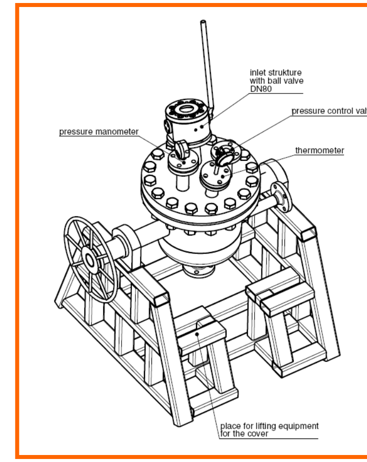
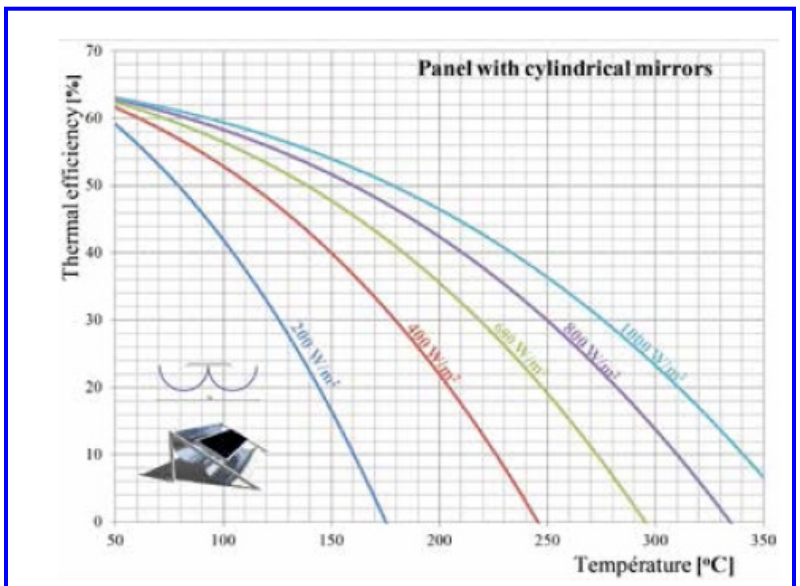
אוניברסיטת בן-גוריון בנגב
Ben-Gurion University of the Negev

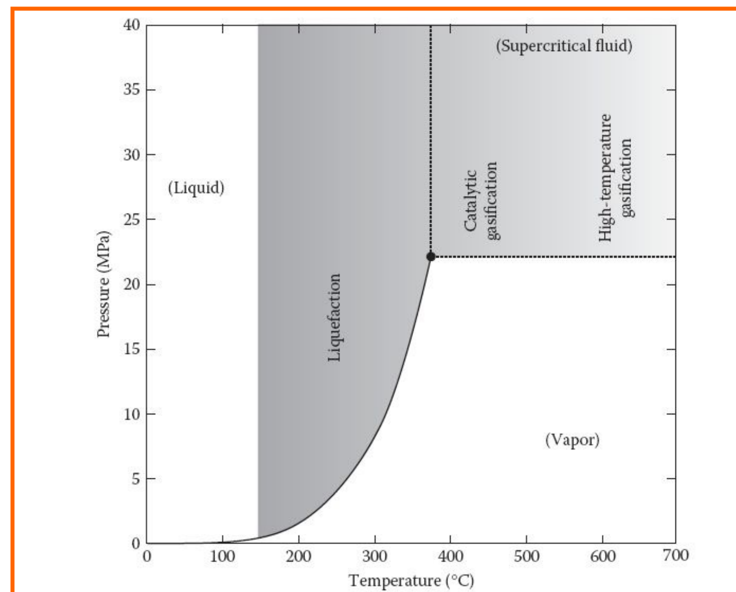
The BGU / CERN Solar Hydrothermal Reactor



Bertolucci, Bressan, Caspers -- CERN
Garb, Gross -- BGU
Pauletta – SRB Energy

EUROSUN 2014, session 4.2 (Solar Heat for Industrial and Commercial Applications)





Corresponding author: Yaakov Garb, The Swiss Institute for Dryland Environmental and Energy Research, Ben Gurion University of the Negev, Israel. ygarb@bgu.ac.il

Structure of presentation

- Brief history of BGU/CERN collaboration
- Novelty & promise of the niche / device
- Components of solar hydrothermal device
  – Hydrothermal processes
  – Hydrothermal conversion of biomass and biowaste
  – SRB high temperature/efficiency panels
- Joint system: broad description & status
- Questions…..?

BGU / CERN collaboration

- History of technology transfer initiatives and analysis
  - CERN: technology transfer (inc. for developing country contexts)
  - BGU: analysis of environmental technology translation processes
- Dec. 2013, exploratory CERN visit to BGU
- Initial joint technology development/translation project
  - BGU: laboratory for waste and biomass conversion, inc. hydrothermal
  - CERN: vacuum technologies from particle accelerators: SRB high temperature, high efficiency solar panels
  - → **The BGU / CERN hydrothermal reactor**
- Early 2014: Visits to define system, assembly of hardware
- Q3/Q4 of 2014 onwards: assembly, characterization, field testing

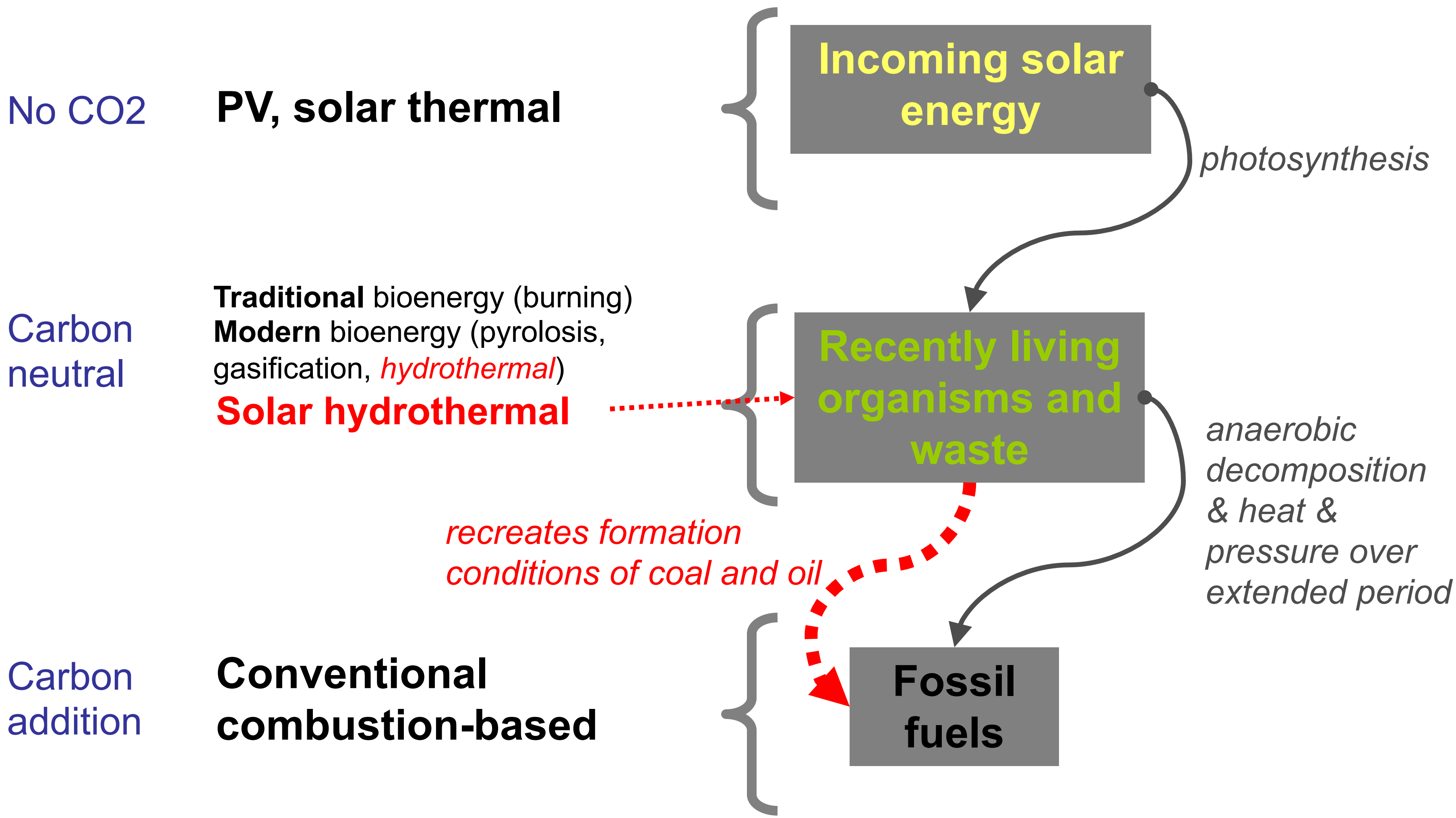
The basic idea

- High vacuum SRB solar panels produce high efficiency high temperature process heat in most climatic contexts
- Use this to power a small hydrothermal reactor
  - At hydrothermal conditions (high temperature and pressure), water becomes very reactive and a good solvent, allowing a range of transformations of organic materials
  - High temperatures also sterilize and neutralize many toxic organic compounds
- **Thus**: a hydrothermal reactor can convert biomass (including waste materials) into useful solid and liquid fuels, as well as nutrients
- A **moveable solar-powered reactor** makes it viable to process feedstocks that would be wasted or a nuisance
- In short: our reactor allows a powerful hydrothermal water solvent/reactant to rapidly process moist biomass *in situ* using only sunlight

Several layers of novelty & promise

- SRB reactors: high temperature/efficiency, no focusing
- Hydrothermal (HT) reactor
  - Wet biomass requires energy to dry, smelly, pathogens, heavy
  - HT allows organic reactions to directly convert wet biomass into sterile useable (solid, liquid) fuels, nutrients, products
  - 100% carbon efficiency
- A solar hydrothermal combination allows operation using only sun and available feedstock
- Moveable solar hydrothermal reactor allows off grid operation: bring reactor to feedstock not feedstock to reactor
- Important new use scenarios made available through:
  - Freely available inputs
  - Off-grid operation suited to rural contexts
  - Versatile range of feedstocks and products from single device

Using solar energy to convert biomass to fossil fuel analogs



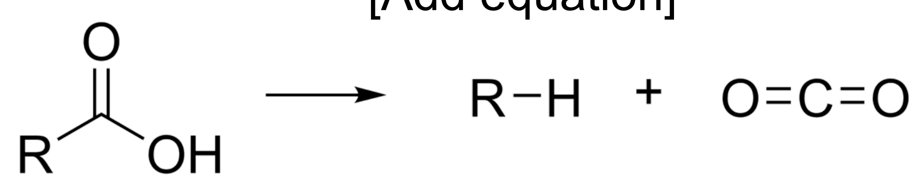
Hydrothermal processes

- Conversion of biomass into high carbon products (eg.coal) is through reduction of hydrogen and carbon contents
  - release of H2O and CO2 from molecular structure.
- Dry pyrolysis: high temp in absence of oxygen—charcoal
- Wet pyrolysis (=hydrothermal carbonization): high temp and pressure in presence of water--hydrochar

