WORK PACKAGE 1 - FEASIBILITY STUDY FOR POWER-TO-X PRODUCTION ON BORNHOLM

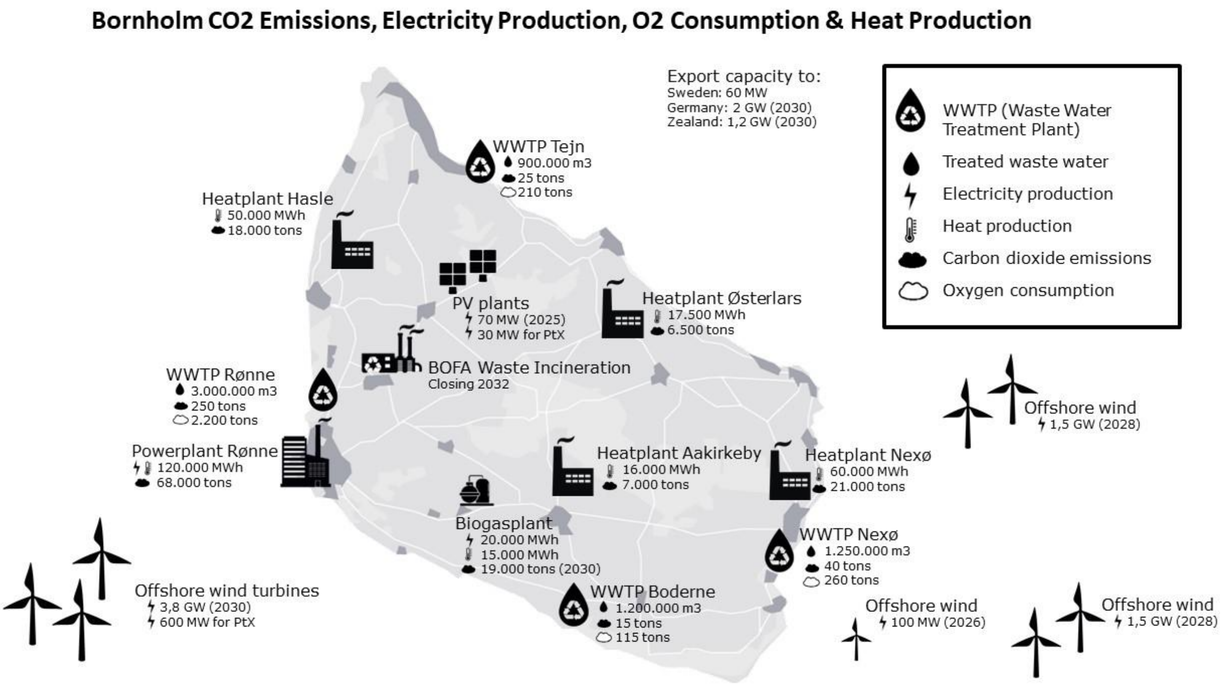
Summary

In work package 1 (WP1) the purpose is to map the local sources and quantities of the key inputs to Power-to-X production: green power, biogenic carbon (CO2) and water.

In 2030 the biggest source of green power to be used in Power-to-X-production on Bornholm is offshore wind, with a planned 6,8-6,9 GW to be installed. For water the most relevant local source on Bornholm is wastewater which has a capacity of 7 mio. m3. If the capacity of the Power-to-X plant needs more water in its production, seawater would be the only alternative on Bornholm. The most reliable source of CO2 in 2030 is from the biogas plant. With plans of increasing the biogas production, the CO2 source will increase from app 5.000 tons/year to app. 20.000 tons/year.

The available quantities for each source by 2030 are illustrated in figure 1. An estimate is given for the quantities available to Power-to-X production where it is relevant.

