Alaska (upper) and Telecom link in Chile.

(Larjola J. "Organic Rankine cycle (ORC) based waste heat / waste fuel recovery systems for small CHP applications". Chapter 9 in: Small- and micro-combined heat and power (CHP) systems, Advanced design, performance, materials and applications. Woodhead Publishing Limited, Oxford 2011)

Early ORC-plants: 500 kW ORC-plant built by Sundstrand in the beginning of 1980-decade



Upper detail shows generator and gearbox, lower detail turbine, recuperator and condenser.

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Advantages of ORC technology

- Suitable technology in achieving green house gas emission reductions:
  - CO_2 emission reductions
  - CH_4 emission reductions in biomass/biogas applications
- Improves the energy efficiency of industrial processes where suitable heat source is available
- Allows the use of low-power and low-temperature applications (compared to e.g. steam Rankine)
- Suitable in small-scale distributed CHP-production

Advantages of ORC technology

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- Allows the use of totally hermetic processes
- Relatively maintenance free technology
- ORC turbogeneratos, having rotational speeds typically over 20 000 rpm, can be designed to be relatively small sized
- The specific enthalpy drop of organic vapours in turbine is small when compared to water vapour. This makes turbine design easy. In most cases a single stage turbine with reasonable tip speed is sufficient.
- It is easy to make even a very small ORC (e.g. 25 kW) with a high efficiency single stage turbine, whereas water vapour process must be made in most cases with a three or four stage turbine, thus resulting in a practical minimum size of 2000–3000 kW.

Typical ORC applications

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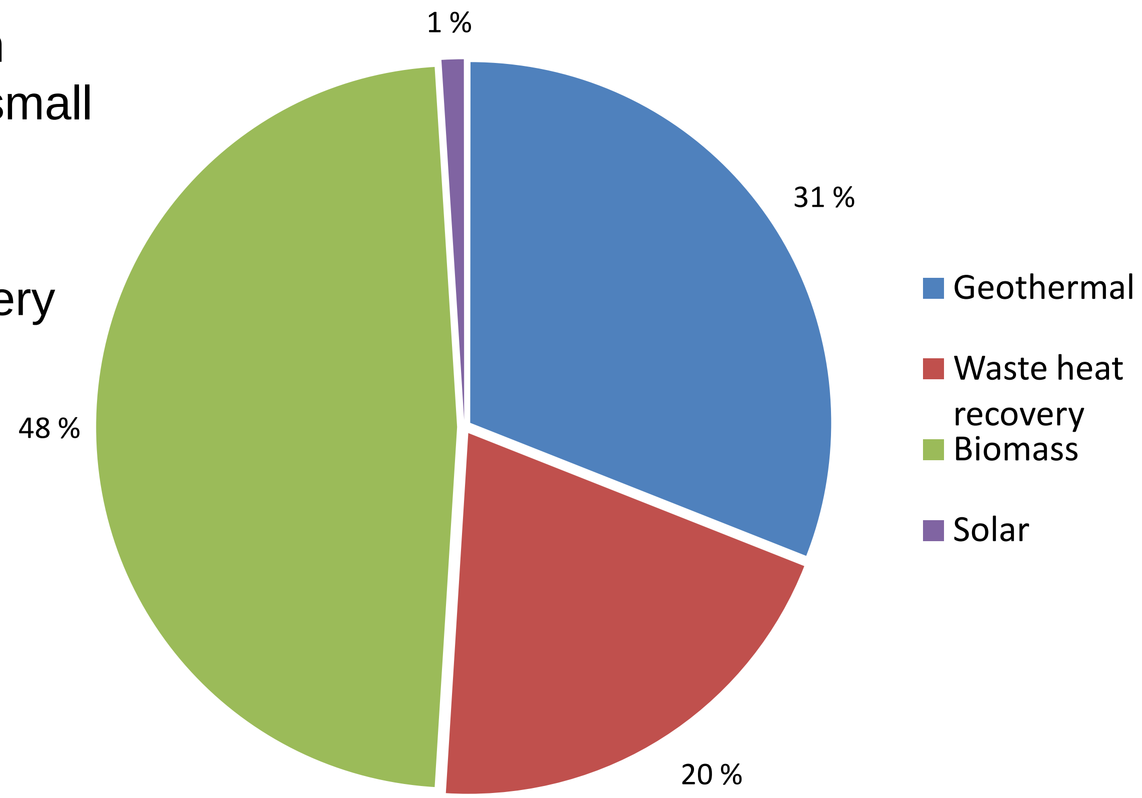
- Exhaust heat recovery from reciprocating engines and small gas turbines
- Industrial waste heat recovery
- Biomass applications
- Concentrated solar power
- Geothermal energy



