Reversible Solid Oxide Electrolysis integrations to wastewater treatment plants

for green gas and power balancing services

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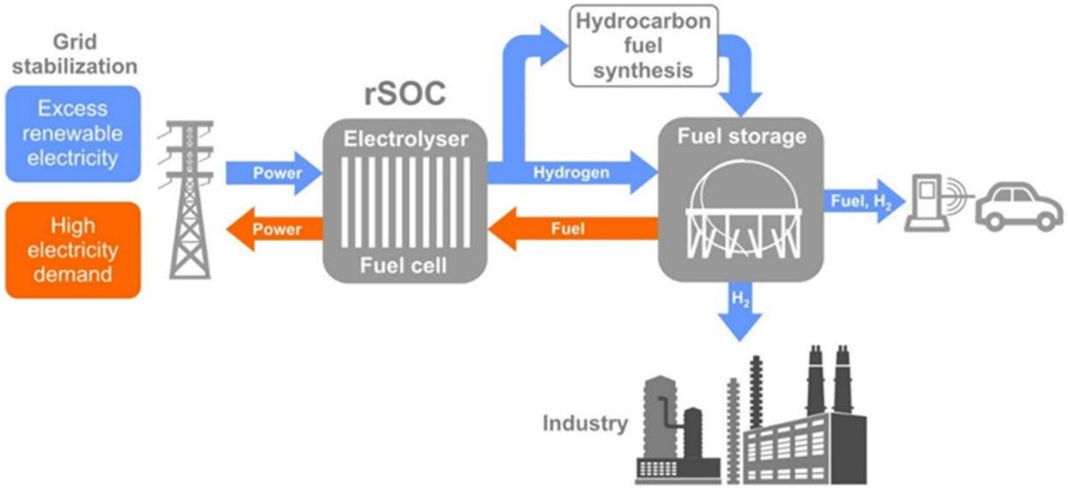
Wastewater to energy – An Untapped Resource

- 80% of 330km3/year of worlds wastewater is discharged in waterways untreated. Wastewater is 1% waste, 99% water.
- By 2025, half of the world's population will be living in water-stressed areas.
- WWTP's represent 1% of electricity demand in developed economies.
- Wastewater sector causes ~3% of manmade, atmospheric greenhouse forcing (CO_2, CH_4, N_2O). (IPCC)

what is and why to develop

Reversible Solid Oxide Cell (rSOC) technology

- Reversible operation ensures high utilisation
- Adaptability to local energy needs and suitable for integration with various energy sources
- High efficiency and capability of co-electrolysis of steam and CO_2
- Fuel flexibility in SOFC mode
- Good technology base for green, flexible and efficient energy systems
- Supports grid stabilization with high penetration of renewable electricity



rSOC = SOFC and SOEC are incorporated in a single unit

- SOEC = Solid Oxide Electrolysis mode, converts surplus power to Fuel, with high conversion rate
- SOFC = Solid Oxide Fuel Cell mode, converts Fuel to power, with high conversion rate and no emissions

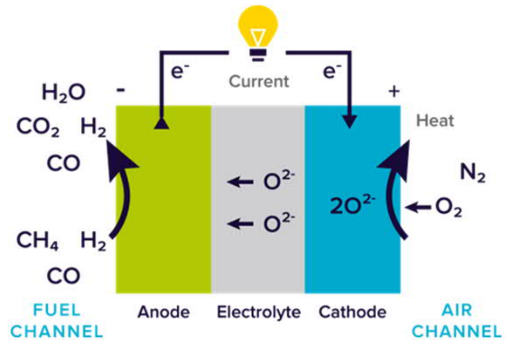
SOLID OXIDE FUEL CELLS (SOFC)

High performance gas-to-power:

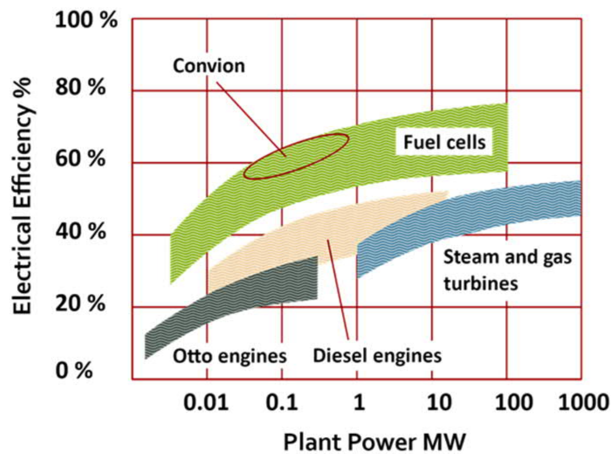
SOFC have the highest conversion efficiency of all Combined Heat and Power (CHP) technologies – regardless of scale.

H2020-DemoSOFC: wastewater to power

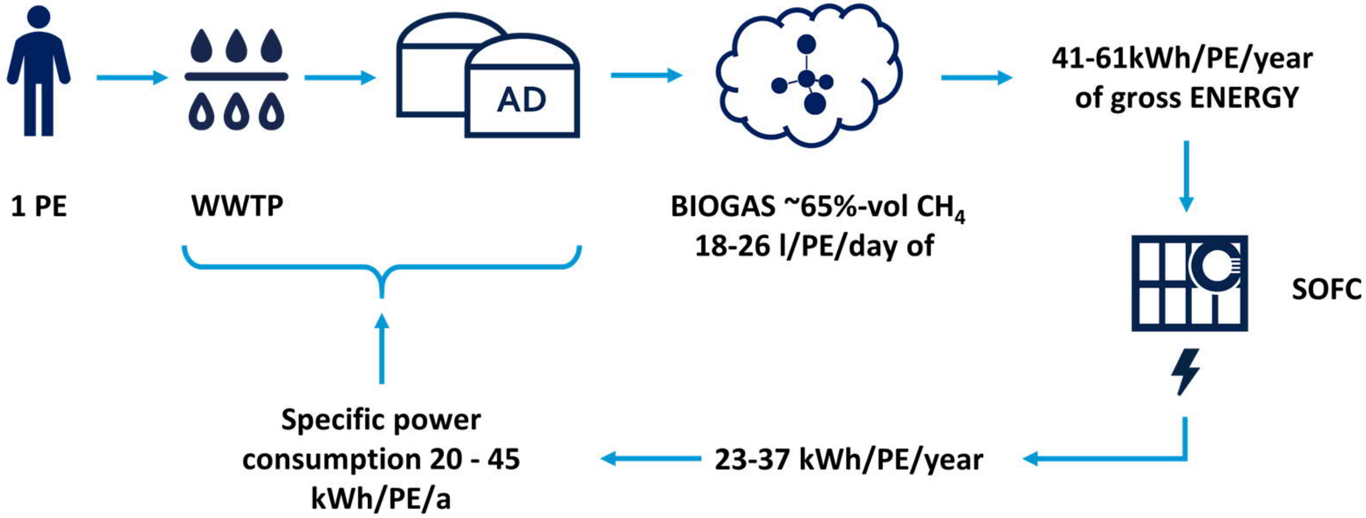
- Waste streams as a resource
  - Waste and water services are essential municipal functions affecting livability of communities and health of environment.
  - Anarobic Digestion (AD) is a scalable technology for processing sewage sludge and producing biogas