[Add equation]

Dehydradtion

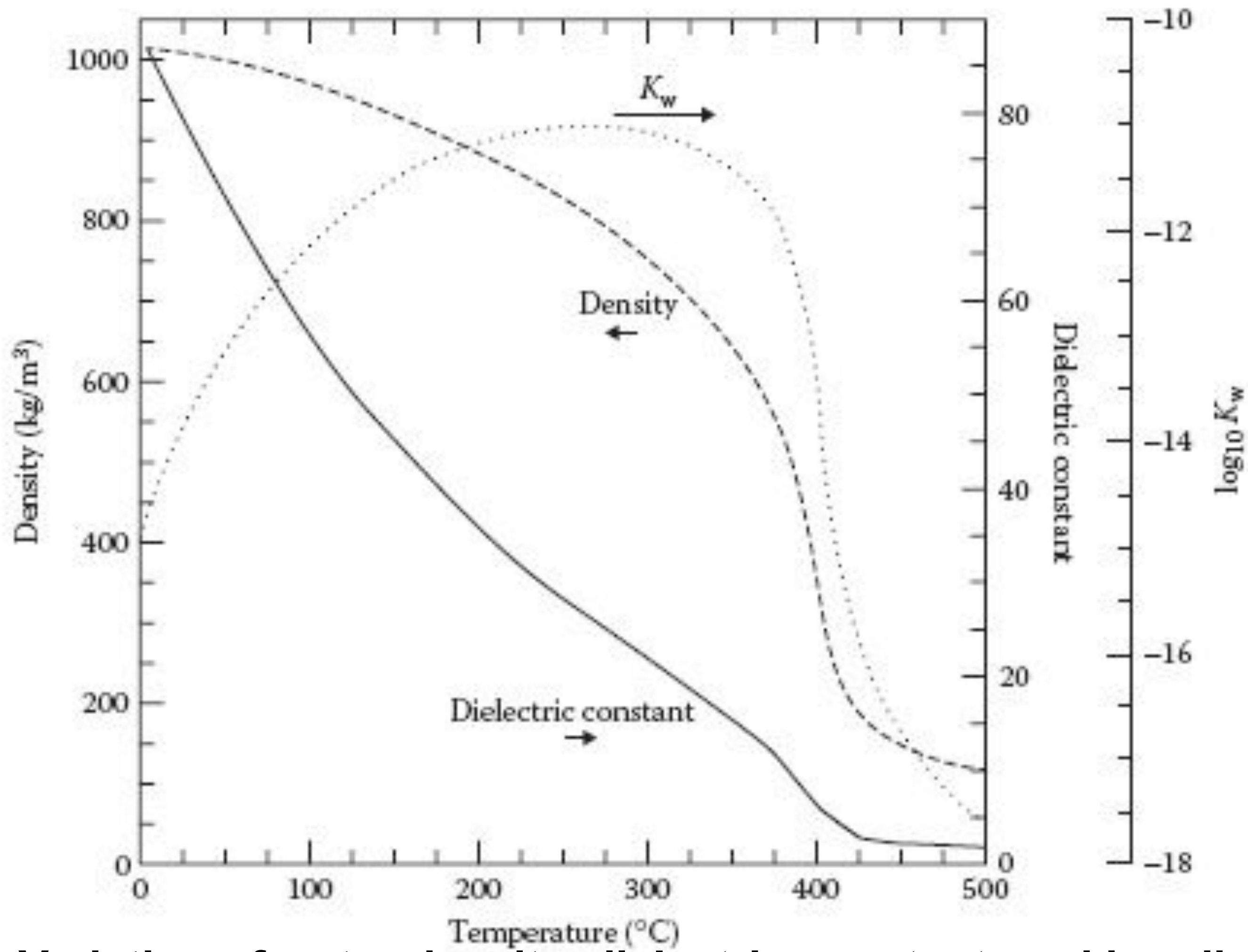
Decarboxylation



Properties of hydrothermal water

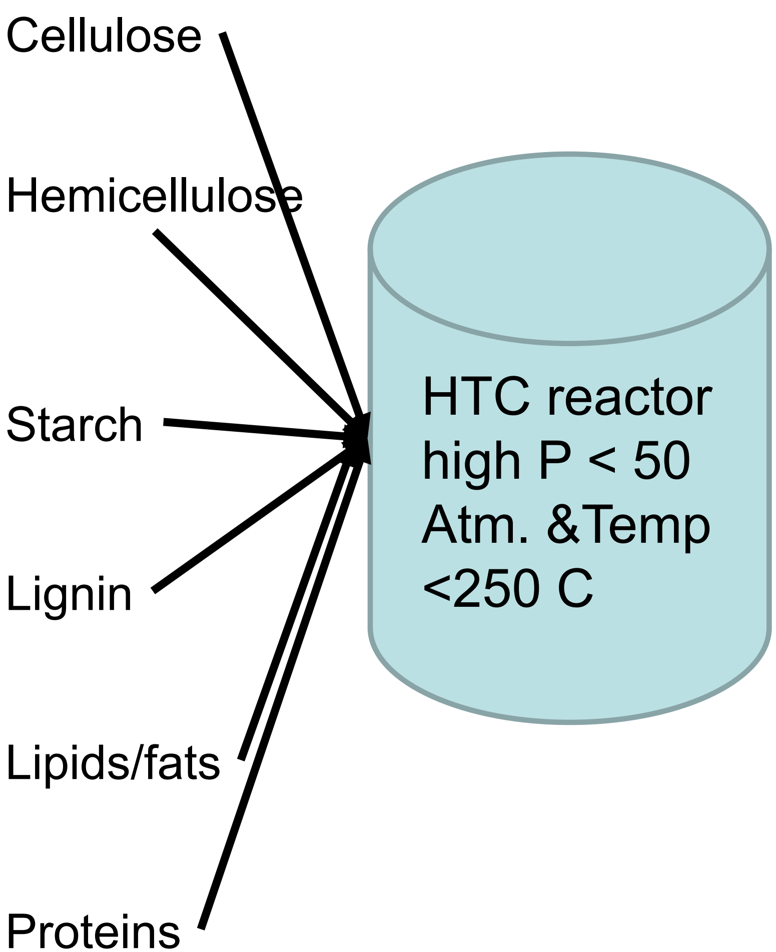
Polarity↓ : higher solubility of organics

K_w↑ more acid-base reactions: higher degradability



Variation of water density, dialectric constant, and ion dissociation constant as function of temperature at 30 MPa

Variety of organic reactions as a function of feedstock, temperature, pressure



Hydrolysis and dehydration – breaking down of organic molecules

$$4(C_6H_{10}O_5)_n \rightleftarrows 2(C_{12}H_{10}O_5)_n + 10H_2O$$

Decarboxylation - removes a carboxyl group ($COOH^-$) and

$$C_6H_{12}O_5 \rightarrow C_{5.25}H_4O_{0.5} + 0.75CO_2 + 3H_2O$$

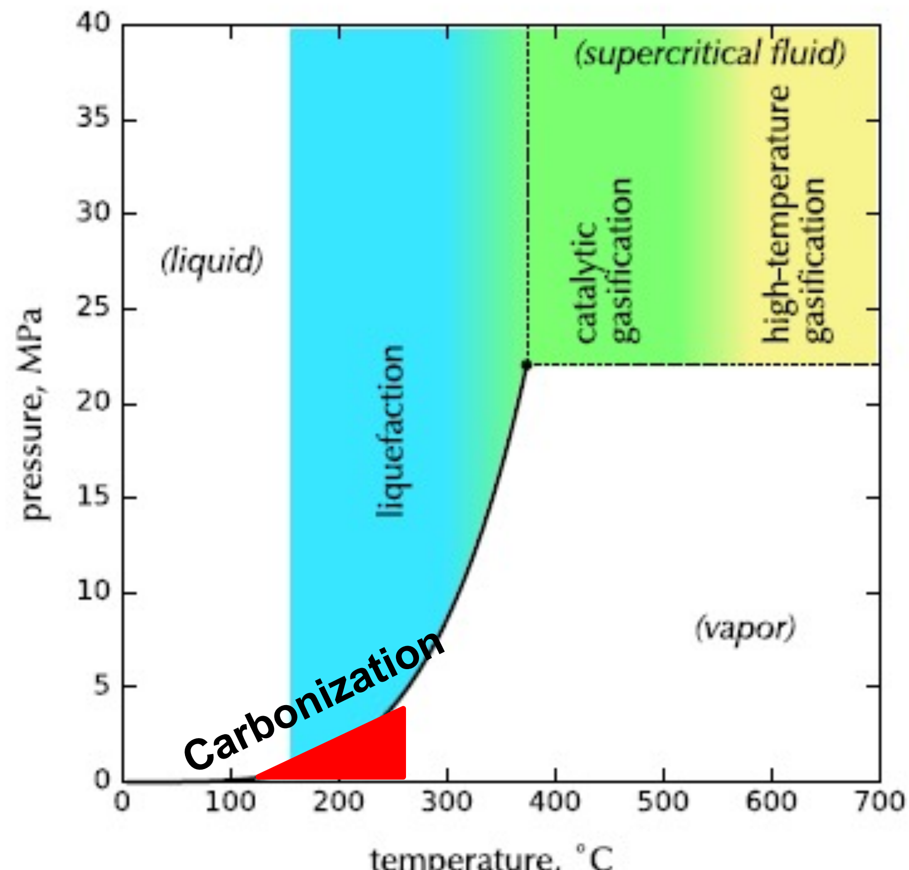
Condensation – Polymerization - Aromatization – OM degraded to monomers which polymerized and aromatized to form the hydro-coal (char)- rate is mainly controlled by temperature, pH and residence time

Zones of hydrothermal biomass processing

- Hydrothermal carbonization (HTC) (180-280 ° C) → hydro-coal (solid fuels).
- Hydrothermal liquefaction (HTL) (280-374 ° C)→ crude oil (liquid fuels).
- Hydrothermal gasification (HTG) often referred to as supercritical water gasification (SCWG) (374-700 ° C) → CH_4

