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Dynamic analysis of off-grid ORC plants with various solutions for the thermal storage

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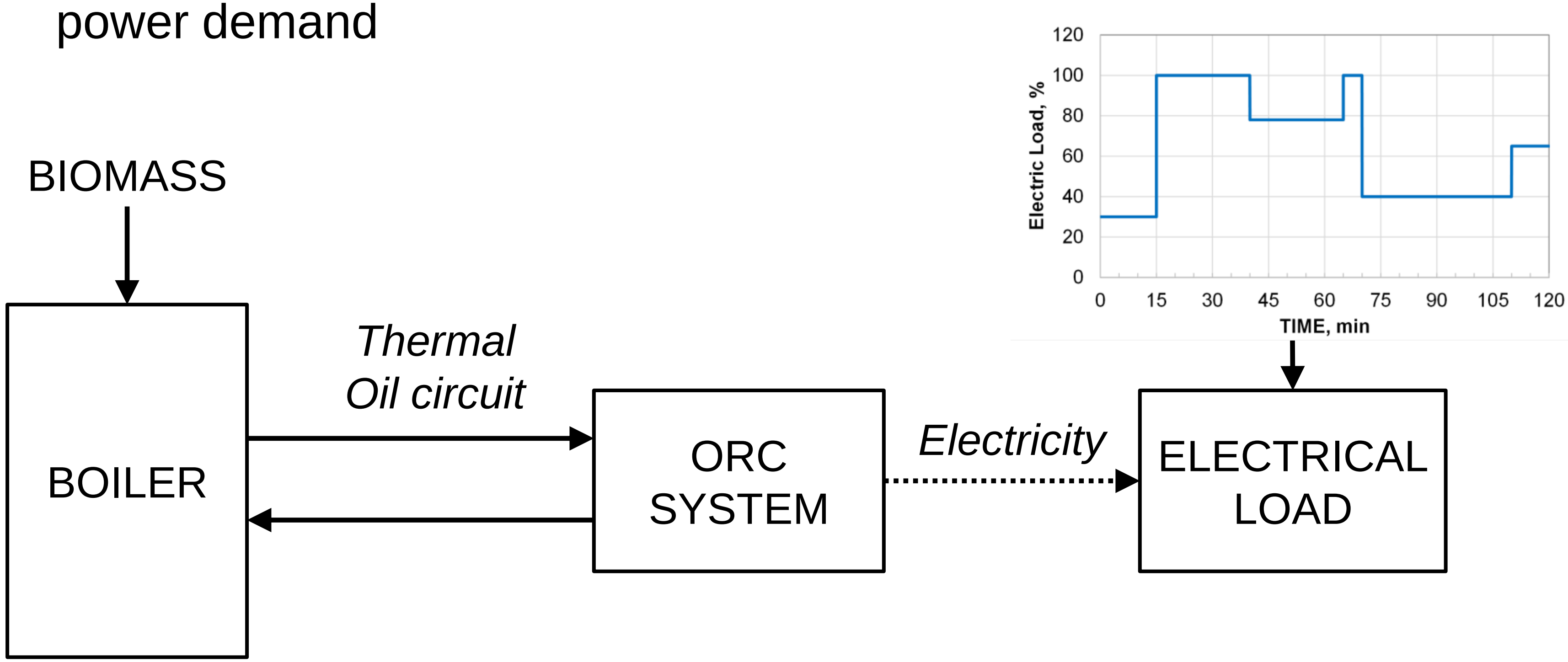
Outline

- Introduction
- ORC system description
- Model definition
- Case study w/o thermal storage
- Case study w/ thermal storage
- Conclusions

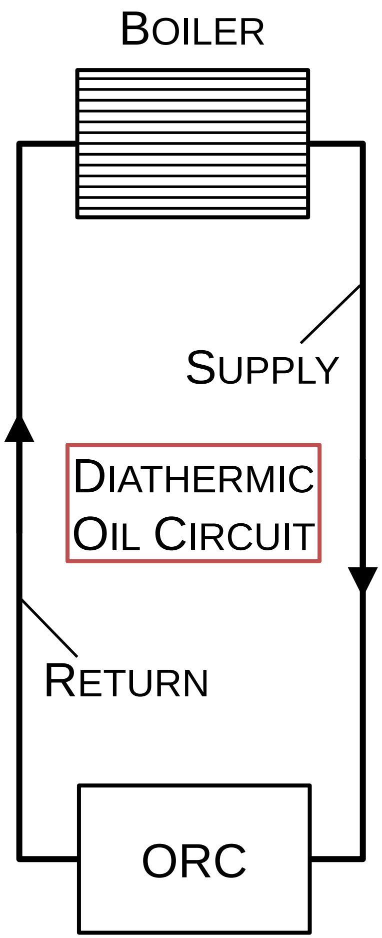
Introduction

Off-grid application of biomass boiler & ORC system

- ▲ Good performance at partial load
- ▲ Low Operation&Maintenance requirements
- ▲ High flexibility
- ▶ Use of thermal storage solutions for real time coupling with electric power demand