•Reference: Quoilin S., Lemort V. "Technological and Economical Survey of Organic Rankine Cycle Systems" 5th European conference Economics and Management of Energy in Industry, Algarve Portugal, April 14 – 17, 2009

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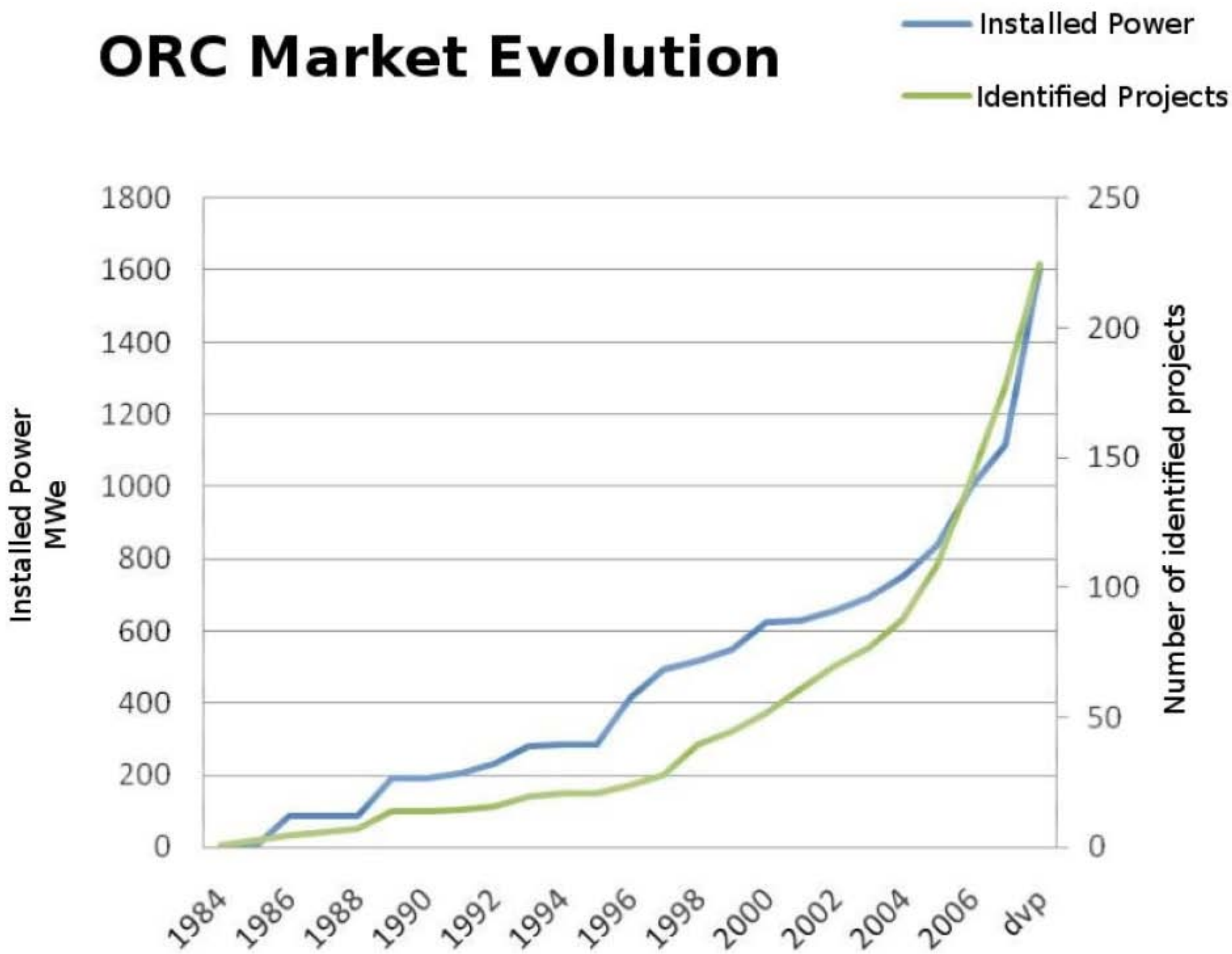
ORC Market Evolution