*All reaction times between 1 and 4 h

Peterson et al., 2008



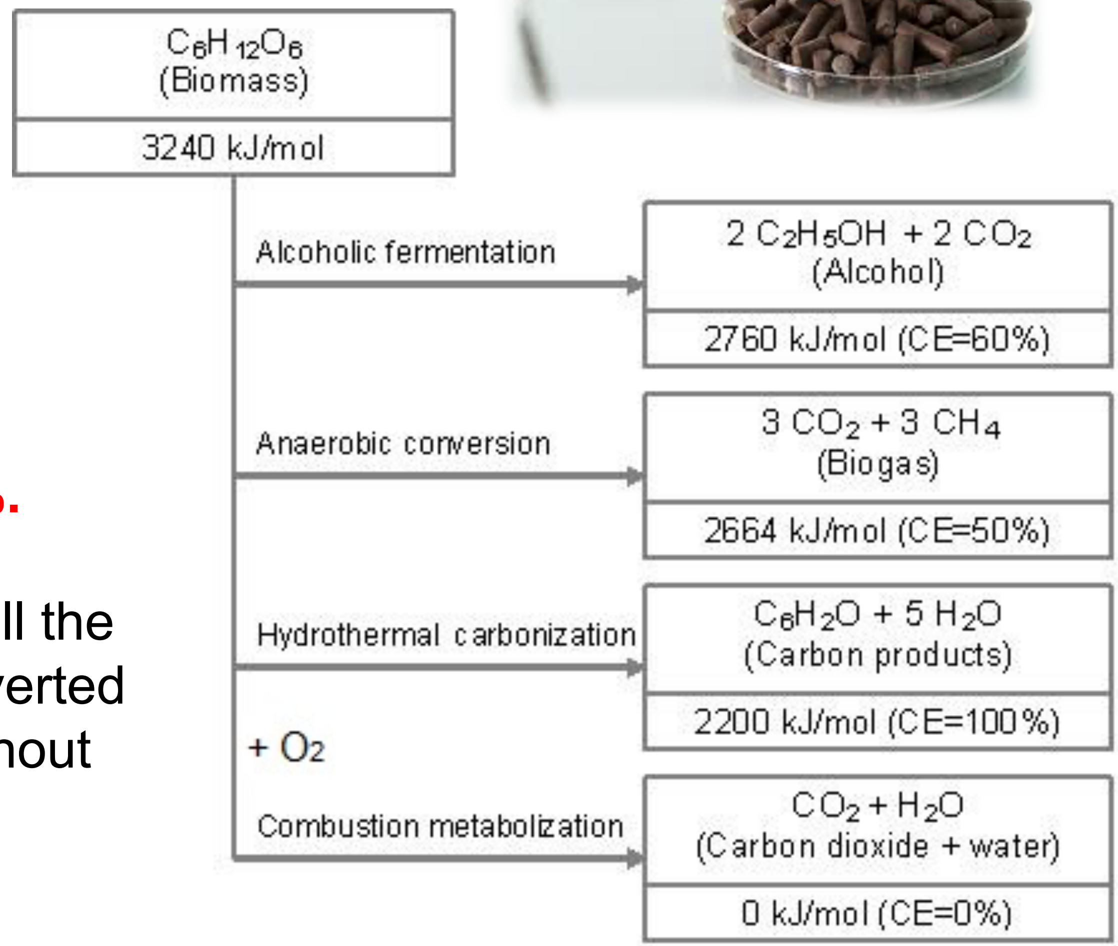
hydrothermal processing regions referenced to pressure–temperature phase diagram of water

Hydrothermal carbonization

When carbohydrates are converted into alcohol →two of six carbon atoms are released as CO_2 → **Carbon efficiency (CE)=60%.**

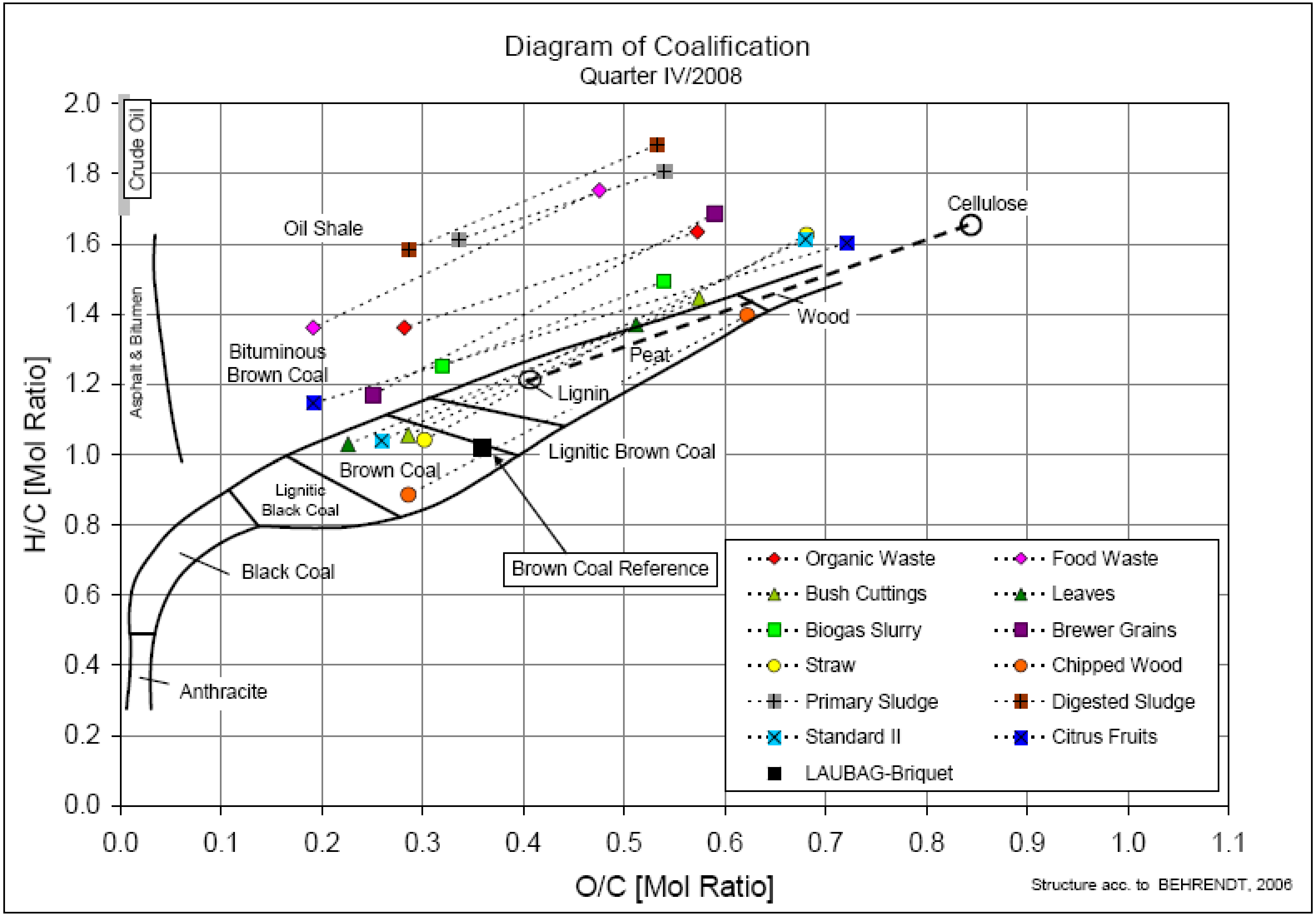
In the anaerobic conversion, about 50% of carbon is released as CO_2 → **CE=50%.**

In the HTC process almost all the carbon from biomass is converted into carbonized material, without generating CO and CO_2 →**CE=100%.**