ORC system description

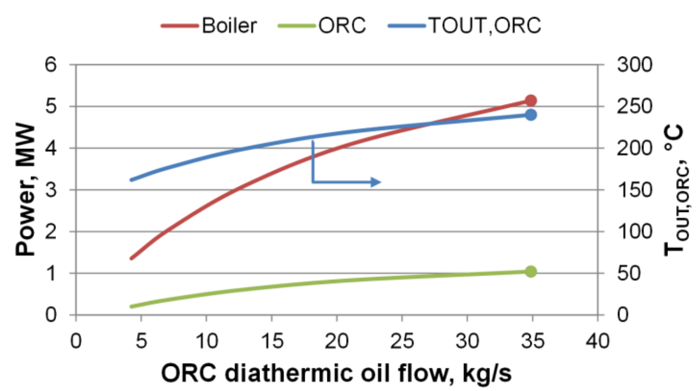


Nominal operating conditions

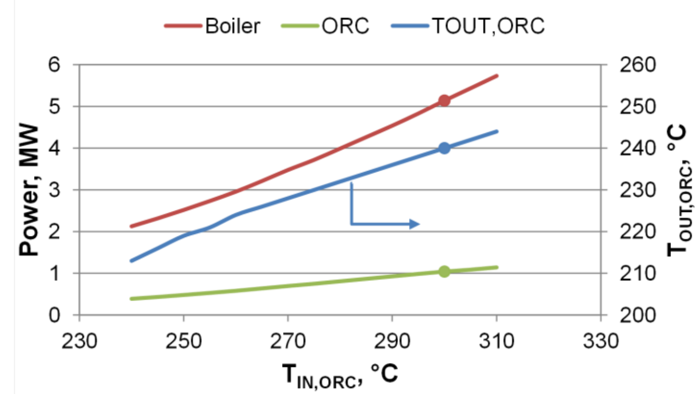
Parameters	units	values
Boiler thermal power	kW	5141
ORC electrical power	kW	1043
ORC efficiency	%	20.2
$T_{OUT,ORC}=T_{IN,Boiler}$	°C	240
$T_{OUT,Boiler}=T_{IN,ORC}$	°C	300

Partial load performance

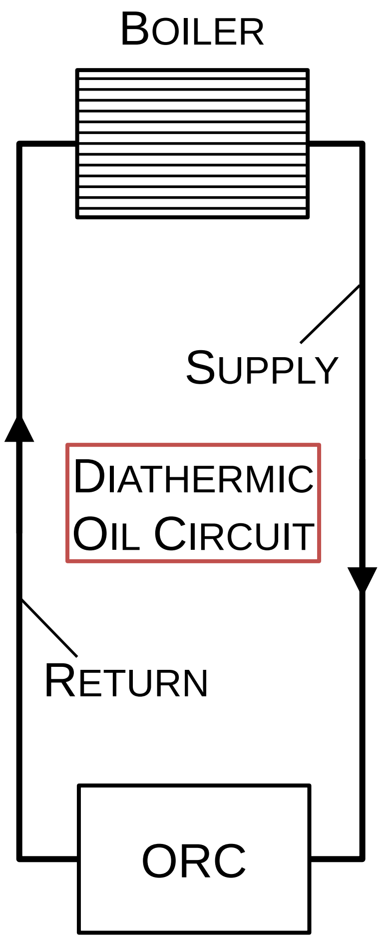
@ $T_{IN,ORC}$ = 300°C



@ $\dot{m}_{oil}$ = 34.8 kg/s



ORC system description



Boiler

Parameters	units	values
Piping ID/th	mm	80 / 7
Oil mass	kg	1000
ρ_{oil}	kg/m^3	840
Equivalent length	m	240
Overall oil mass flow	kg/s	38.4
Oil velocity	m/s	8.2

One-dimensional finite difference methods for solving differential equations with spatial resolution of 0.5 m (480 nodes)

$$\rho_{oil} c_{p,oil} \frac{\partial T_{oil}(x)}{\partial t} = -u_{oil}\rho_{oil}c_{p,oil}\frac{\partial T_{oil}(x)}{\partial x} + \frac{4U}{D_{int}}\left[T_{steel}(x) - T_{oil}(x)\right]$$

$$\rho_{steel} c_{p,steel} \frac{\partial T_{steel}(x)}{\partial t} = k_{oil}\frac{\partial^2 T_{oil}(x)}{\partial x^2} + \frac{U}{t}\left[T_{oil}(x) - T_{steel}(x)\right] + \frac{\dot{Q}}{\pi D_{int} t L}$$

Boundary conditions

$$T_{oil,x=0} = T_{in,Boiler}$$

$$\frac{\partial T_{steel,x=0}}{\partial x} = 0$$

$$\frac{\partial T_{steel,x=L}}{\partial x} = 0$$

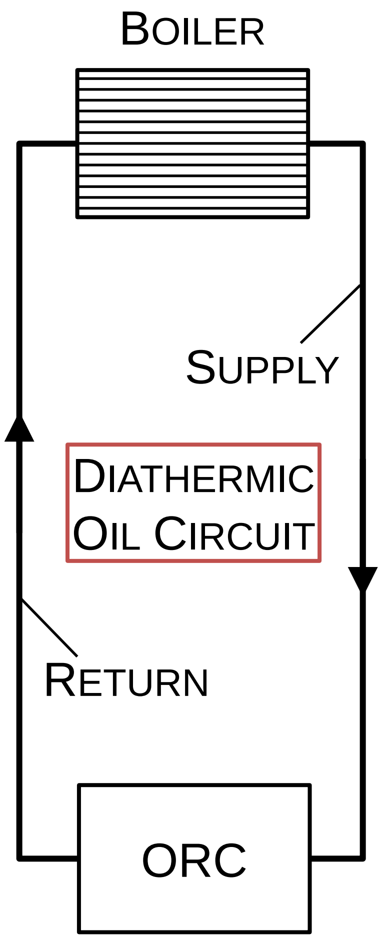
$$Nu = 0.023 Re^{0.8} Pr^{n}$$

Dittus-Boelter

Forced convection for turbolent flow

Uniform thermal power distribution generated by the biomass combustion

ORC system description



Supply & Return Piping

Parameters	units	values
Piping ID/th	mm	150 / 10
Oil mass	kg	1000
ρ_{oil}	kg/m³	840
Length	m	50
Oil velocity	m/s	2.3