Figure 1: Map of Bornholm



Task 1.1 – Green power

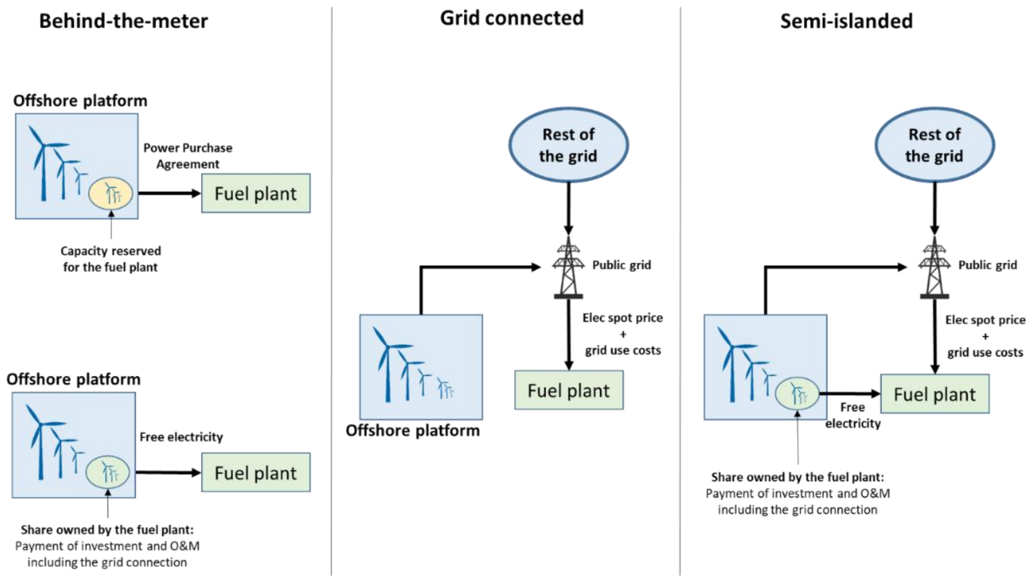
On Bornholm four sources of green power are relevant to investigate further as input in the Power-to-X production: 1) Onshore wind power, 2) solar power directly connected to the Power-to-X plant, 3) offshore wind power and 4) Green power from the grid.

Technical setup between renewable energy source and Power-to-X plant

Three types of power supply set-ups are possible:

- Behind-the-meter (or off-grid): the power-to-X plant is directly connected to the renewable energy supply. This can be done by owning a share of the renewable power assets that can be freely used or by negotiating a power purchase agreement (PPA) allowing to use a given renewable capacity at a given price.
- Grid-connected: the power-to-X plant is solely connected to the public grid. The fuel producer is then entitled to pay for the grid costs and the electricity spot price.
- Semi-islanded: this solution combines a mix of public grid electricity supply and a direct connection with owned renewable assets

Figure 1: Power supply set-up



However, solutions that are grid connected have some notable disadvantages:

- The future grid prices (both market and tariffs) are highly uncertain
- The renewable certification for fuels produced using some electricity from the grid is also uncertain

For these reasons, the different stakeholders of this project agreed to focus in priority on the behind-the-meter solution.

Onshore wind power

There is currently established a capacity of 37MW onshore wind turbines on Bornholm. In the current Energy Strategy 2040 from the municipality of Bornholm there are no plans to increase the capacity[1]. Therefore, it is decided to not include the use of power from onshore wind in the Power-to-X production in the following analysis.

[1] Energistrategi 2040 Bornholms Regionskommune.pdf (brk.dk)

Solar PV

There is currently established a capacity of 20MW PV on Bornholm. The energy system on Bornholm can sustain production from a further 50MW PV. The capacity is planned to be increased by a maximum of 50MW before 2025 in the Energy Strategy 2040 from the municipality of Bornholm[2]. Out of the 70 MW a capacity of 30-40MW is assumed could be used in Power-to-X production. The area requirement for additional PV is 1-1,2 ha/MWp[3].

Table 1: Capacity of PV

Source	Capacity
PV (2022)	20MW
Increase in capacity by 2025	50MW
PV (2025)	70MW

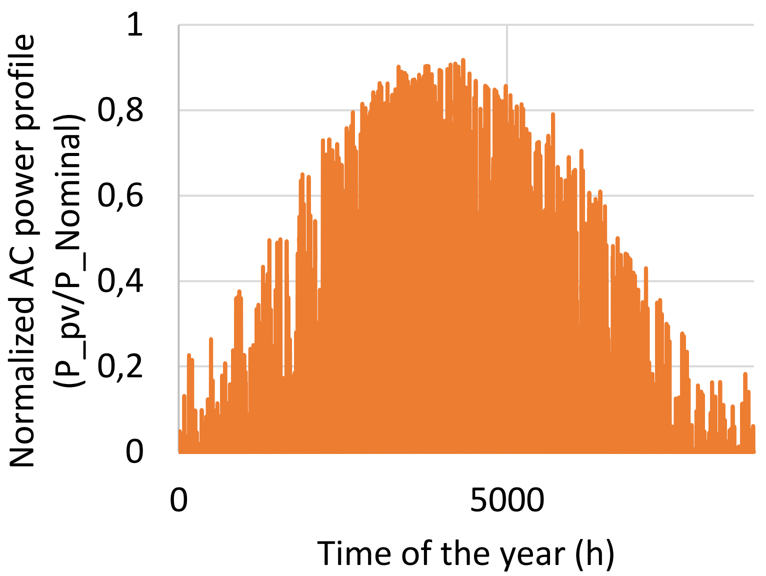
Table 2: PV Capex and Opex for 2030[4]

PV-Type	Capex (€$_{2019}$/kW)	Opex (€$_{2019}$/kW/y)	Lifetime (Years)	Annuity factor
Fixed-axis	396	7.6	40	0.0839
One-axis tracking	459	9.3	40	0.0839

The annuity factor is calculated using the Capital recovery factor formula with a discount rate of 8%.