- SOFC and AD as combined resource
  - **Solid Oxide Fuel Cell's (SOFC)** have the highest conversion efficiency.
  - AD is a bacterial process converting organic matter in a digester to biogas with an approximate composition of 60%-vol CH4, 40%-vol CO2.
    - **SOFC can flexibly use AD biogas as a fuel without separating CO2** and without a compromise in efficiency.
    - A general advantage of fuel cells is that they **can operate at varying fuel gas compositions with high efficiency**



H2020-DemoSOFC: Concept of energy autonomy in WWTP's



- Wastewater contains enough of embedded energy for its treatment.
- SOFC makes possible energy autonomous water and sanitation services.

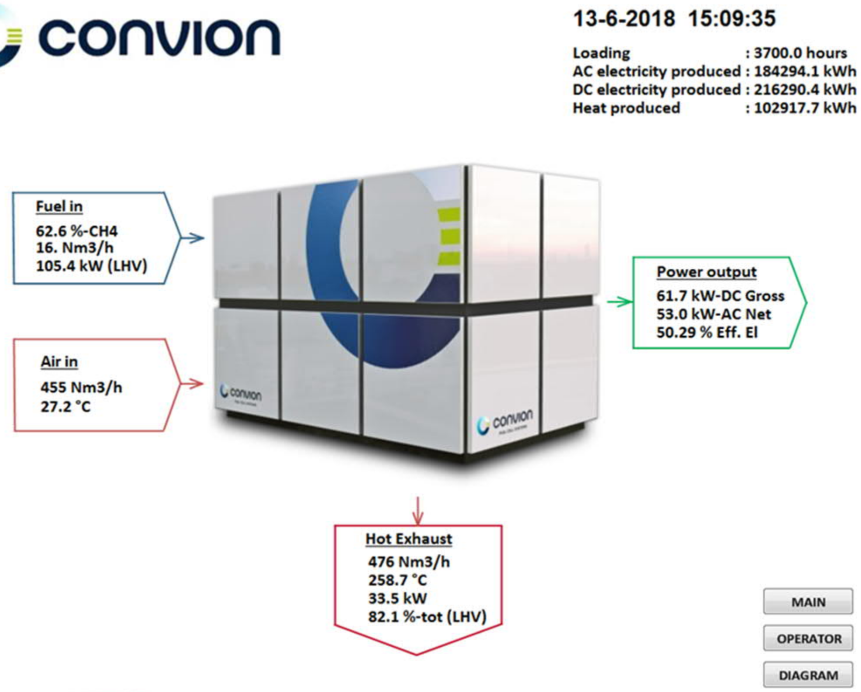
H2020-DemoSOFC project

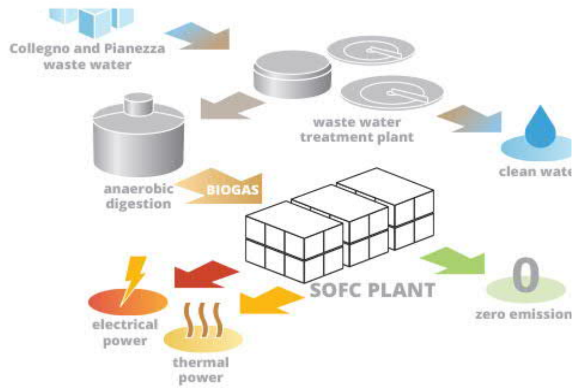
- Rationale
  - Underutilized feedstocks and essential services
  - Why SOFC is so transformative to capturing energy of waste?
  - Concept of energy autonomous wastewater treatment

- Demo: 175 kW bio-gas fuelled **SOFC power plant** installed at **waste water treatment plant in Turin, Italy**
  - 1st Convion 58 kW system started in October 2017
  - 2nd Convion 58 kW system started in October 2018
  - Electrical efficiency >50% (peaks of 56%), average total efficiency 82%
  - High efficiencies achieved independent of CH_4 concentration in the AD biogas
  - 6000 h operating hours reached

- Significant replication potential: 23000 wastewater treatment plants in Europe, corresponding to 930-2550 MW SOFC power