One-dimensional finite difference methods for solving differential equations with spatial resolution of 0.5 m (100 nodes)

$$\rho_{oil} c_{p,oil} \frac{\partial T_{oil}(x)}{\partial t} = -u_{oil} \rho_{oil} c_{p,oil} \frac{\partial T_{oil}(x)}{\partial x} + \frac{4U}{D_{int}} \left[T_{steel}(x) - T_{oil}(x) \right]$$

$$\rho_{steel} c_{p,steel} \frac{\partial T_{steel}(x)}{\partial t} = k_{oil} \frac{\partial^2 T_{oil}(x)}{\partial x^2} + \frac{U}{t} \left[T_{oil}(x) - T_{steel}(x) \right] + \frac{\dot{Q}}{\pi D_{int} t L}$$

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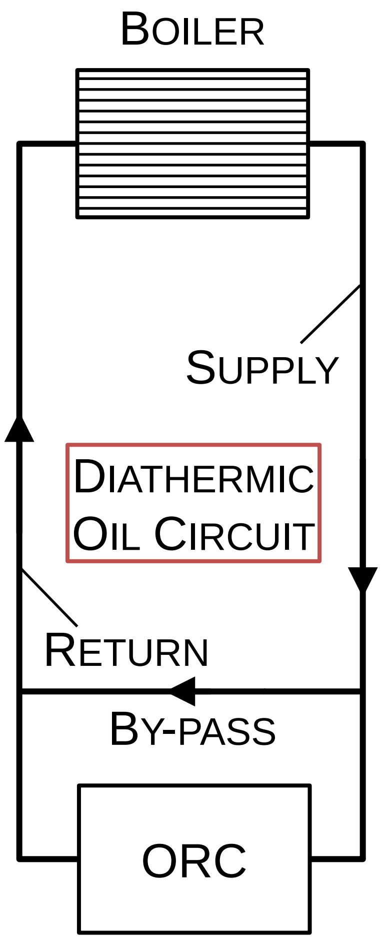
Dittus-Boelter