•Reference: Quoilin S., Lemort V. “Technological and Economical Survey of Organic Rankine Cycle Systems” 5th European conference Economics and Management of Energy in Industry, Algarve Portugal, April 14 – 17, 2009

Commercial technologies

- Turbine types
  - Axial and radial turbines rotating at synchronous speed
  - Radial turbine connected directly to high speed generator
  - Axial or radial turbines connected to generator trough gearbox
  - Screw expanders
- Direct vaporizer or thermal oil circuit. Thermal oil cycles used in mostly biomass applications.
- Feed pump types
  - Multistage pump with separated motor
  - High speed pump connected directly to high speed generator
- Turbogenerator bearings
  - Oil lubricated bearings
  - Process fluid lubricated bearings
  - Active magnetic bearings

Some ORC manufacturers

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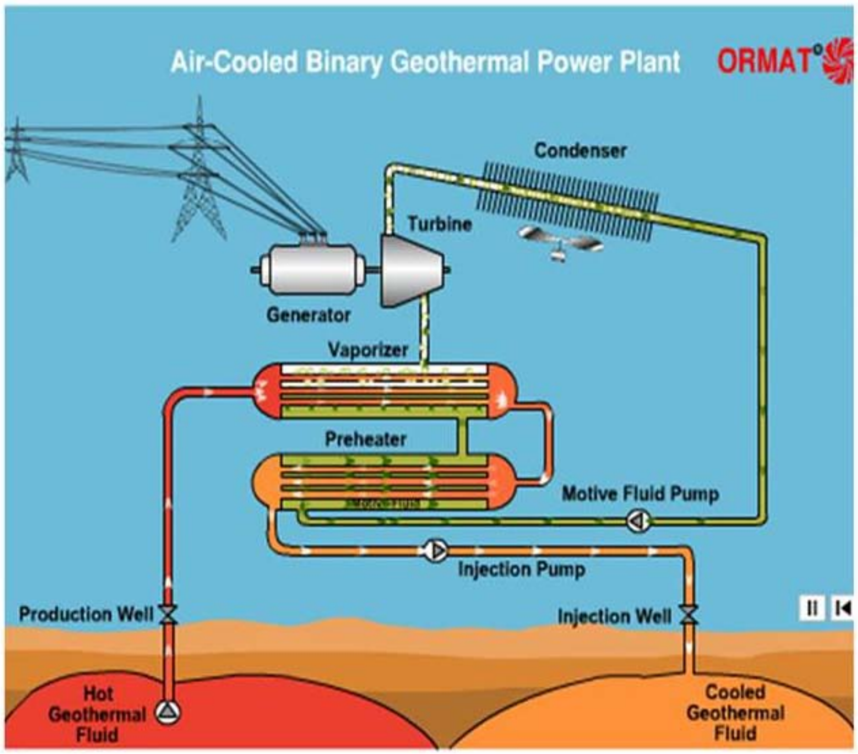
- Turboden: Biomass CHP applications and industrial waste heat recovery, 400 kW – 2 MW, www.turboden.eu
- ORMAT: Geothermal and solar power applications , 250 kW – 20 MW, www.ormat.com
- Adoratec: Biomass CHP applications, 300-2400kWe, www.adoratec.com
- Calnetix (GE energy): Waste heat, 125 kW, www.geheatrecovery.com
- Tri-O-Gen: Exhaust gas and biogas flare applications, 160 kW, www.triogen.nl/en/
- GMK: Biomass and industrial applications,