- Partners: Polito, Smat, Convion, Imperial College London, VTT





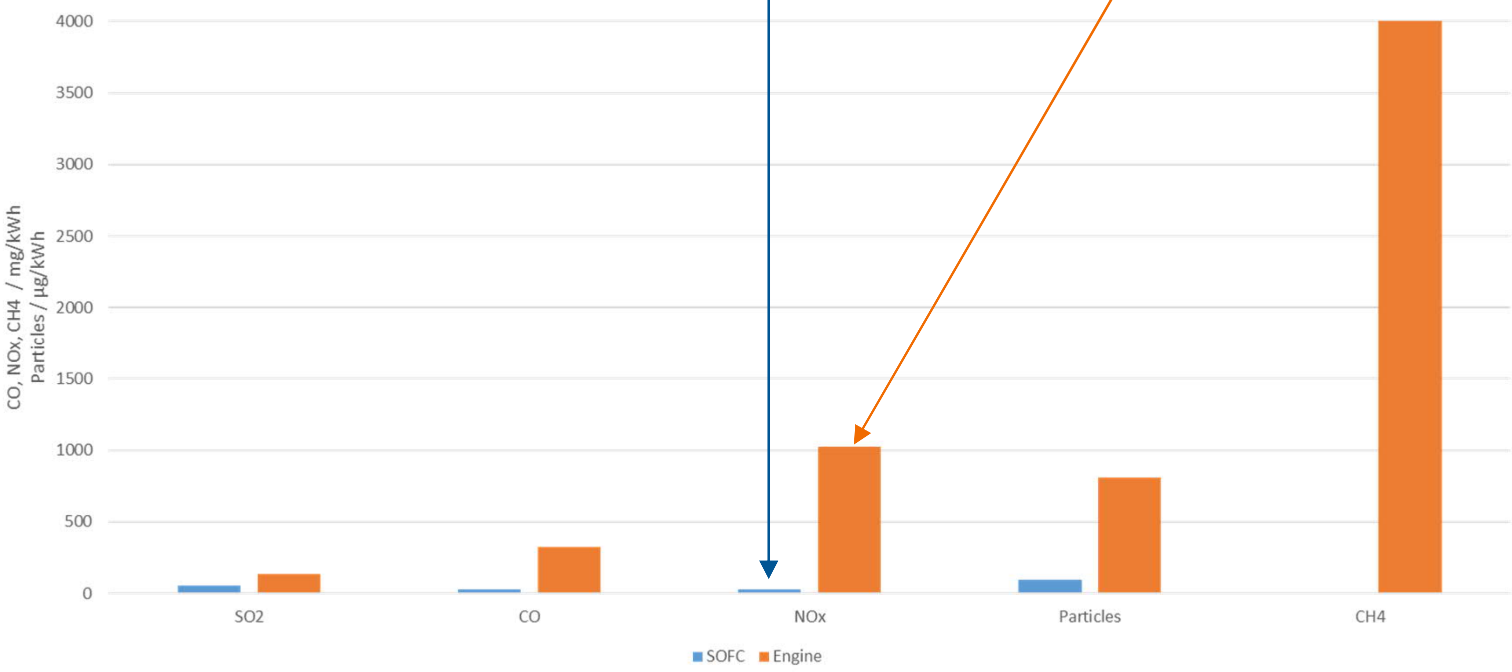
(No) emissions from the SOFC system

Practically no emissions from the **SOFC**

- **No** SO2, CO, NOx or CH4 **detected** from SOFC exhaust. *Graph shows detection limits of the instrument*.
- Particle emissions were lower than values in ambient air

Emissions from a **biogas engine** located at similar waste water treatment plant

- Local emissions (CO, NOx, SO2, particles) should be reduced especially in urban environment to increase quality of life



Emission measurements carried out on-site

rSOC = Reversible
solid oxide fuel cell /
solid oxide electrolysis

in the same device opposite operating modes:

* high-performance gas-to-power
* high-performance power-to-gas

allows hot swap between these opposite operating modes

H2020-BALANCE:
Motivations to develop
Reversible Solid Oxide Cell (rSOC) technology

- Reversible operation ensures high utilisation
- Adaptability to local energy needs and suitable for integration with various energy sources
- High efficiency and capability of co-electrolysis of steam and CO_2
- Fuel flexibility in SOFC mode
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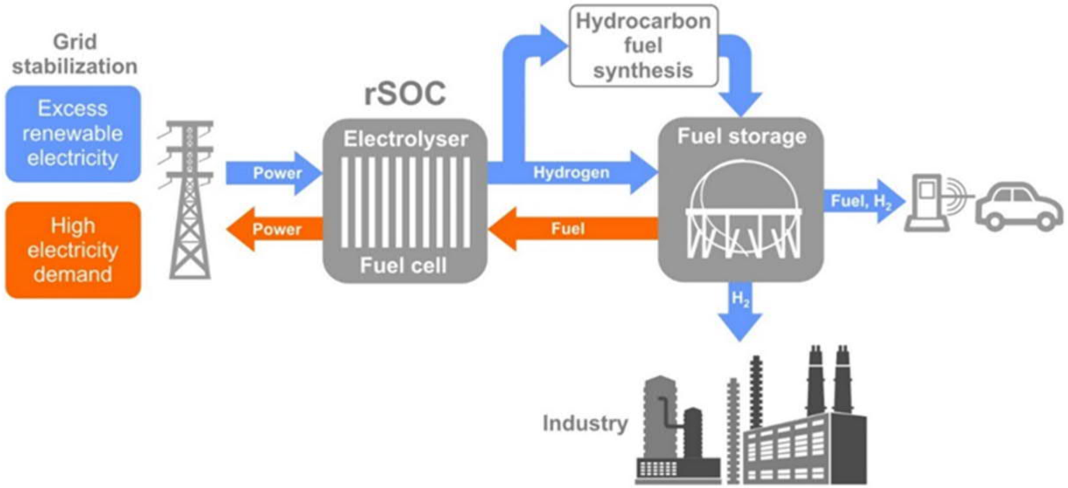

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H2020-BALANCE project

- **Movable 10kW reversible solid oxide cell (rSOC) system has been modeled and implemented in pilot demonstration scale**
- System running **5000h+** since mid Aug 2019 in various operation conditions
- Reversibility and dynamic operation (i.e. transitions between SOFC and SOEC modes) has been investigated in system level
- **Multi-stack multi-module rSOC system** operation has been demonstrated and enthalpy flows through the entire system has been analyzed

rSOC system level	AC power for steam production included	Free 150 ºC steam flow assumed
AC to H_2 efficiency (HHV)	71 %	81 %
AC to H_2 efficiency (LHV)	60 %	69 %

Future steps:

- System efficiency can still be improved in a larger system:
  - Pre-heat the water: up to **2 %-point extra**
  - Relative reduction of heat loss: **7 %-point extra** if negligible heat loss
  - **More efficient AC/DC converter** (currently 89%)

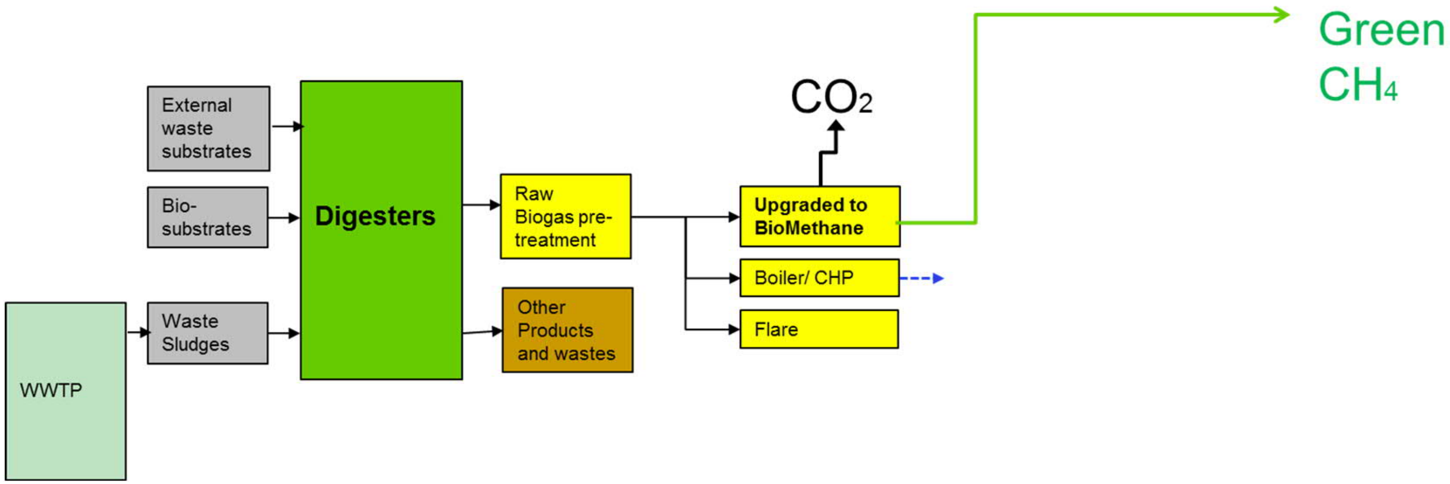
Biomethane production at wastewater treatment plants