Forced convection for turbolent flow

No heat generation source

ORC system description

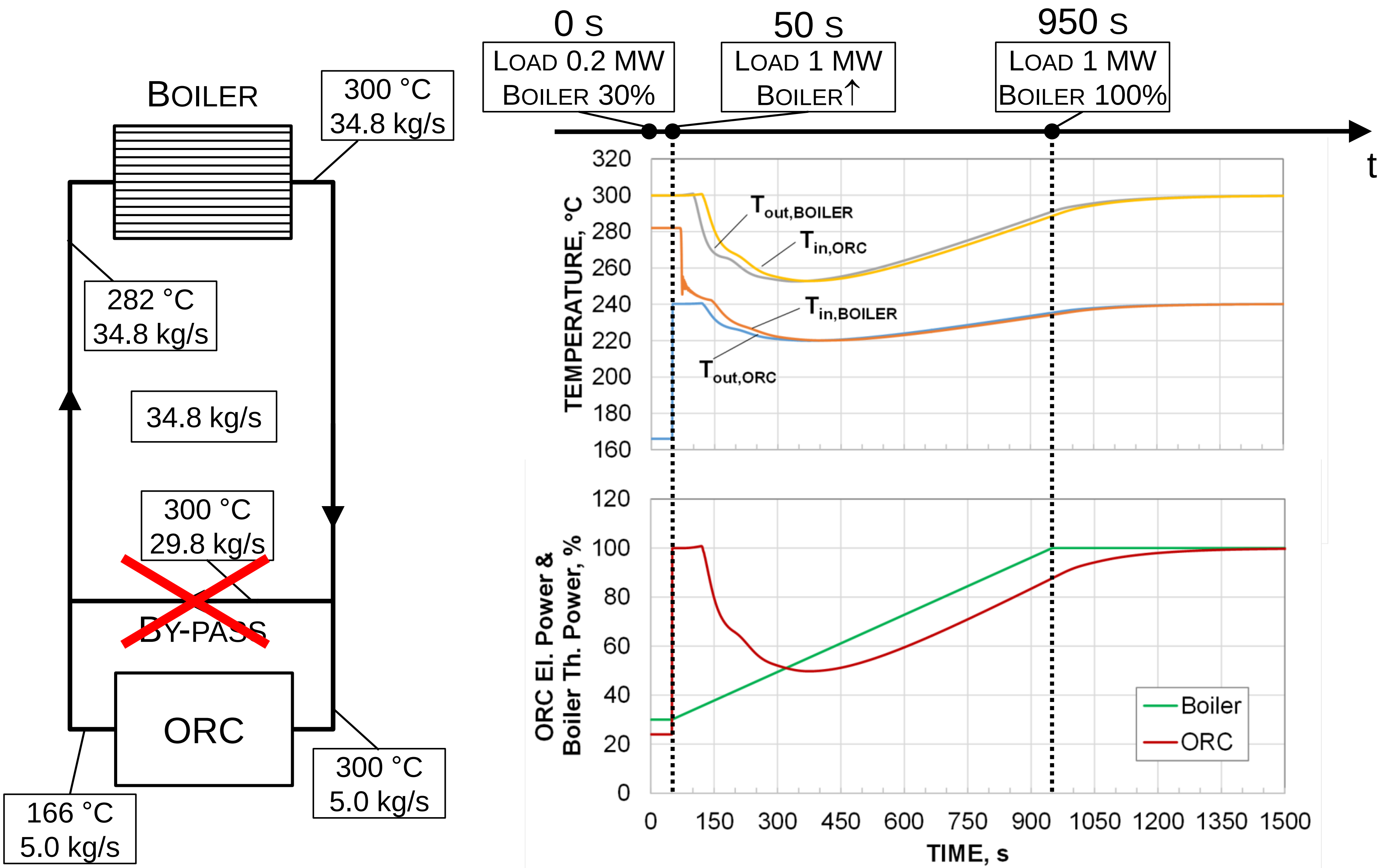


Case study

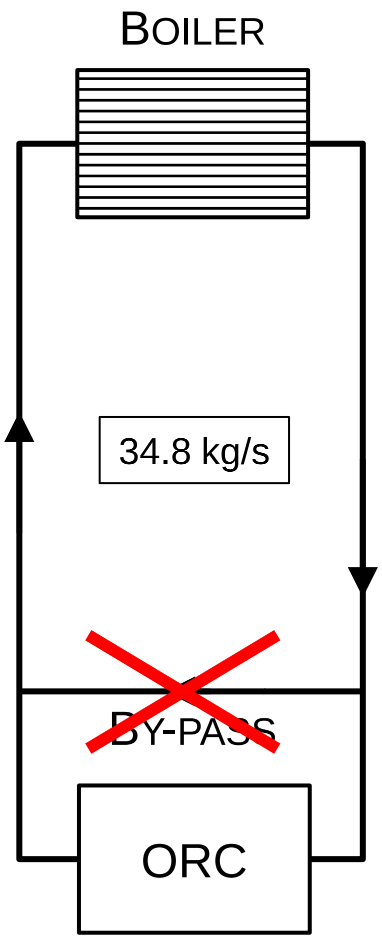
Time (s)	Interval (s)	Event	Control
t = 0	-	Electrical Load 0.2 MW	Boiler power 30% ORC power 24% ORC oil flow 5.0 kg/s
t = 50 Stepwise	900 (15 min)	Electrical Load ↑ 1 MW	ORC power 100% Boiler power ↑ ORC oil flow 34.8 kg/s
t = 950	1000	Nominal conditions	ORC power 100% Boiler power 100%

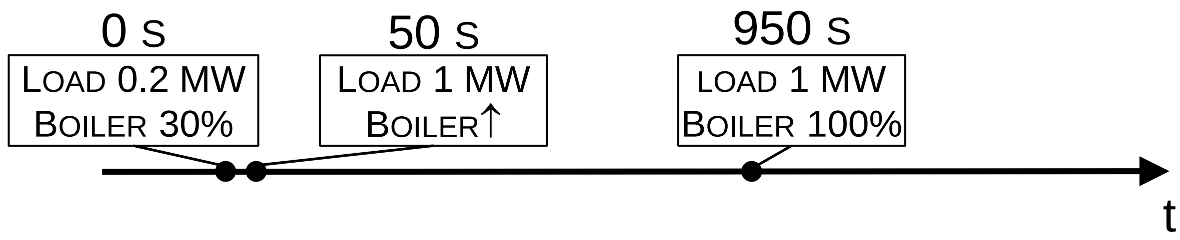
Hp: ORC response assumed instantaneous
Boiler ramp of 15 min from 30% to 100%