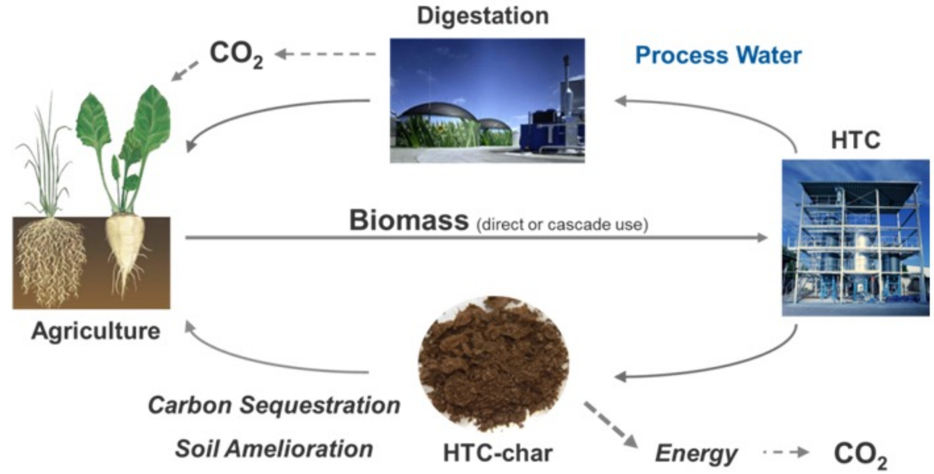


Titirici et al., 2007

Reduction of H/C and O/C ratios

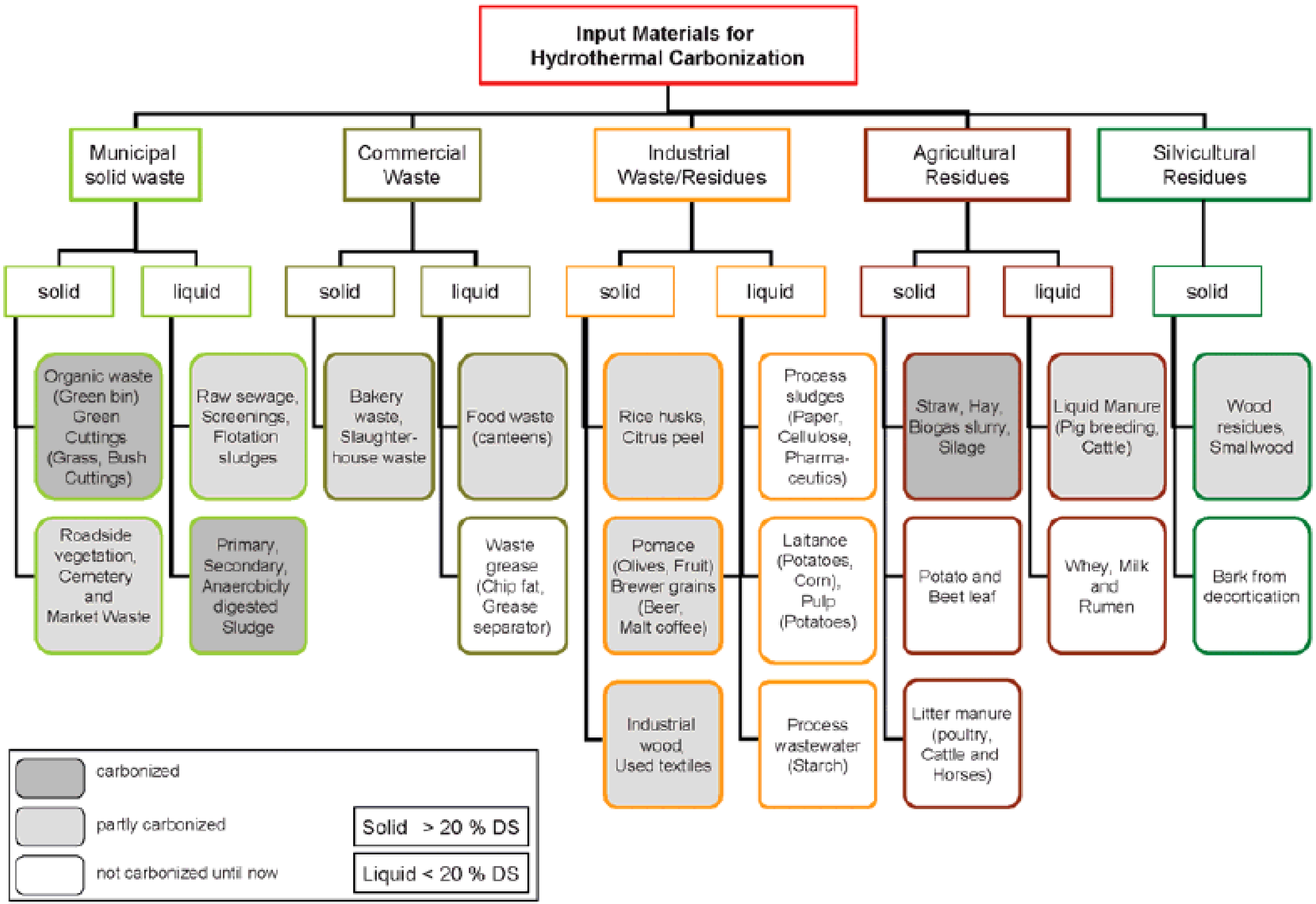


Advantages of HTC over biological approach



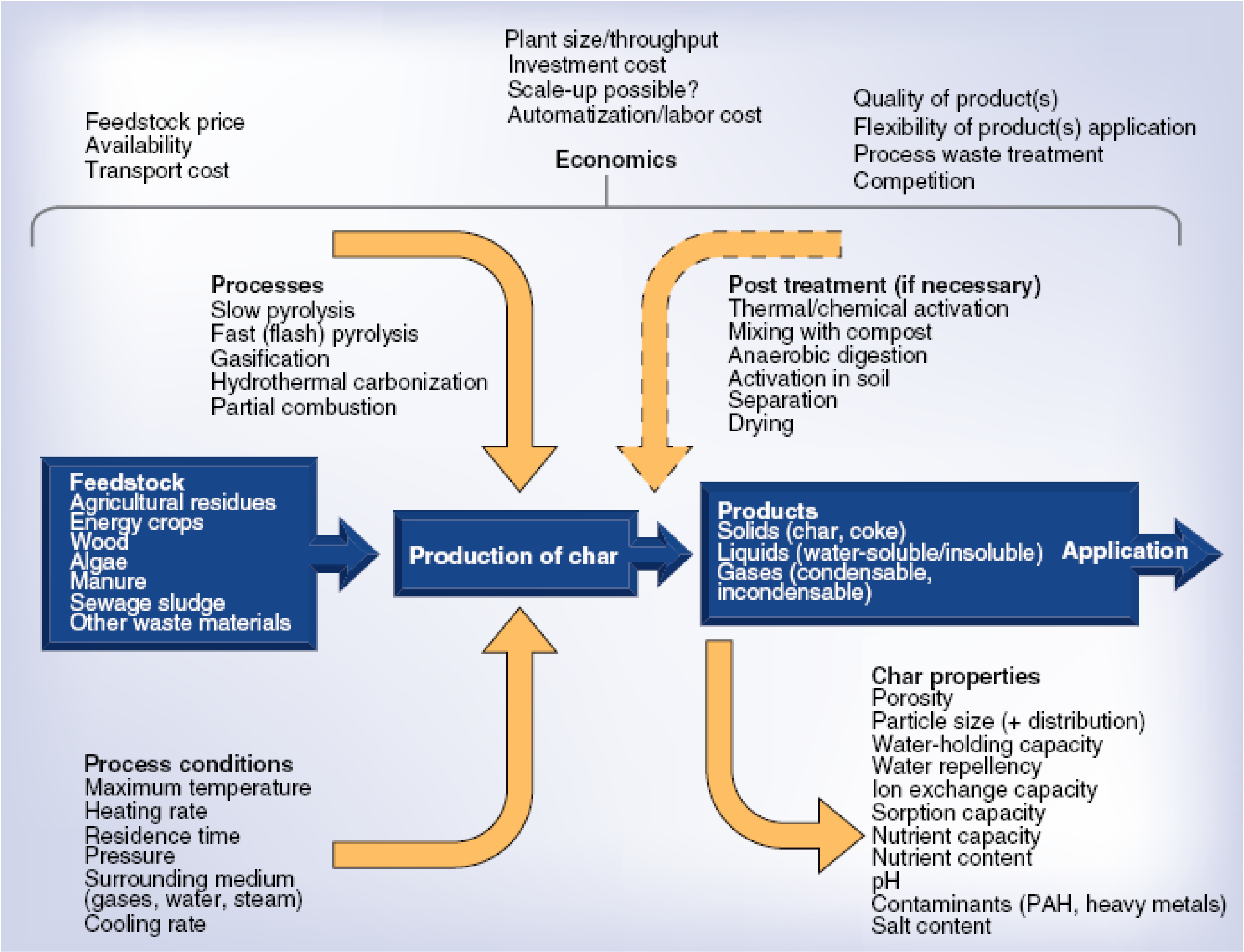
- Short time reaction
- Small size reactor
- Treatment of bio-toxins
- Destruction of pathogens and organic micropollutants
- Reduce GHG emission and odours
- Production of bio-coal (energy) or bio-char (soil amendment)
- Allowing nutrient recovery (N-P-K)

Overview of potential input material for HTC



(From Sardinia, 2009)

Factors influencing the production and applications of char



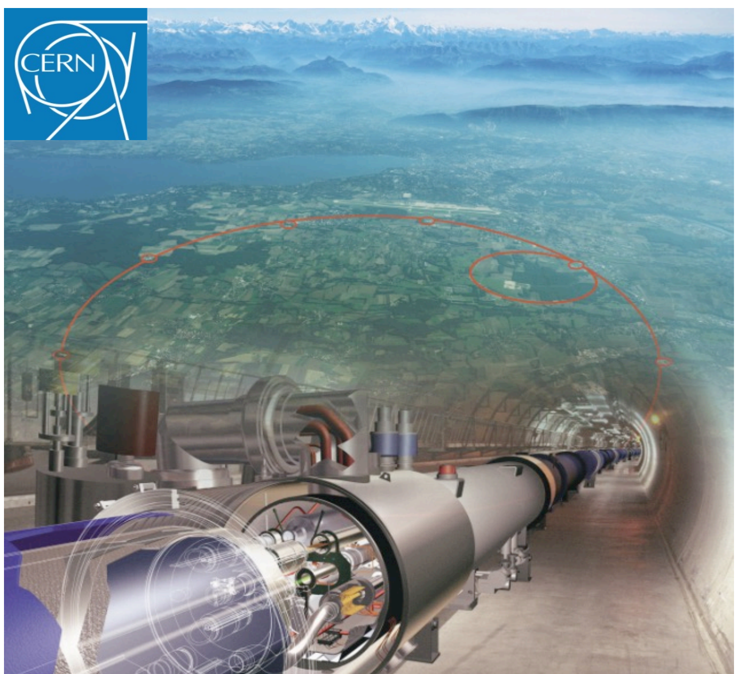
SRB high temperature/efficiency panels

Achieving high temperature high efficiency flat solar panels

- High temperature solar thermal usually regarded as requiring focusing (concentrators)
  - Focusing loses diffuse light (=30% in sunny areas, 50% in central Europe)
- Can also be achieved by reducing thermal losses from gas conduction/convection, mechanical contacts, radiation emission using
  - Vacuum
  - Selective coating

CERN (SRB) enabling technologies

- Ultra Vacuum
- Getter Pump
- Selective Treatment
- Metal Glass Weld



- Technology born at CERN
- Industrial development at SRB Geneva
- Production at SRB Valencia

Design challenges achieved

- Vacuum (10^{-7} Torr) over 20 + year panel lifetime
- Mechanical structure to withstand 10 T/m^2 applied on glass
- Getter pump powered by sun to retain 10^{-4} Torr for decades with no external pumping
- Low cost materials with low outgassing
- Seal between metal frame and glass vacuum-tight
- A selective layer with high absorbency and low emissivity

Physics World Focus on: Vacuum technology

physicsworld.com

Accelerators

Lonely journey A proton can travel more than 100 billion kilometres through the LHC's beam pipes without encountering a single residual gas molecule.

Extreme vacuum engineering

Upgrades to CERN's Large Hadron Collider are pushing vacuum engineering into uncharted territory, says **José Miguel Jimenez** of the lab's technology department

Travelling at almost light-speed in opposite directions, bunches of protons complete 11 245 laps of the 27 km-circumference Large Hadron Collider (LHC) every second. To deliver large amounts of data to the detectors, which are located at four points around the ring where the protons collide, the LHC's beams need to circulate for several hours at a time. But to help achieve such stability, we have to reduce the residual gas density in the beam pipes by 15 orders of magnitude, creating pressure conditions similar to those on the surface of the Moon.

The development of particle colliders has pushed vacuum technology from the ultra-high vacuum (UHV) domain towards the extreme high vacuum (XHV) domain. Indeed, the LHC's beam pipes are so empty that a single proton can make four billion turns of the machine without encountering a single stray gas molecule. Not only does this ensure a long beam lifetime, it also minimizes background noise in the detectors and reduces the radiation delivered to components in the LHC tunnel.

The new European strategy for particle physics, which was released in May this year, confirmed the need to exploit the full physics potential of the LHC over the coming years, and also to prepare the next generation of "discovery" machines that push for higher energy, intensity and brightness (*Physics World* July 2013 p12). This in turn demands innovative high-vacuum solutions that maximize beam lifetime and minimize beam-induced background in the detectors.

Octagonal solutions

The LHC is not technically a circle but is made up of eight 2.3 km-long arcs and eight 1.1 km-long straight sections, each of which requires different vacuum approaches. The arcs, which are held at a temperature of 1.9 K to operate the LHC's superconducting bending magnets, are maintained under vacuum using cryo-pumping. This causes gases on the cold surfaces to condense (just as water freezes on the windscreen of a car) and – once frozen – these molecules no longer interact with the circulating beams. But at 1.9 K the surface of the beam pipe can only condense a small fraction of hydrogen gas, which is the dominant species in the residual vacuum. We therefore line the beam pipes in the curved sections of the LHC with a perforated "beam screen" that is held at a slightly higher temperature so that it screens the captured hydrogen from the circulating beams.