Biomethane production at (some) WWTPs today

In the Biomethane process, the AD biogas is upgraded to a green high quality gas with same fuel usability as Natural Gas

- Biomethane CH4 content above 98%
- CO2 is removed from the raw AD biogas

This CO2 is today emitted to the atmosphere



Power-to-gas ($CO_2 + 4H_2 \rightarrow CH_4 + H_2O$)

Methanation technologies: Biological methanation

Packed bed lab-scale reactor

Figure from: Burkhardt M, Busch G. Methanation of hydrogen and carbon dioxide. Appl Energy 2013;111:74–9. doi:10.1016/j.apenergy.2013.04.080.

Completely stirred tank lab-scale reactor

Figure from: http://powerstep.arctik.tech/grid-gas-production.php#gal-bio-meth-3

	Biological methanation
Plant size	± Best suited for small to mid-scale distributed plants
Utilisation	± Pilot plants used within biogas plants and waste water treatment plants
Operating conditions	+ low temperature, low pressure
Tolerance of impurities	+ High
Minimum load	+ No minimum load
TRL-level	– in demonstration phase (companies involved: Electrochaea, MicroPyros, MicrobEnergy GmBH, Qvidja Kraft)

GHSV = volumetric flow rate (m^3/h) of feed gas without any inert gas and with a stoichimetric H2/CO2-ratio/reactor volume (m^3)

Power2Gas integration for Biomethane production

In the Biomethane process, the AD biogas is upgraded to a green high quality gas with same fuel usability as Natural Gas

- Biomethane CH4 content above 98%
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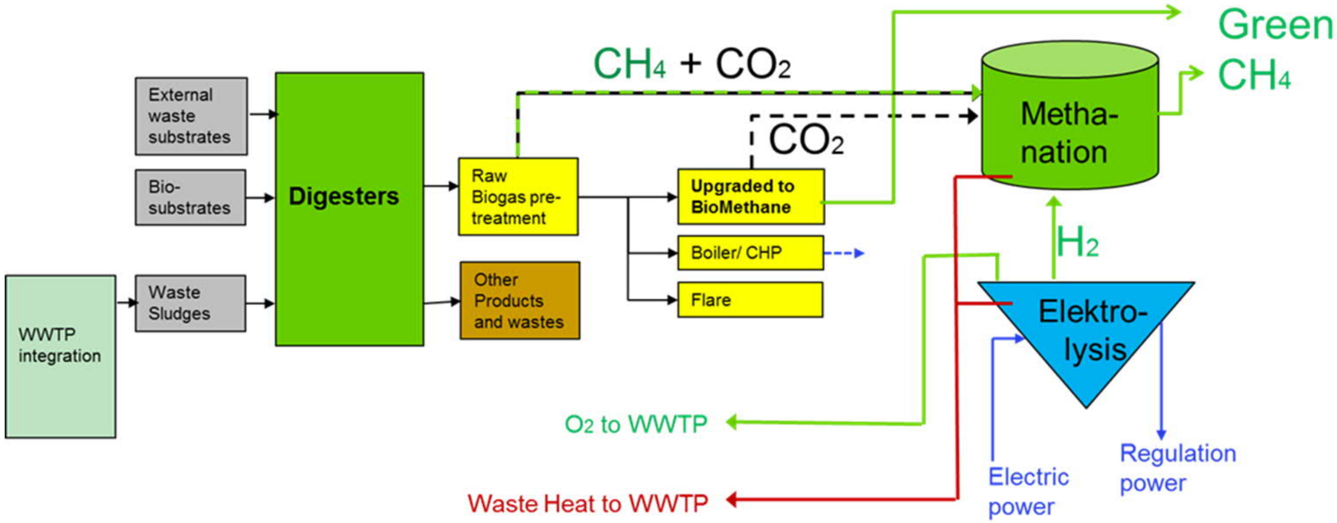
With Power2Gas integration, the CO2 is utilized and Biomethane (CH4) production can be increased by 50-100%



Techno-economic evaluation

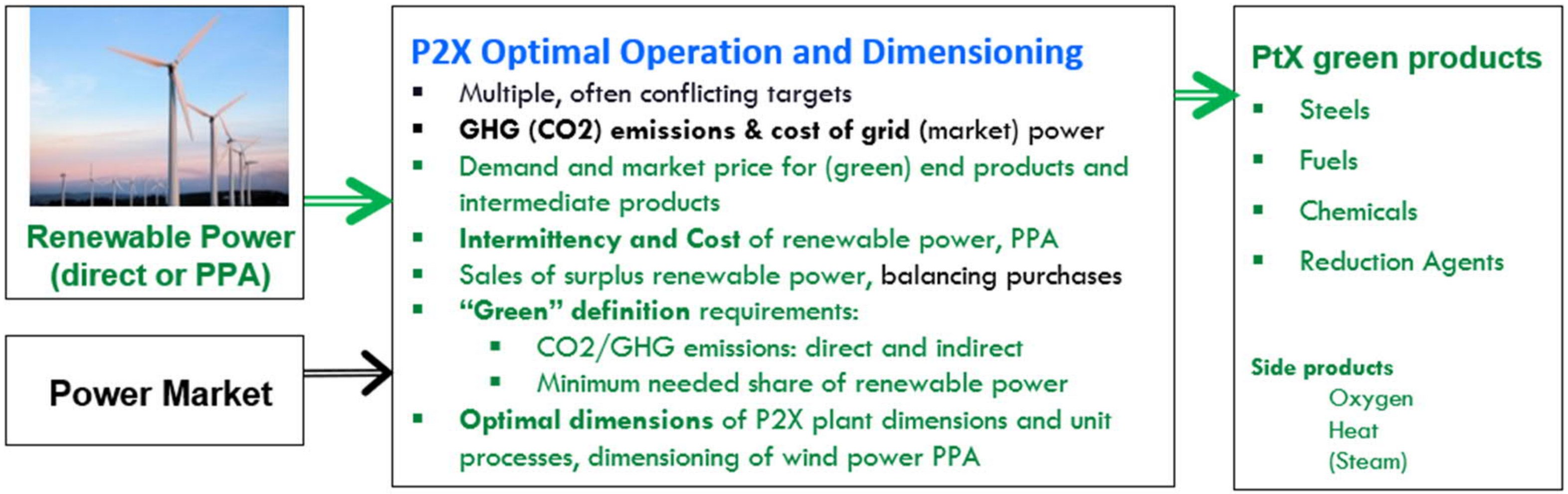
rSOC and
biological methanation
integrated to a city-scale WWTP