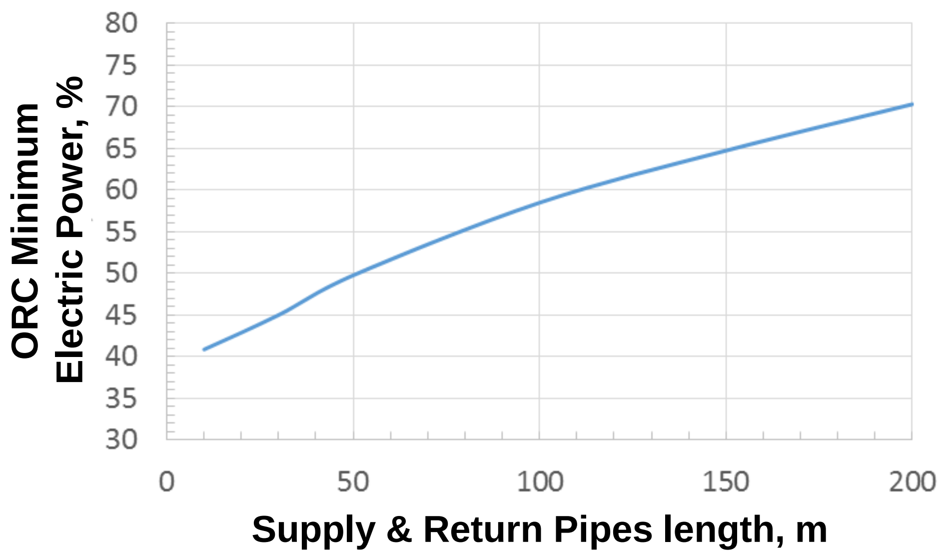
Case study without thermal storage



Case study without thermal storage



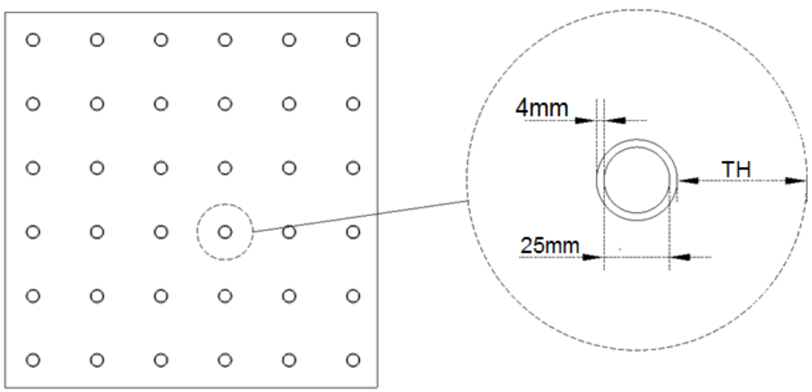




- ▼ ORC min power < 100% even with longer pipes
- ▲ Solution: Introduction of thermal storage

Thermal energy storage (TES)

- Solid sensible heat storage for limiting ORC electric power undershoot
- One block of storage material crossed by carbon steel pipes
- Optimization of parameter TH (thickness) as distance between pipes
  - ⇨ Storage design and weight defined by **TH** and storage **material**



Parameters	units	values
N pipes	-	36
Pipes length	m	50
Oil velocity	m/s	2.3
TH	mm	0 ÷ 50

- Two dimensional finite difference method with cylindrical coordinates monitoring temperature distribution on both radial and axial direction

$$\rho_{storage} c_{p,storage} \frac{\partial T_{storage}(x,r)}{\partial t} = k_{storage} \frac{\partial^2 T_{storage}(x,r)}{\partial x^2} + k_{storage} \left(\frac{1}{r} \frac{\partial T_{storage}(x,r)}{\partial r} + \frac{\partial^2 T_{storage}(x,r)}{\partial r^2} \right)$$

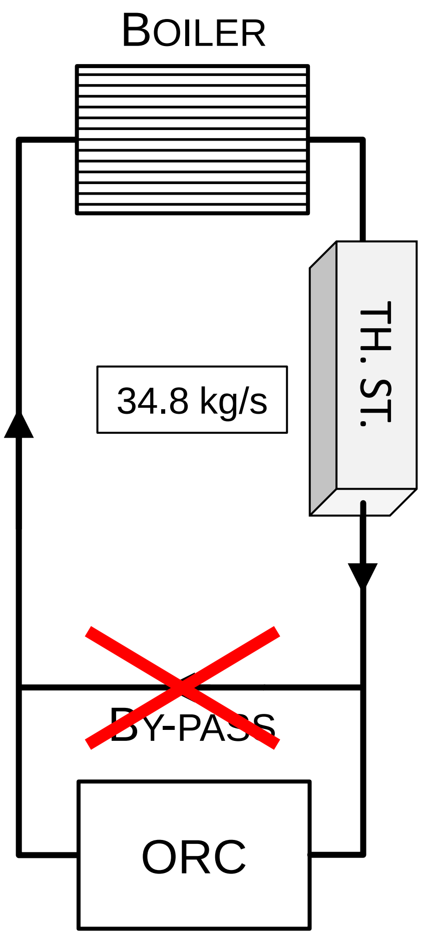
6 CASES
- Storage material
- Max T diathermic oil
- Storage position

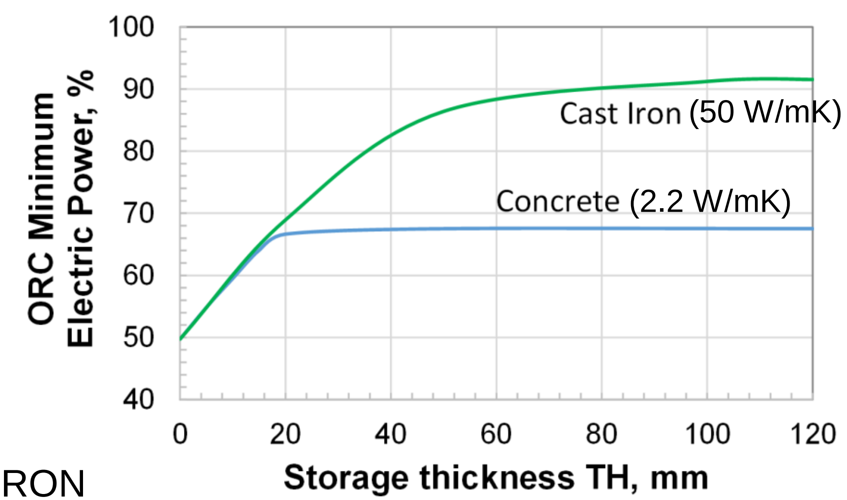
⇨

(a) Concrete / 300 °C / after boiler
(b) Cast iron / 300 °C / after boiler
(c) Concrete / 370 °C / after boiler
(d) Cast iron / 370 °C / after boiler
(e) Concrete / 370 °C / before boiler
(f) Cast iron / 370 °C / before boiler