The room-temperature straight sections are more complicated because they house equipment such as beam injectors, extractors, collimators and also the four large particle detectors ATLAS, CMS, LHCb and Alice, inside which the two beams travel through the same beam pipe. The straight-section vacuum, which is monitored by 1500 pressure gauges, relies on the extensive use of non-evaporable getter (NEG) coatings. This technology, which was born and industrialized at CERN at the end of the 1990s, chemically binds gas molecules to the coated beam-pipe surface. Even though the sections contain 800 ion pumps, without NEG coatings the LHC vacuum would have difficulty in operating at top performance.

Without NEG coatings, the LHC would have difficulty in operating at top performance

August 2013

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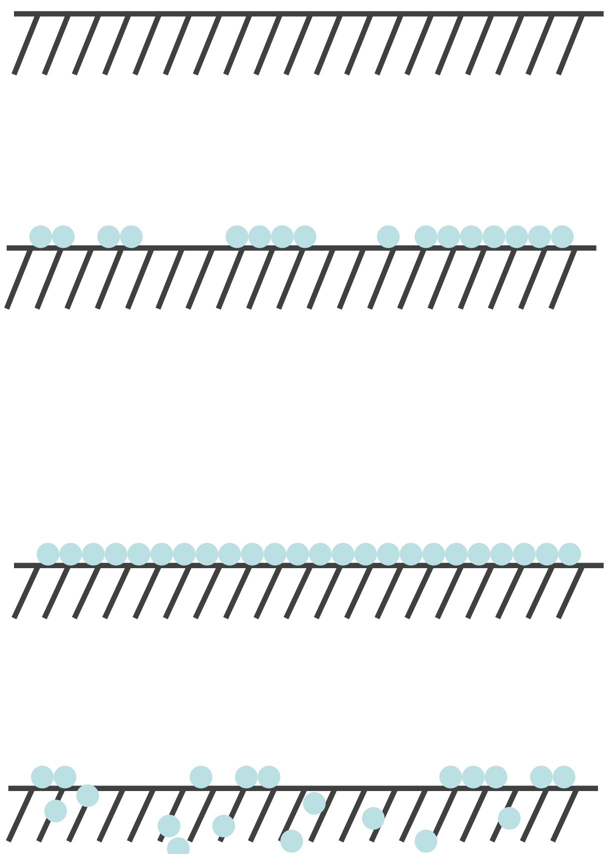
Getter pump technology



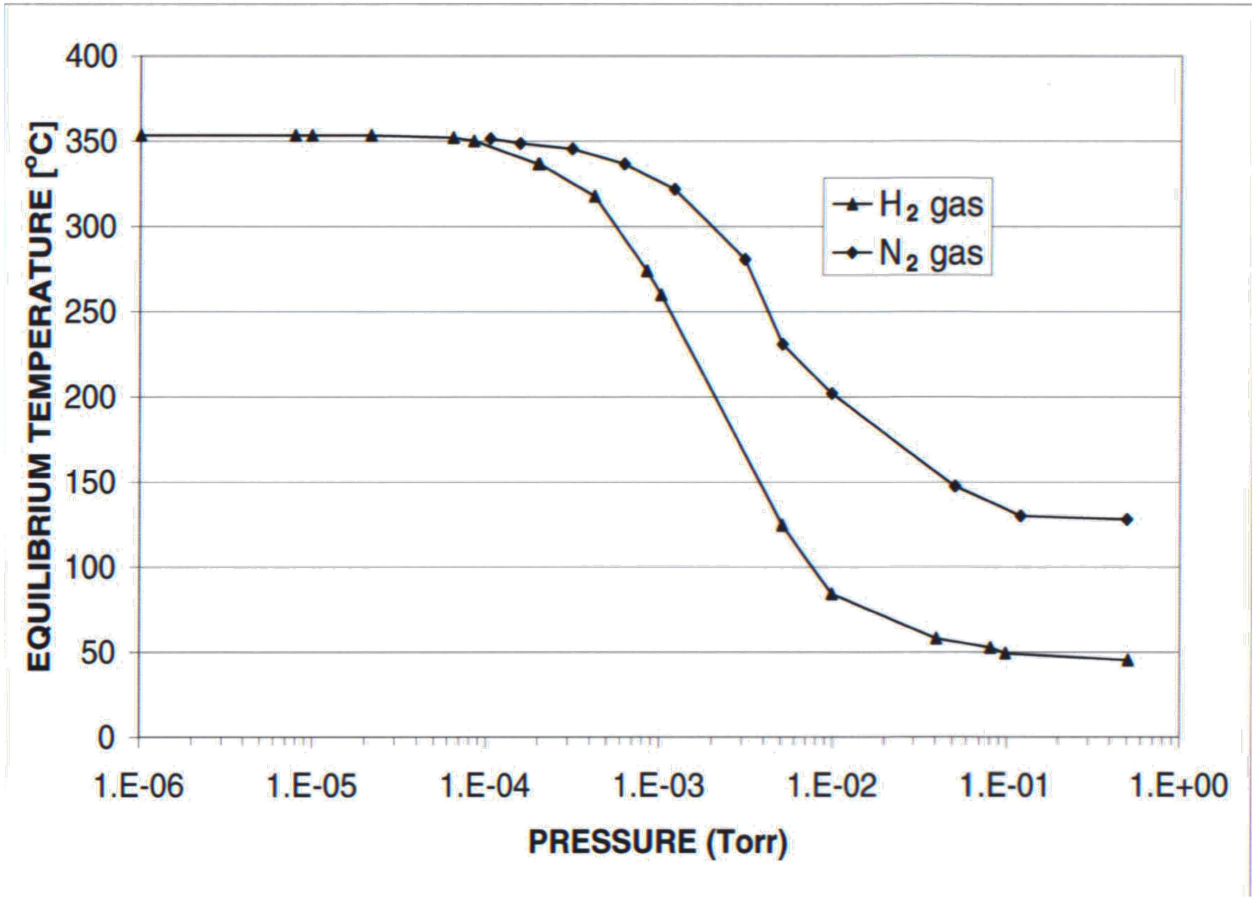
Clean surface

Partially covered surface

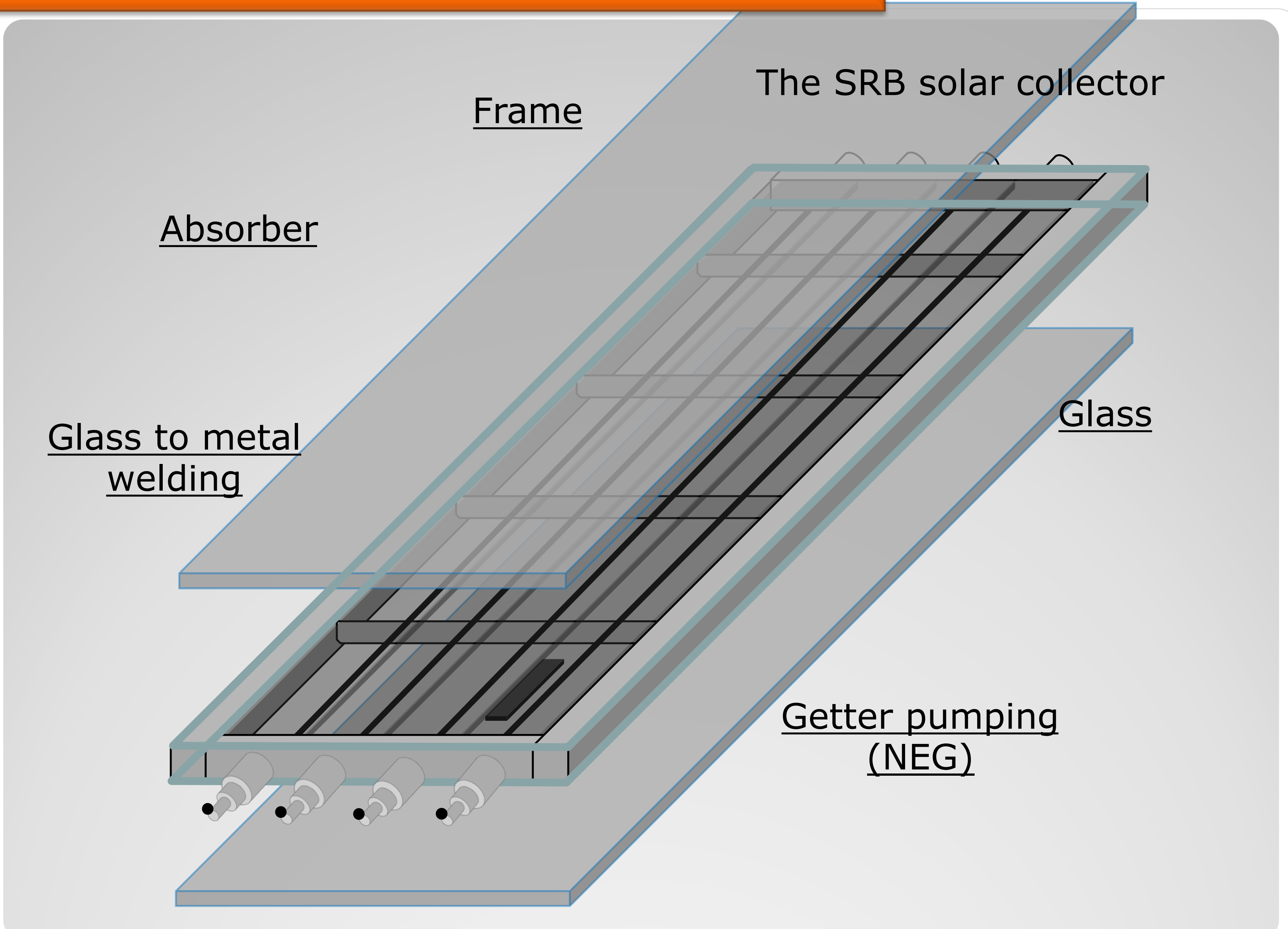
Saturated surface

Surface cleaned by heating

What is the vacuum level required for the solar panels ?