utilizing surplus renewable power

VTT's P2X-optimization for dimensioning and operational optimization

PtX process unit dimensions are dependent on
- wind (and solar) power
- volatile power market
- green product definitions
- inflexible H_2 demand at customer or downstream process
- optional flexibility in customer's production

⇒ **Model gives cost-optimal dimensions for**
- Electrolysers
- H_2-compressors
- H_2-storages size
- needed renewable power site or PPA-contract
- grid interface, optional battery etc..
- optionally customer's flexible production

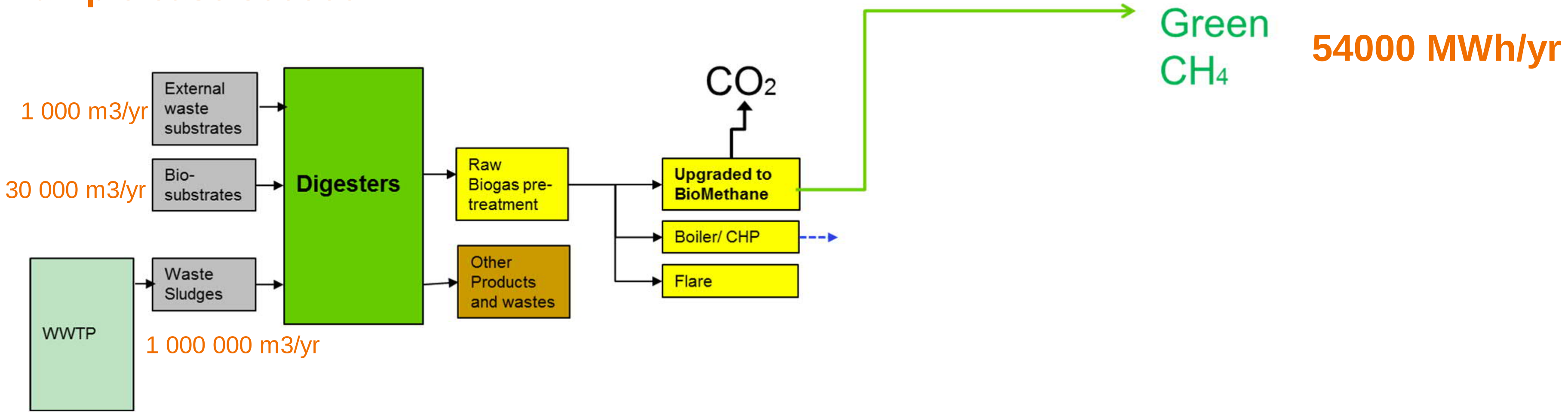


Biomethane production at example WWTP

In the Biomethane process, the AD biogas is upgraded to a green high quality gas with same fuel usability as Natural Gas

- Biomethane CH4 content above 98%
- CO2 is removed from the raw AD biogas
- Biomethane is used in city buses
- Biomethane can optionally stored in BioLNG storage

Example case 800000 PE WWTP

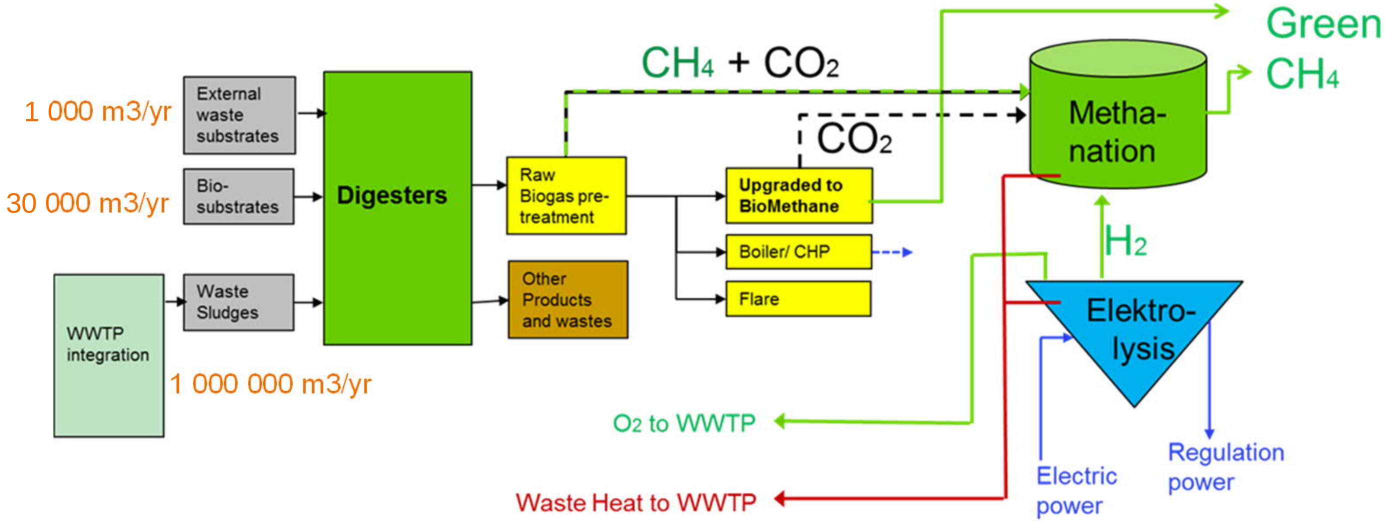


Power2Gas integration plan at example WWTP

Here, the AD biogas is upgraded to Biomethane (98%CH_4) in a **biological methanation reactor**.