[2] Energistrategi 2040 Bornholms Regionskommune.pdf (brk.dk)
[3] technology_data_catalogue_for_el_and_dh.pdf (ens.dk)
[4] technology_data_catalogue_for_el_and_dh.pdf (ens.dk)

Figure 2: Normalized solar profile AC for fixed-axis PV using BEOF tool (2018)



The expected annual energy production of fixed-axis solar PV is derived from a simulation tool of BEOF that has been validated against real data. The weather year simulated is 2018 and no other years are available. The tool simulates a 20 MW fixed-axis PV plant assuming and include system losses. An additional loss of 5 % is further added to consider the conversion losses DC/AC.

As the simulation tool does not handle tracking systems, the power profile for the 1-axis azimuth tracking system is taken from renewable.ninja. In the simulation, the DC/AC conversion and system losses are assumed at 10%. The solar panels have a tilt of 38° and an azimuth of 180° (following the optimal tilt and azimuth angles from Global Solar Atlas).

Table 3: PV LCOE and capacity factor in Bornholm using costs projection for 2030 and 2018 weather profile.

PV-Type	Capacity factor (%)	LCOE (€$_{2019}$/MWh)
Fixed-axis	13.9 %	33.6
One-axis tracking	18.3 %	29.9

The discount rate used is 8%.

Offshore wind power

There are plans to establish a capacity of 6-6,8GW offshore wind close to Bornholm before 2030. The Energy Island Bornholm is currently planned to be established in 2030 and will have a capacity of 3GW. The overall capacity can increase to 3,8GW if overplanting is allowed. The power produced at the offshore wind farm will be directed inland to a transformer station being built south of Aakirkeby on Bornholm[5]. In 2022 Copenhagen Infrastructure Partners (CIP) announced a partnership with Ørsted to establish two projects under the open-door scheme in Denmark called "Bornholm Bassin Syd" (1,5GW) and "Bornholm Bassin Øst" (1,5GW). Both projects are planned to be established before 2028 if possible[6]. In the current Energy Strategy from the municipality of Bornholm it is also set as a goal to support the establishment of 100MW offshore wind[7]. It is assumed that 30MW could be used in Power-to-X production.

The Danish TSO Energinet and German TSO 50Hertz is currently planning an export capacity of 1,2GW to Zealand and 2GW export capacity to Germany[8]. This means that if everything is exported a minimum of 600MW could be used for local Power-to-X production. It is still unknown if it will be possible to increase the overall capacity of the Energy Island and the export capacities. The current export capacity for the seacable connecting Bornholm and Sweden is 60MW.

Table 4: Export capacities from Bornholm

Export from Bornholm	Capacity
Sweden (2022)	60MW
Zealand (2030)	1,2GW
Germany (2030)	2GW

Table 5: Capacity of offshore wind

Source	Capacity
Bornholm	100MW
Energy Island Bornholm	3-3,8GW
CIP	3GW

Four types of offshore wind turbines with different hub-height and specific power are considered for this study. The naming scheme for each turbine is as follows, the first part represents the specific power (i.e. SP198 indicates a specific power of 198 W/m2), and the second part of the name is the hub height (i.e. HH100 indicates a hub height of 100m). Each power generation technology is characterized by its cost and the associated hourly power generation profile around.

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[5] Invitation to market dialogue regarding Energy Island Bornholm offshore wind farm and other future wind farms | Energistyrelsen (ens.dk)
[6] Ørsted and Copenhagen Infrastructure Partners join forces to develop approx. 5.2 gigawatts of offshore wind in Denmark - Copenhagen Infrastructure Partners (cipartners.dk)
[7] Energistrategi 2040 Bornholms Regionskommune.pdf (brk.dk)
[8] Aftaletekst tillægsaftale Energiø Bornholm.pdf (kefm.dk)

Table 6: Type of turbines, Capex and Opex considered for an offshore wind park in 2030

Name	Power (MW)	Hub Height (m)	Rotor Dia. (m)	Capex (€$_{2019}$/kW)	Fixed O&M (€$_{2019}$/kW/y)	Var. O&M (€$_{2019}$/MWh)	Lifetime (Years)	Annuity factor
SP379-HH100	8	100	164	1998	37.6	2.8	30	0.0888
SP379-HH150	8	150	164	2297	37.6	2.8	30	0.0888
SP450-HH100	9.5	100	164	1801	37.6	2.8	30	0.0888
SP450-HH150	9.5	150	164	2053	37.6	2.8	30	0.0888

The annuity factor is calculated using the Capital recovery factor formula with a discount rate of 8%.