Variations of absorber temperature as a function of panel pressure


The SRB solar collector
Frame
Absorber
Glass to metal welding
Glass
Getter pumping (NEG)

Competitive advantages of SRB collector

- Temperatures > 300° C without focusing mirrors
- Utilizes diffuse light (> 50% in Central Europe)
- Cylindrical mirrors, equally good for direct and diffuse light may raise maximum temperature > 400° C

SRB

Various thermal solar heaters

Temperature scale 30° C | 60° C | 110° C | 250° C | 400° C

Applications

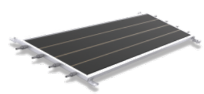
Sanitary water

- Heating
- Air conditioning

- Tele heating (district heating)
- Air conditioning
- Industrial heating (drying, sterilization, steam production, central thermal hybrid plant for electricity)

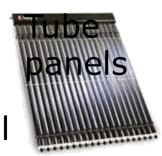
Thermodynamic production of electricity

Panels SRB



Thermal panels

Conventional panels



Tube panels

Vacuum tubes with parabolic mirros

Competitive advantages

More efficient in cold climates

Higher yield compared to photovoltaics

Less sensitive to the pollution of mirrors
More effective for diffuse light

Example of implementation

GENÈVE
AÉROPORT

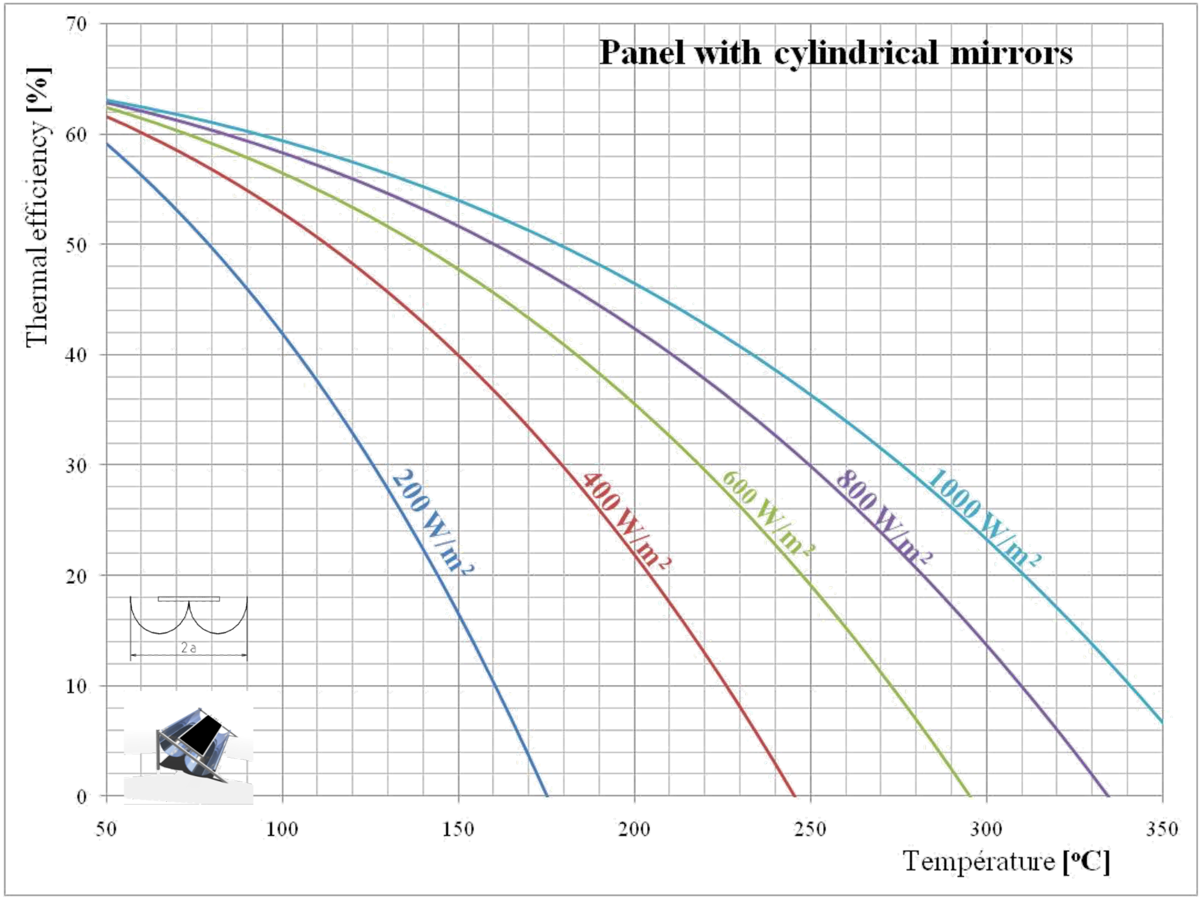
- Orientation: south
- Tilt: 0º
- Aperture area: 1139 m^2
- Installed power : 630kW @ 130° C
- Heat transfer fluid : synthethic oil
- Solar field inlet /outlet temperature: 90ºC
- Solar field outlet temperature: 130° C
- Annual solar energy yield: 566 MWh
- Annual cooling energy production: 285 MWh

Broad description & status of joint system

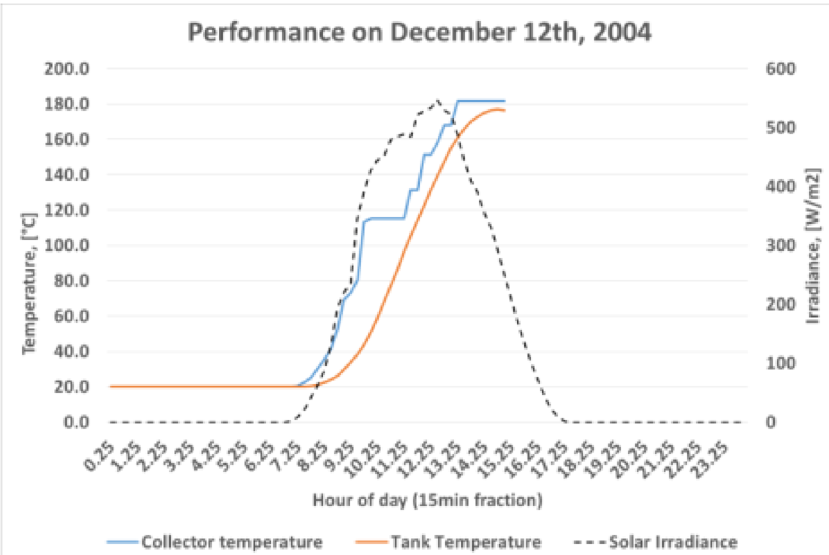
Initial simulation results

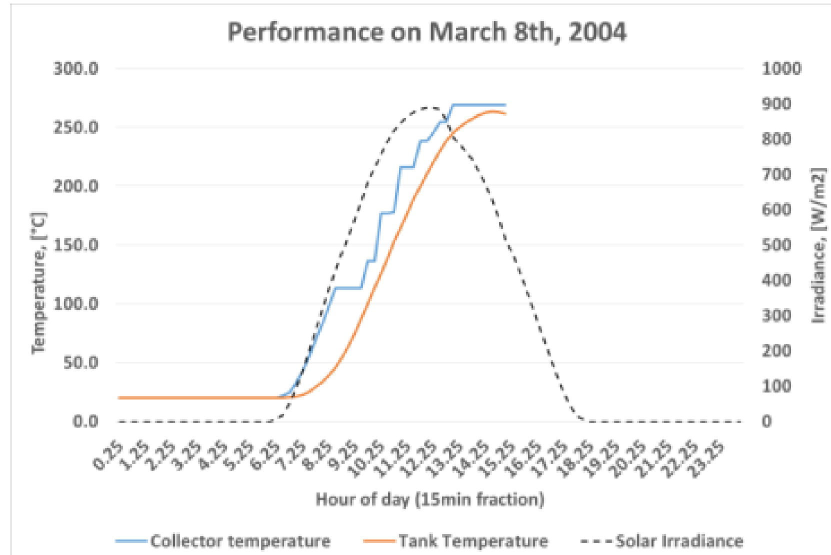
- 17.8 kWh needed to heat vessel and 50 liter content from 20° C to 250° C
- Number of 50 liter batches transformed to solid fuel a year using 4 collectors (16m^2)
  - 411 (no recovery between days/batches)
  - 519 (50% recovery between days)
  - 695 (50% recovery between two reactors in tandem and 50% between days)

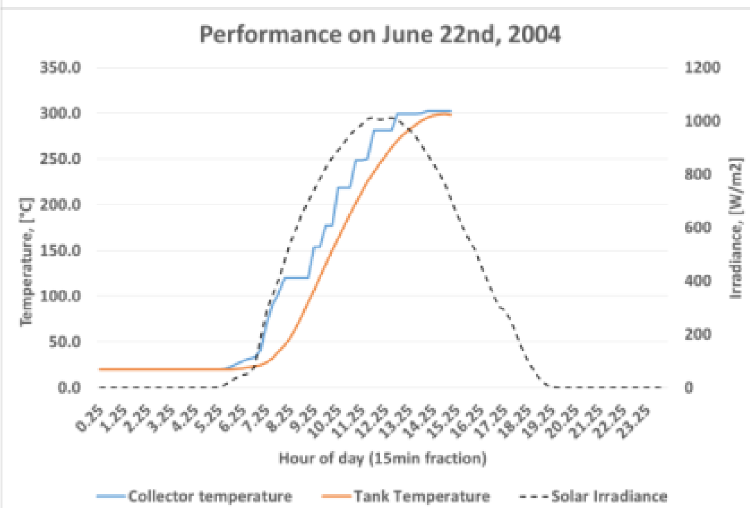
Thermal efficiencies as function of the temperature

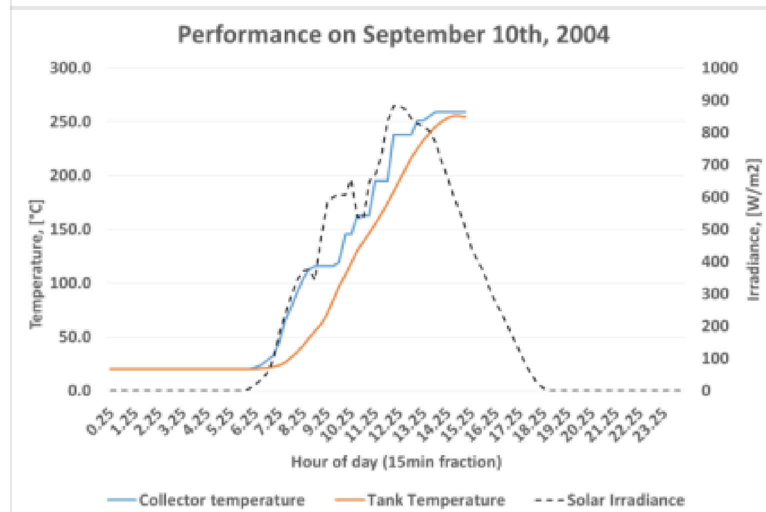


Simulation results of thermal performance showing collector and tank temperatures with solar irradiance on 4 representative days of year.