- During this process, the CO_2 in the AD biogas is converted in the biological methanation to additional Biomethane using green H_2 fed from electrolysis.
- The **electrolysis can be a rSOC**:
  - provides H2 (SOEC mode) to AD biogas upgrading during cheap or surplus power hours
  - Provides valuable balancing power (SOFC mode) during expensive power hours
- Biomethane could be fed into the gas grid, used in city buses or optionally stored in BioLNG storage

Example case 800000 PE WWTP



Maximum potential

54000 + 30000 = 84000 MWh/yr

How to get cheap renewable power?

Wind power PPA long term contract and availability

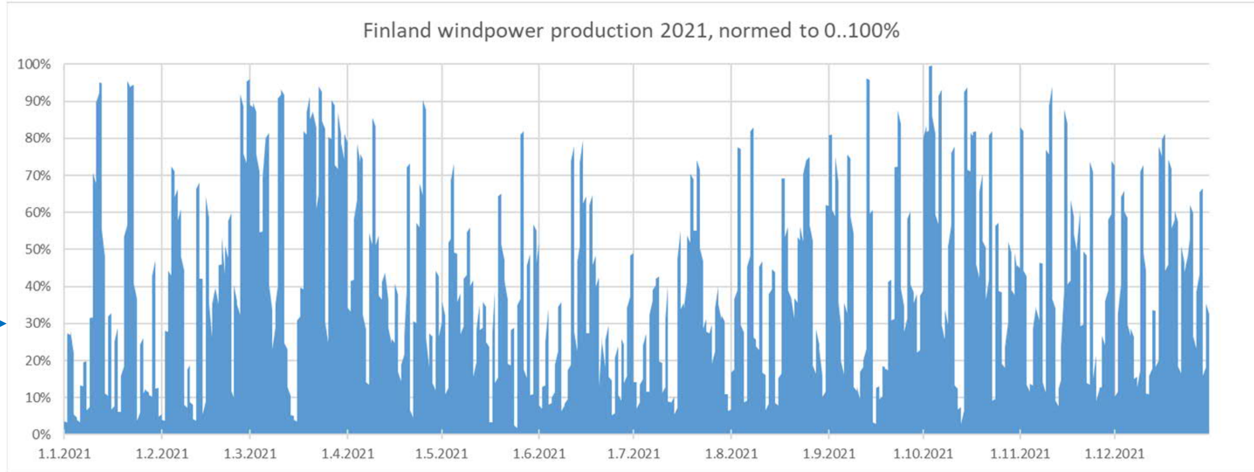
PPA and Wind power Investment

- IRENA's reported average 1192 €/kW for land-based wind power costs in 2020

  => LOCE approx 40 €/MWh

  @WACC6% and 25yr lifetime

- Power Purchase Agreement (**PPA**) for wind power is typically **Take-as-Produced**
  - *WP PPA Take-as-Produced profile used in this study*



Average WP production profile for Finland in 2021
Equivalent to 3171 FLH (36% capacity factor)
Mainly land based wind power

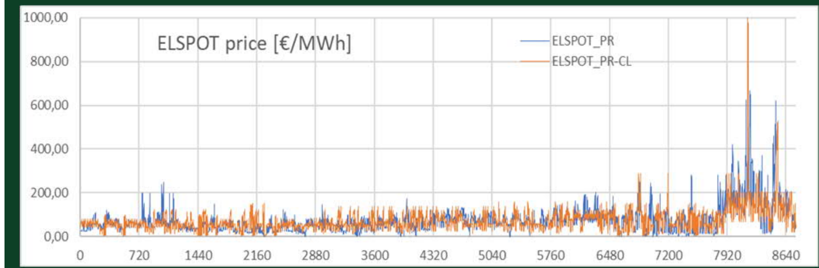
Time series from actual production normed to 0..100% with installed WP capacity at same period

Data sources: www.fingrid.fi

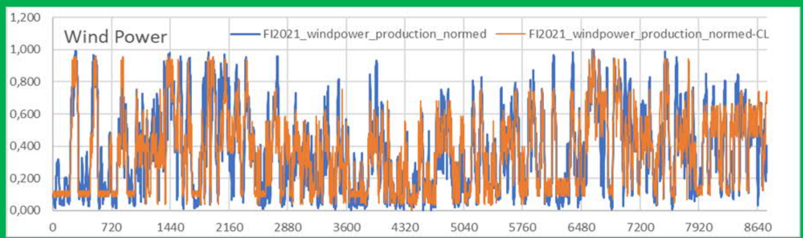
Power2Gas integration at example WWTP
Potential of Dynamic operation

Example case 800000 PE WWTP, in Finnish wind and power market conditions of 2021

Wholesales Power price (Spot)



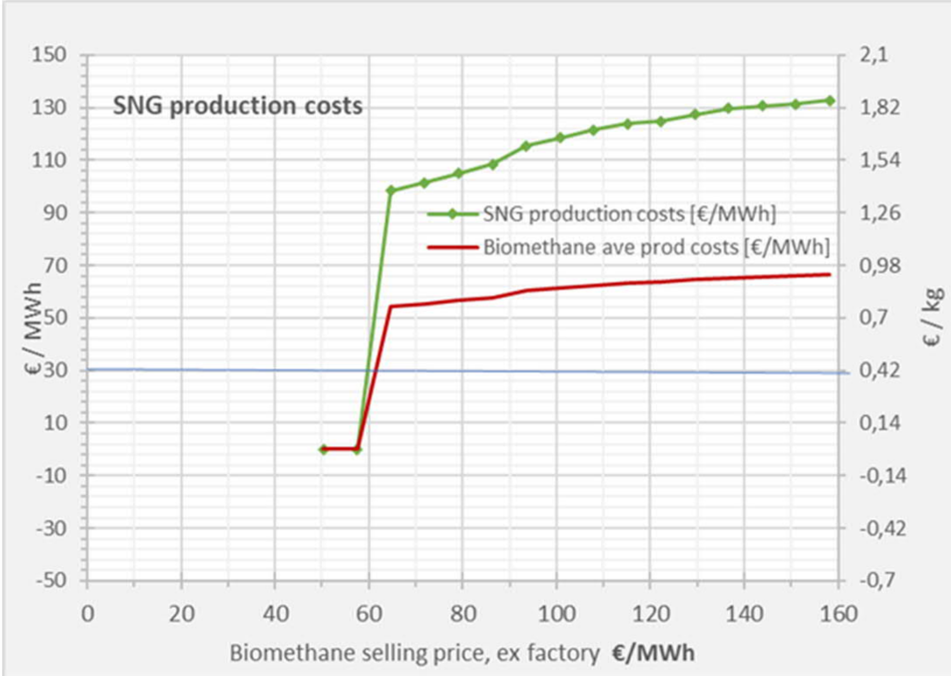
Wind power available (PPA)



Load following assumed to be used for adjusting wind power forecasting errors (to avoid balancing costs).