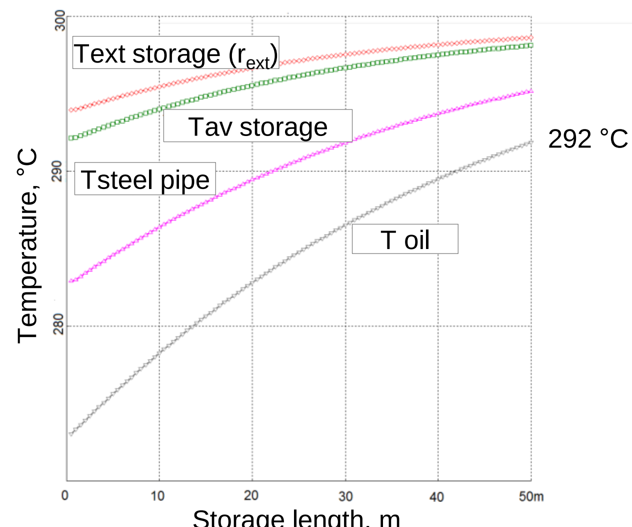
Results with thermal storage

Cases (*a,b*): T=300°C / after boiler

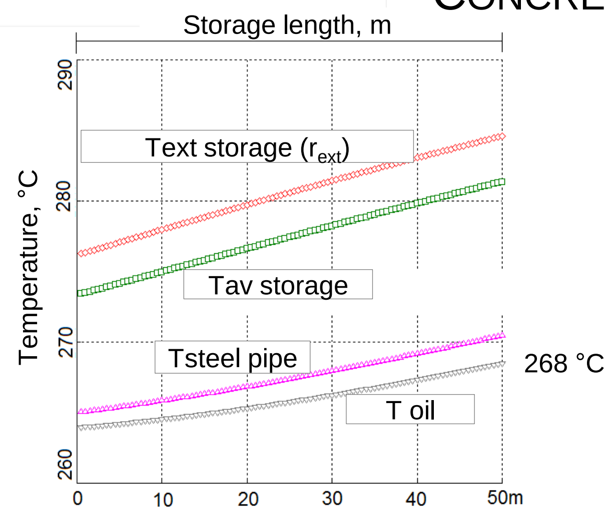




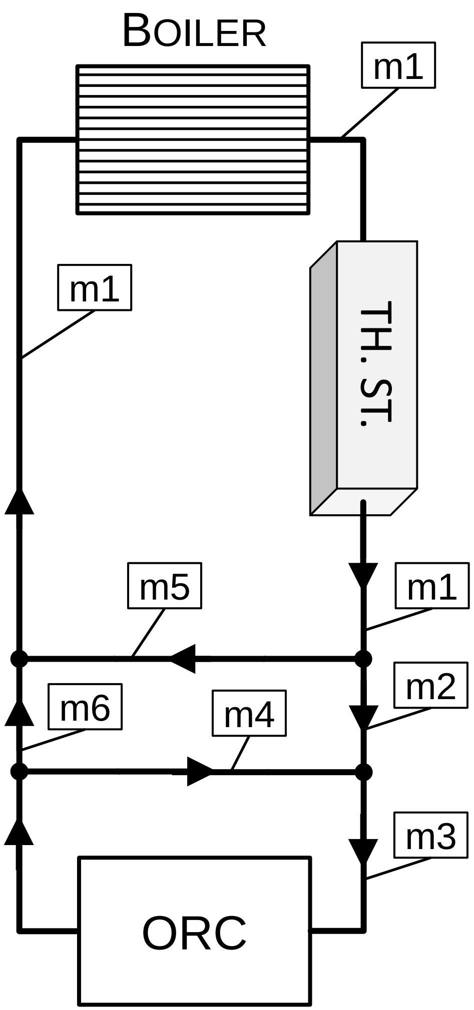
CAST IRON



CONCRETE



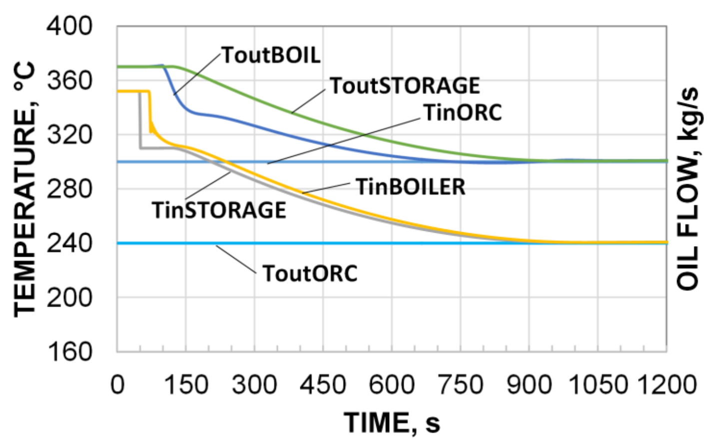
Results with thermal storage

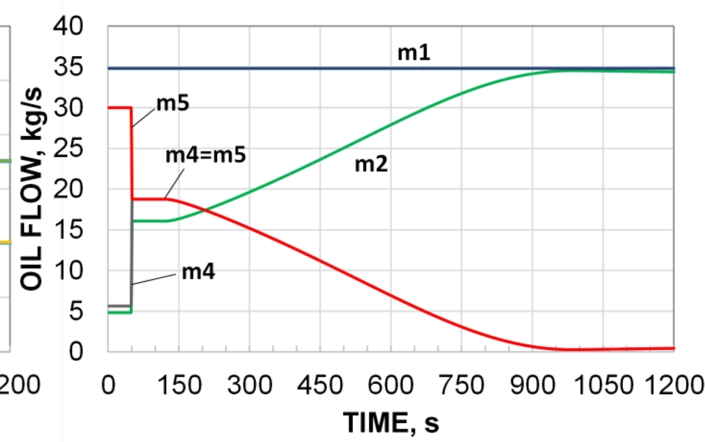


Cases (*c,d*): T=370°C / after boiler

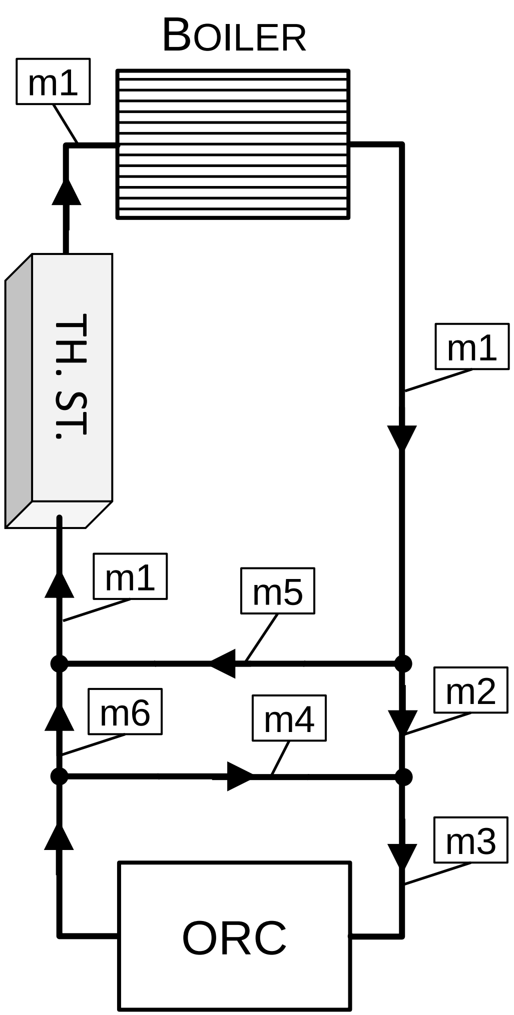