  0,5 - 2 MW electric power, 3 -8 MW heat power, www.gmk.info
- Electratherm: 50 kW, www.electratherm.com
- Infinity turbine: 10 – 50 kW www.infinityturbine.com
- Freepower: Exhaust gas and biogas flare applications ~ 130 kW, www.freepower.co.uk

•Source: Manufacturer websites

Present day ORC in geothermal application. Some plants built by Ormat



Principle of ORC using geothermal heat as heat source, and two example plants in Iceland (left) and in Costa Rica (right)

(Larjola J. "Organic Rankine cycle (ORC) based waste heat / waste fuel recovery systems for small CHP applications". Chapter 9 in: Small- and micro-combined heat and power (CHP) systems, Advanced design, performance, materials and applications. Woodhead Publishing Limited, Oxford 2011)

Present day ORC with thermo-oil circuit: typical plant of Turboden

Schematic of Turboden power conversion module and one power conversion module in the factory ready for delivery.

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Present day ORC: direct vaporizer and high speed technology by Tri-O-Gen

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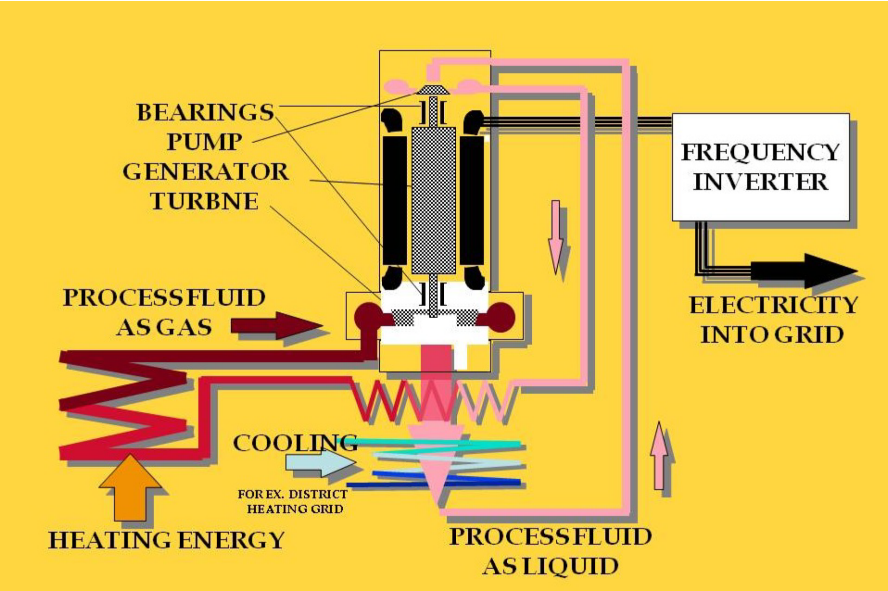

Process diagram of the Tri-O-Gen ORC-plant based on high speed technology and corresponding power conversion module of Tri-O-Gen. Heat source gas is introduced directly to the process fluid vaporizer (grey in the middle).

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Future scenarios

- Many new manufacturers have started during last decade, still only few major companies
- Interest towards small-scale ORC systems have increased during recent years. Nowadays most of the commercial plants are in size of several hundred kW. ORC may replace Strirling and gas engines in power range of 10 – 200 kW
- More suitable and environmental friendly working fluids
- High electricity and fuel prices makes ORC technology a feasible choice in many applications
- Supercritical ORC cycles may be introduced in order to increase efficiency
- Due to increased manufacturing volume the specific prize of ORC is expected to decrease significantly during the near future. This will increase number of applications, and also enable smaller size ORC-systems.