In 2021, green gas production would have been **profitable** for both

- Mobility (sell price 1.5-2.5 €/kg), and
- Biomethane to grid, at sell prices > **60-70EUR/MWh**



CAPEX related assumptions:
WACC 6%
Optimistic local site costs estimate

Power2Gas integration at example WWTP

Potential of Dynamic operation

SUSTAINABLE PLACES

VTT

Example case 800000 PE WWTP, in Finnish wind and power market conditions

01-12/2021

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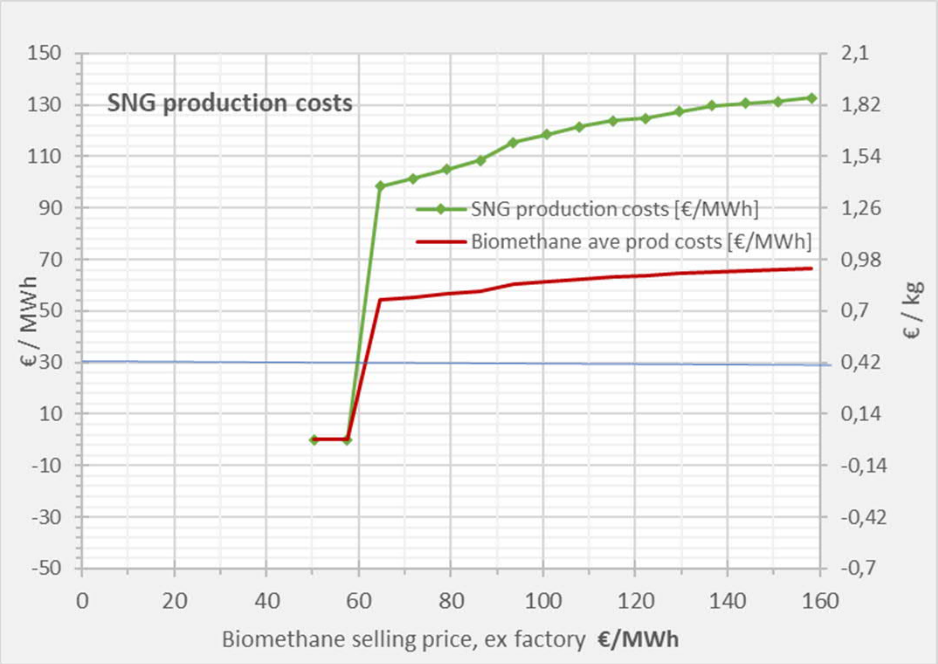
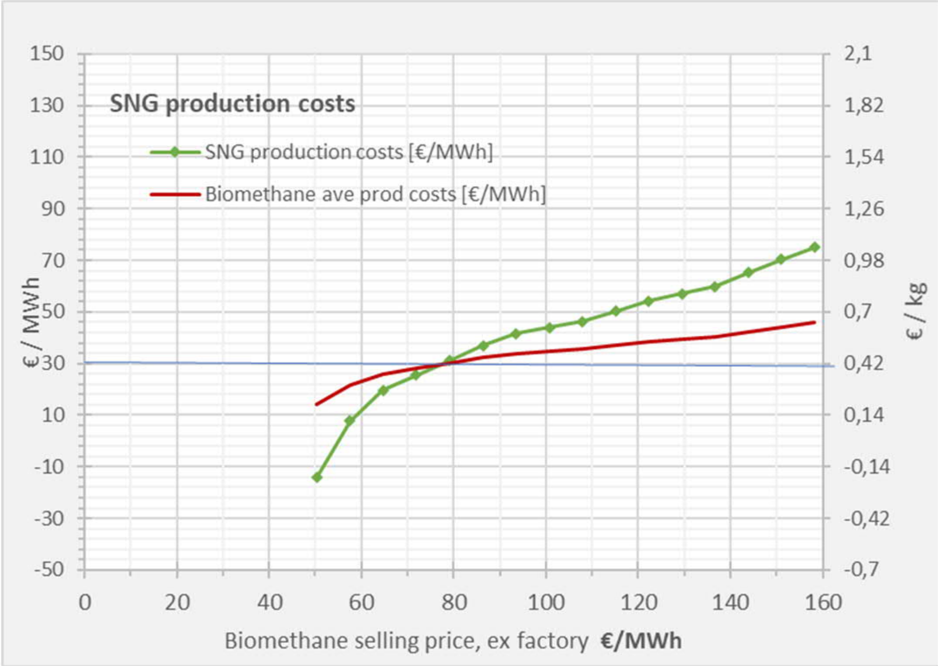


08/2021-07/2021, gas crisis year

During current gas crisis, green gas production would have been **very profitable** for

- Mobility (sell price 2.0-2.5 €/kg), and
- Biomethane to grid, at sell prices > **50EUR/MWh** (current is 225 in Germany!)



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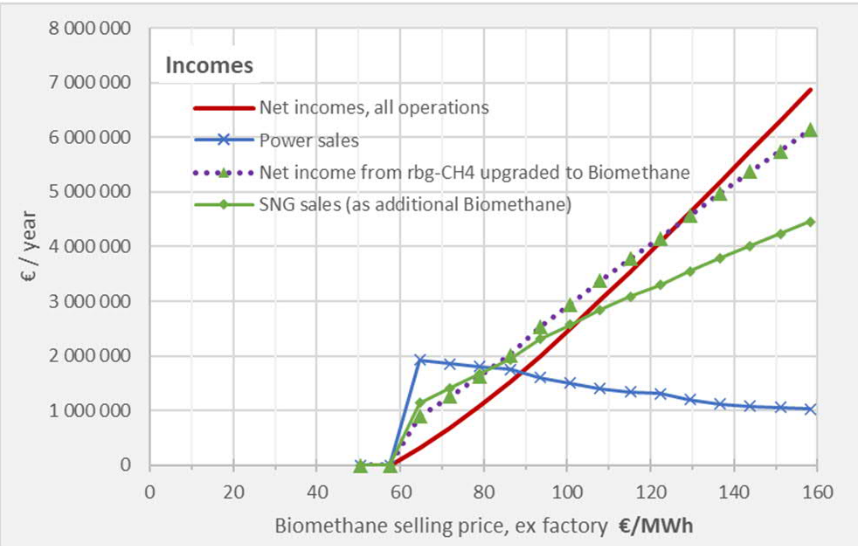