Time (s)	Control
t = 0	m1 = 34.8 kg/s m3 = 5.0 kg/s (ORC 24%)
t = 50 Stepwise	m1 = m3 = 34.8 kg/s ORC 100%

Example Concrete TH=12mm





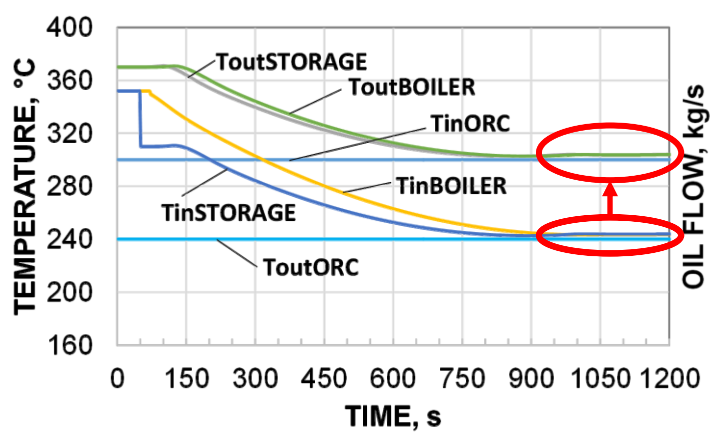
Results with thermal storage

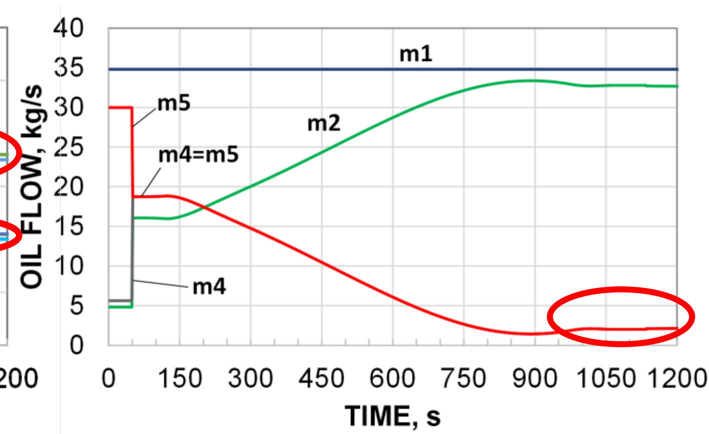


Cases (*e,f*): T=370°C / before boiler

Time (s)	Control
t = 0	m1 = 34.8 kg/s m3 = 5.0 kg/s (ORC 24%)
t = 50 Stepwise	m1 = m3 = 34.8 kg/s ORC 100%