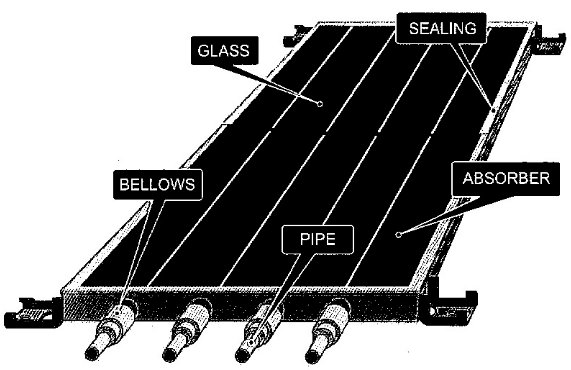


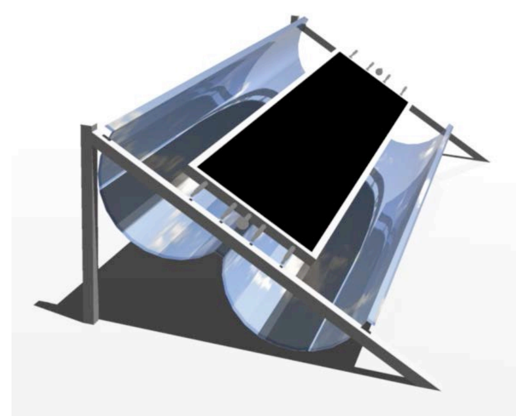


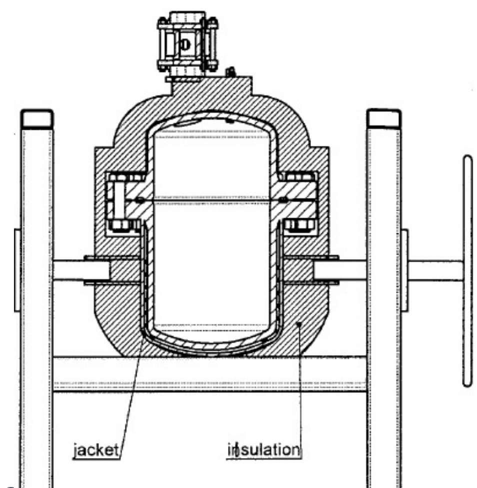


Setup of pilot installation

- Four panels (X $4m^2$) and one 30 liter reactor
- Sensors on reactor (heat, pressure) and panels
- Reactor heating switchable between solar and electric energy source







SRB Energy solar thermal collector (left) and its assembly in a standalone structure with cylindrical mirrors (SRB Energy C

Need to characterize the system

- Biochemical: reactions and their shaping by controlling factors
- Outputs: energetic and nutritive qualities
- Safety and convenience of operation
- Energetic:
- Economic
- Transportability of device

Feasibility, above all

- Existing economic evaluations of HTC have assumptions not relevant to our case
  - Large capital cost for reactor
  - Significant cost of energy inputs
  - Need to transport inputs and outputs long distances
- In our case, we the use case is more like….
- A $10,000 reactor able to produce 50 kg/day of HTC-coal (calorific value of 27 MJ/kg) *in situ* from free (or even nuisance-full) inputs …

QUESTIONS….?

END

Accreted odds and ends

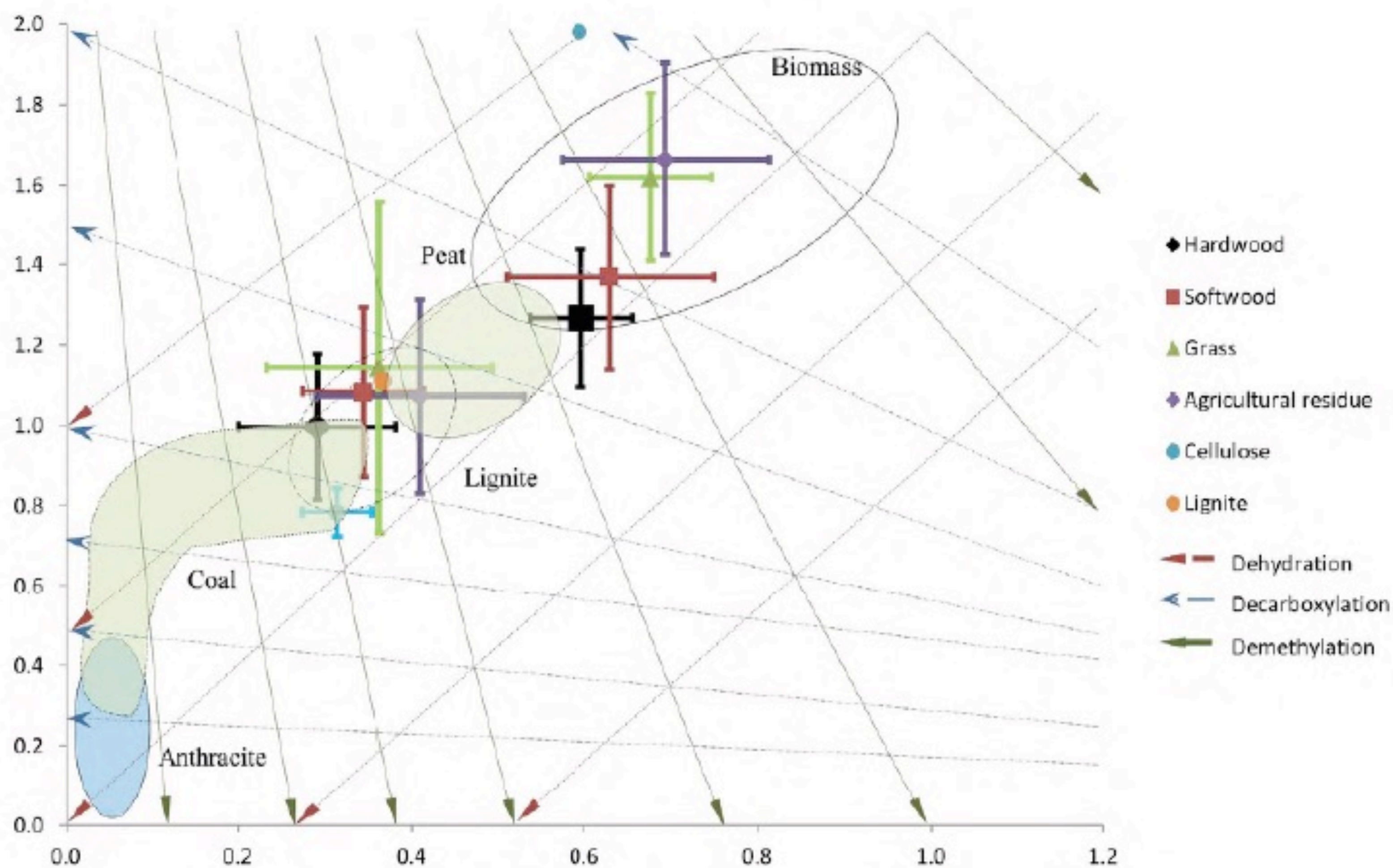
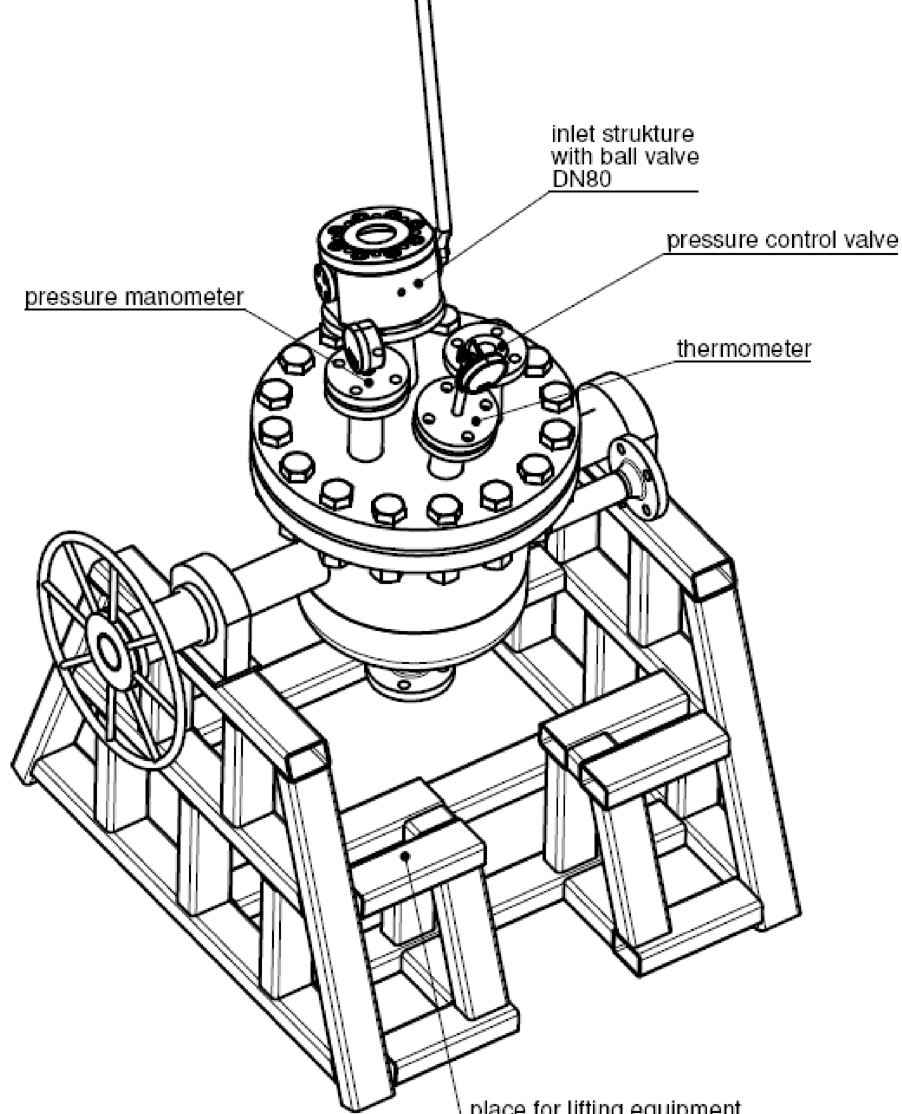
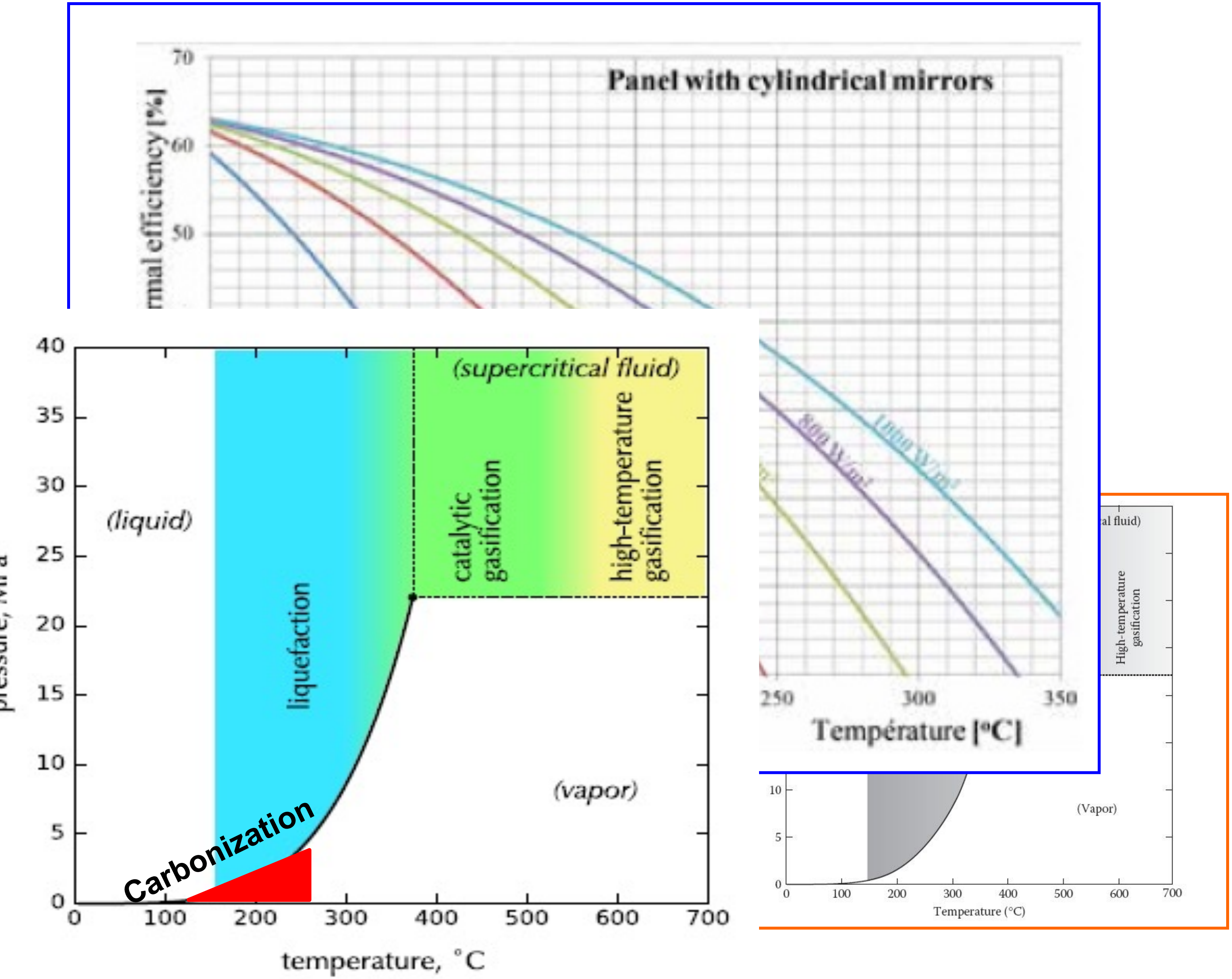