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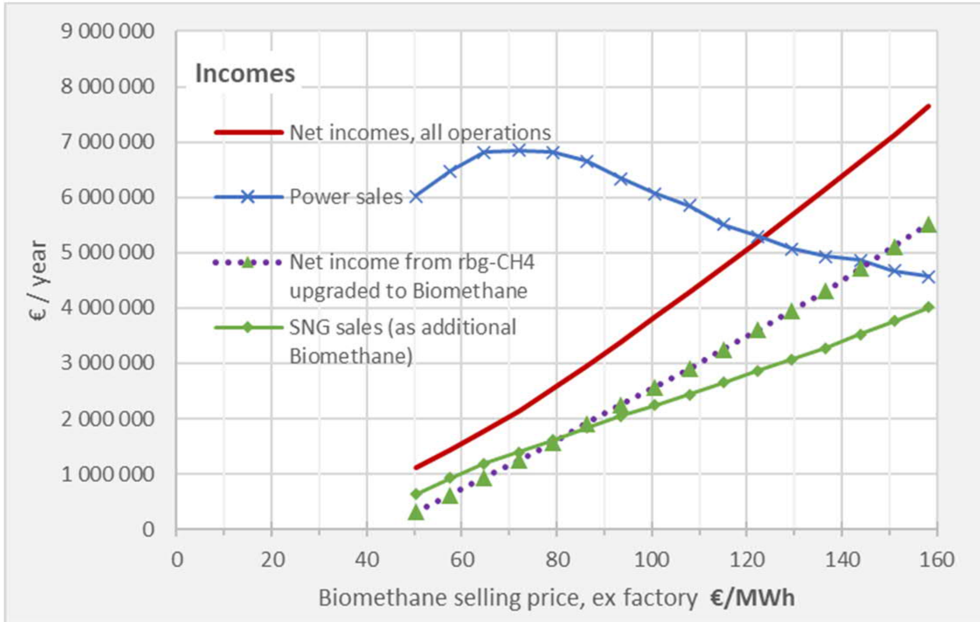

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Power2Gas integration at example WWTP
Needed capaciies

Example case 800000 PE WWTP, in Finnish wind and power market conditions

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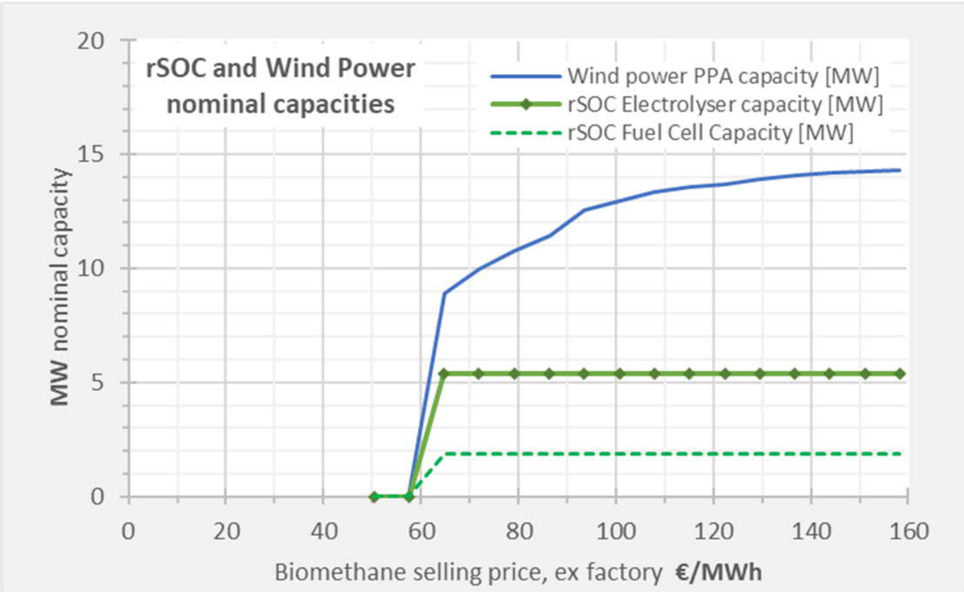

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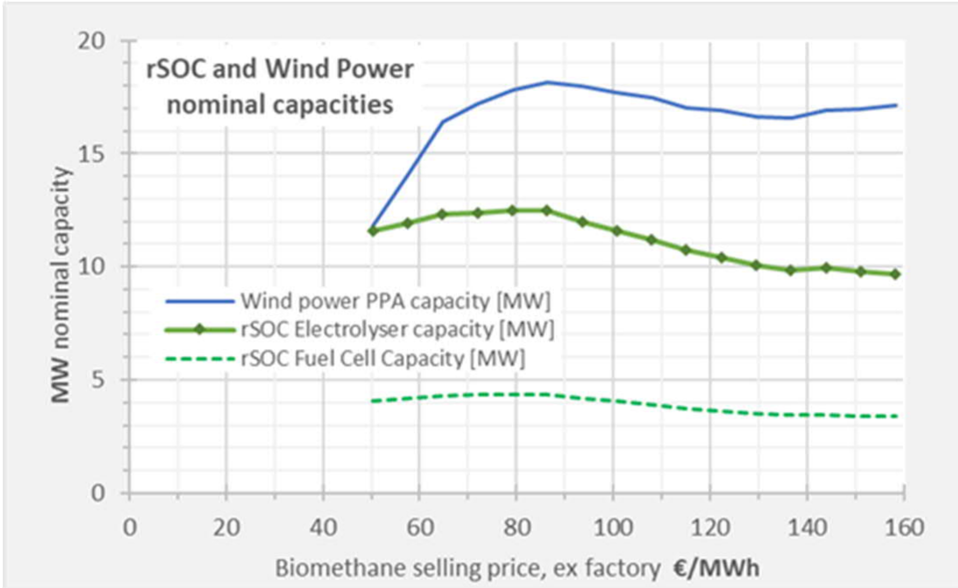

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Techno-economic evaluation conclusions

A Power-to-Gas/Gas-to-Power concept using
rSOC and **methanation** would for a city level **800 000 PE WWTP**

(1) be **very profitable** in current gas crisis market environment

(2) allow for **integration of 15-20 MW intermittent wind power** and shift the power to times when the power is really valuable and needed.

(3) Supply the **city or energy community with up to 86 GWh green gas** that can be stored and used whenever the Community needs for e.g. peak heating or mobility

(4) make the city WWTP to an energy balancing hub

Thank you for your attention. Any questions?

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