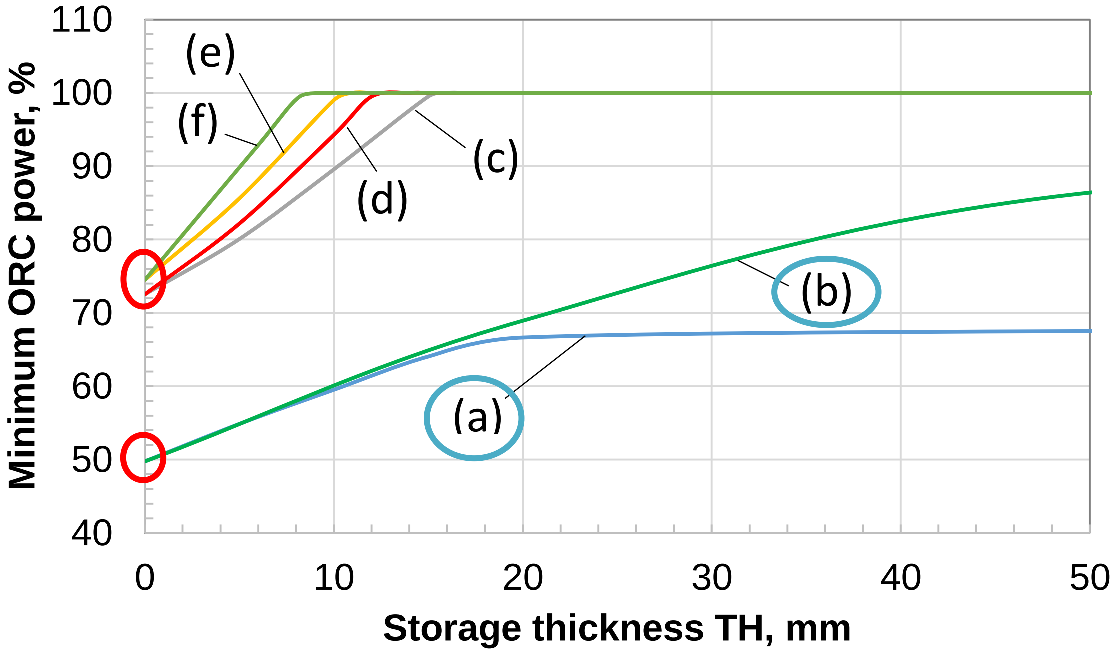
Example Cast Iron TH=8mm





Results with thermal storage

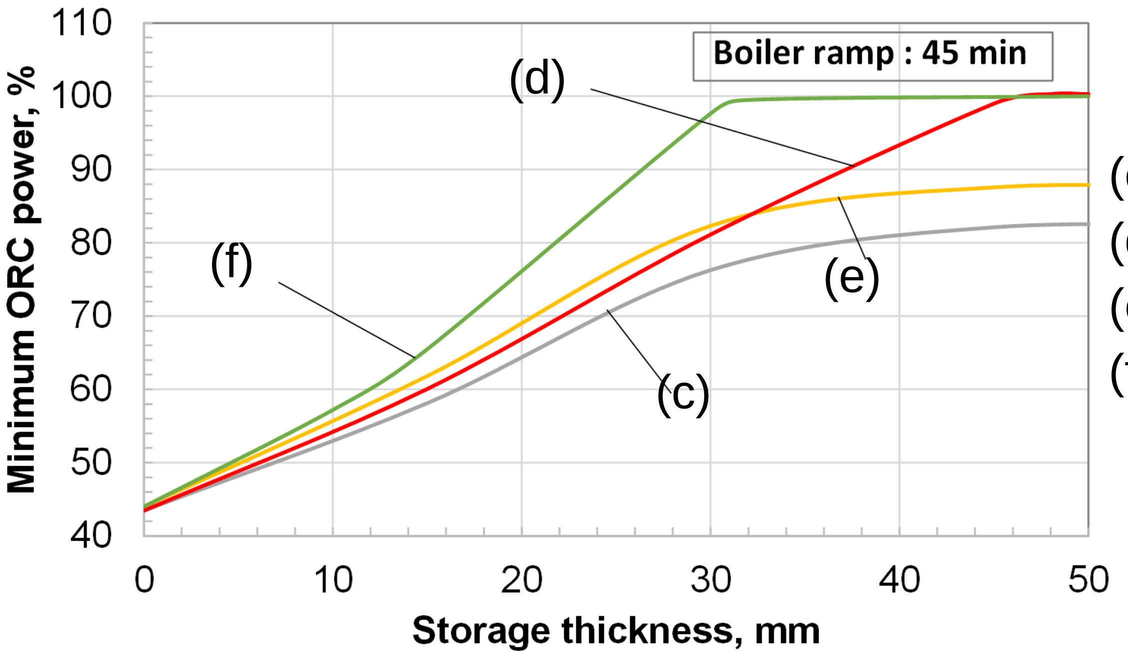
- Cases with max T 370°C allows ORC to operate at 100% with TH > 15 mm
  - Cast Iron (*d,f*) has better performance than concrete due to its higher thermal conductivity (50 vs 2.2 W/mK)
  - Cast Iron density penalizes storage weight 19 tons (*f*) VS 11 tons (*e*)
- Storage before boiler implies potentially higher heat flux to oil due to lower temperatures



(a) Concrete / 300 °C / after boiler
(b) Cast iron / 300 °C / after boiler
(c) Concrete / 370 °C / after boiler
(d) Cast iron / 370 °C / after boiler
(e) Concrete / 370 °C / before boiler
(f) Cast iron / 370 °C / before boiler

Results with thermal storage

- ▲ Higher performance of cast iron highlighted with boiler ramp of 45 min
  - ❖ Use of concrete (*c*,*e*) penalizes ORC power production



(c) Concrete / 370 °C / after boiler
(d) Cast iron / 370 °C / after boiler
(e) Concrete / 370 °C / before boiler
(f) Cast iron / 370 °C / before boiler

Conclusions

- A **dynamic model** of an **off-grid** system based on **1 MWel** Turboden **biomass ORC plant** was developed in Aspen Custom Modeler
- **Thermal storage solutions** composed by a **bunch of pipes** employing either concrete or cast iron as coating materials were considered
- System **without storage** shows a **poor capacity** to comply with load variations (**Min power ~50%, Transient of 1200 s**)
- Adoption of a diathermic oil storage with maximum temperature of 370°C can maintain ORC system at the required electrical power
- Despite greater weight (**19 vs 11 tons**), **cast iron** has better performance than concrete due to **higher thermal conductivity** (**50 vs. 2.2 W/mK**)
- Techno/economic optimization of storage temperature and design will be investigated in the future

Thank you for your attention!

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