Figure 2: van Krevelen diagram of hydrochar from various feedstock with major reaction lines.


inlet strukture
with ball valve
DN80
pressure control valve
pressure manometer
thermometer
place for lifting equipment
for the cover


Panel with cylindrical mirrors
70
60
50
250
300
350
Température [°C]
(supercritical fluid)
catalytic gasification
high-temperature gasification
(liquid)
liquefaction
(vapor)
Carbonization
0 100 200 300 400 500 600 700
0 5 10 15 20 25 30 35 40
temperature, °C
High-temperature gasification
(Vapor)
Temperature (°C)

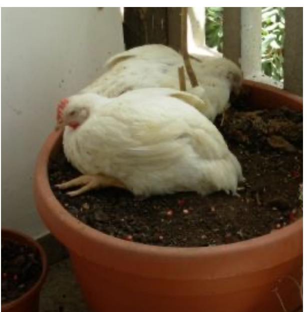
Hydrothermal processes

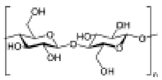
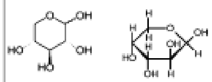
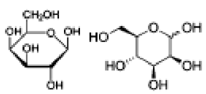
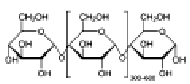
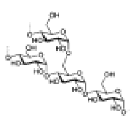
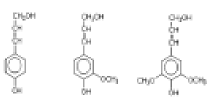
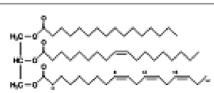
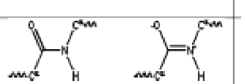
- AMIT SLIDES, supplemented by YG ones

- HTC can be defined as combined dehydration and decarboxylation of a Biomass to raise its carbon content with the aim of achieving a higher calorific value
- $C_6H_{12}O_6 \rightarrow C_6H_2O + 5\ H_2O + \text{Energy}$
- Early patents can be traced back to 1850: 'wet carbonization' of peat as a method for dewatering ☆
- It is known that char can be produced through dewatering of peat
- The following range of operational conditions are known
  - Elevated temperature 180 - 290° C
  - Steam saturated pressure
  - The pH-value of the feed should be below 7
  - process times vary between 1 and 72 h
- The carbon is retained

- המים הופכים ראקטיביים בטמפ' ובלחץ וגורמים לתהליך דהידרציה של המוצק והפיכתו (בתנאים אנאירובים ל"ביו-פחם".
- שבירה של מולקולות אורגניות (הורמונים, אנטיביוטיקה).
- חיטוי.

זבל עופות



Component	Chemical structure and monomers/oligomers formula
Cellulose	 cellobiose $[C_6H_{10}O_5]_n$ n~100-10 000
Hemicellulose	$[C_5H_{10}O_5]$  xylose arabinose $[C_6H_{12}O_6]$  galactose mannose
Starch	 amylose  amylopectin
Lignin	 p-coumaryl coniferyl sinapyl alcohols
Lipids/fats	 Triglycerides
Proteins	 Peptide bonds [NHCH(R)C(O)]n n=50-2000, R-various side groups of amino acids

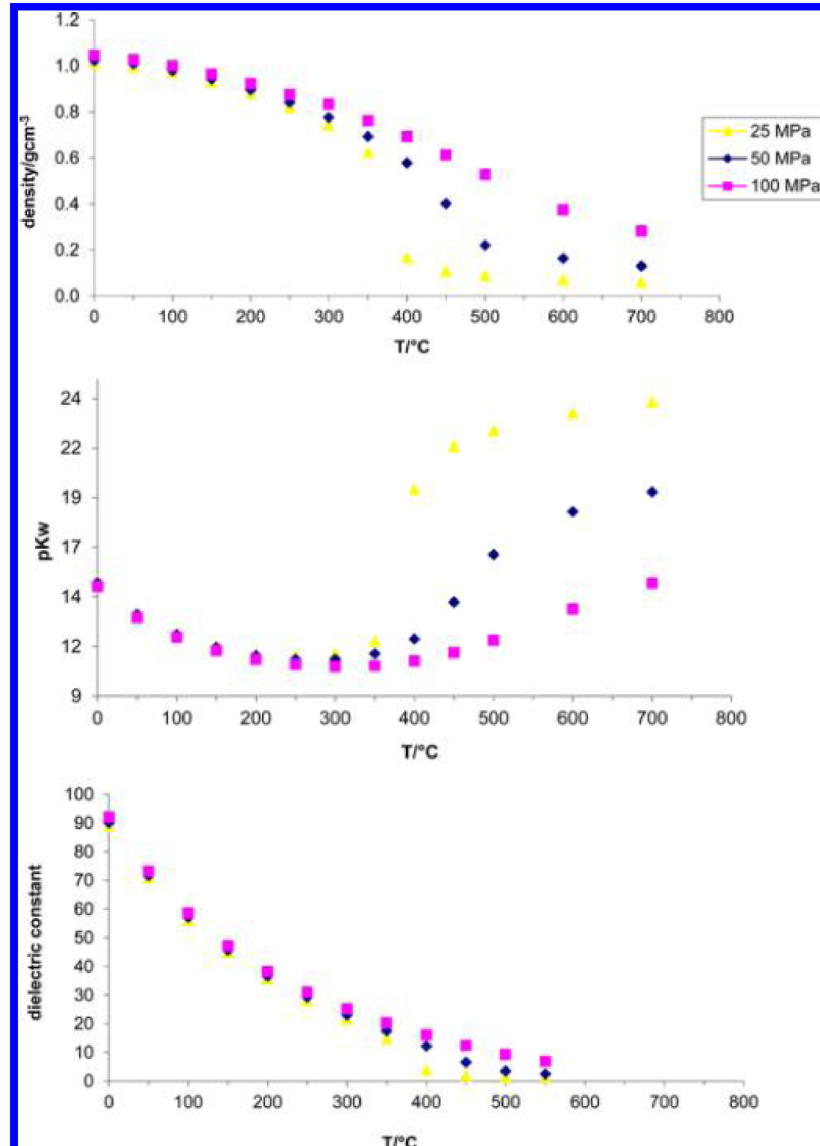
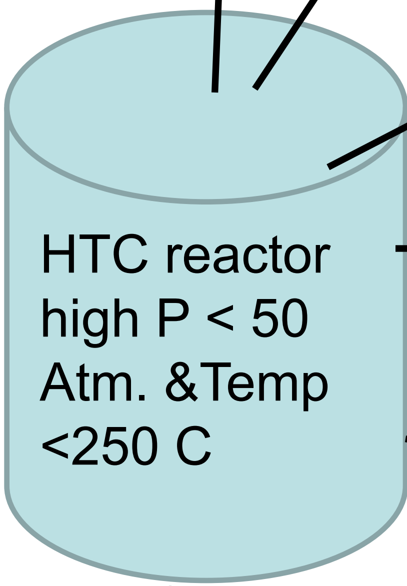


Figure 1. Changes in water density, ionic product, and dielectric constant in the range of 0−800 °C for 25, 50, and 100 MPa.

Range of sophisticated organic reactions using only sun and moist biomass

Polarity $\downarrow$: higher solubility of organics

K_w $\uparrow$ more acid-base reactions – higher degradability



Kind of reaction controlled by temperature, pressure, feedstock, duration

Hydrolysis and dehydration – breaking down of organic molecules (e.g. cellulose) by water.

$$4(C_6H_{10}O_5)_n \rightleftarrows 2(C_{12}H_{10}O_5)_n + 10H_2O$$

Decarboxylation - removes a carboxyl group ($COOH^-$) and releases CO_2

$$C_6H_{12}O_5 \rightarrow C_{5.25}H_4O_{0.5} + 0.75CO_2 + 3H_2O$$

Condensation – Polymerization - Aromatization – OM degraded to monomers which polymerized and aromatized to form the hydro-coal (char)- rate is mainly controlled by temperature, pH and residence time

Off grid operation: bring reactor to feedstock not feedstock to reactor

Free available inputs and off-grid operation suited to developing country contexts