Table 7: LCOE and capacity factors of offshore wind power production around Bornholm

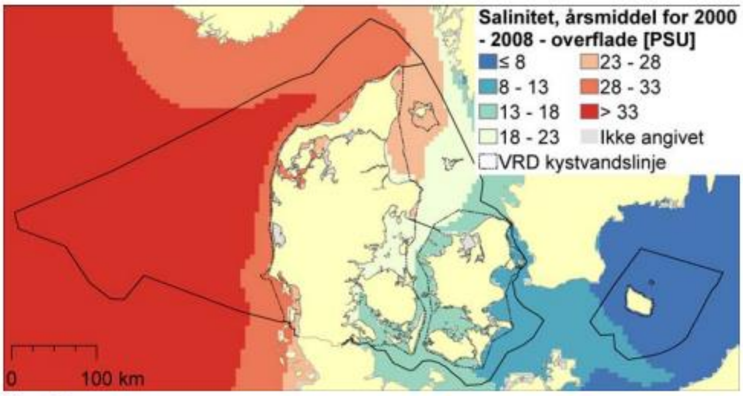
Turbine	Capacity factor (%)	LCOE (€/MWh)
SP379-HH100	44.7 %	57.7
SP379-HH150	49.7 %	58.6
SP450-HH100	41.5 %	57.1
SP450-HH150	46.6 %	56.7

Power from the grid

As discussed previously, using the grid leads to significant uncertainties regarding the renewable fuel certification and the future prices. For these reasons the behind-the-meter set-up will be investigated in priority within this project.

Task 1.2 – Water

In this task the potential of using the following sources of water in Power-to-X production will be investigated: 1) Drinking water, 2) purified wastewater, 3) stormwater, 4) low-quality drinking water and 5) seawater. The analysis will focus on available quantities and expected prices of the different sources.



Kort 6

Salinitet i overfladevandet, gennemsnit af årsmidlerne for 2000-2008. Afgrænsningen af de danske farvande fremgår af den fuldt optrukne linje (Exclusive Economic Zone, EEZ), mens den stiplede linje markerer afgrænsningen af de danske kystvande som defineret i Vandrammedirektivet. Desuden er angivet grænserne mellem de tre farvandsområder Nordsøen/Skagerrak, Kattegat/nordlige Øresund og Bælthavet/Østersøen. Kilde DHI

Note: Ovenstående figur er fra: ÅU - Dansk center for miljø og energi – Havstrateginotat 1.1 aug. 2012

Table 8: Quantities of water available for use in Power-to-X production

Source	Quantity (BEOFs estimate)	Conversion rate to demineralized water (electrolyser quality)	Salinity o/oo	Conductivity µS/cm
Drinking water	< 100.000 m3/year	80-90 %	0,3-0,4	500-600
Low-quality drinking water	< 1 mio. m3/year	80-90 %	0,3-0,4	500-600
Storm water / rain water *	> 1 mio. m3/year	80-90 %	0 – 0.02	
Wastewater	7 mio. m3/year	80-90 %	2	1000
Surface water Baltic Sea**	infinite	80-90 %	7-8	1000 -2000
Surface water North sea	infinite		28-35	

*An assessment of the quality and use of rainwater as the basis for sustainable water management in suburban areas. E3S Web of Conferences 45, 00111 (2018)

** Basisanalyse I for vanddistrikt Bornholm, BRK, Natur & Miljø, Nov. 2004

Table 9 CAPEX and OPEX for water

	Unit	Seawater Bornholm Bassin	Ground water	Surface water	Wastewater effluent	Comment
Capacity (produced water)	m3/h	25	25	25	25	The systems are modular and includes rendudancy for critical components. This scale corresponds to a scale of ca. 140 MW H2 production. Extrapolations to larger scales should be done with different scaling factors in mind. Source: Ramboll assumption
Raw water quality	µS/cm	8000-9300	300-600	1000-3000	200-6000	Source: Seawater: Lehmann et al. 2022; Drinking water: https://mitdrikkevand.-dkindex.php?ID=-4&graphtype=analysis&wp-ID=30&analysisID=12; Wastewater effluent: Esbjerg Vest Renseanlæg 2020-21
Raw water quality		includes particles, organics and high amount of salts	includes minerals and traces of dissolved organics	includes particles, organics and average amount of salts	includes organics, low amount of salts and particles	
Product quality	µS/cm	<0,1	<0,1	<0,1	<0,1	
Recovery	%	40-50	70-75	40-50	70-75	Note: if recovery is 80%, 20 % goes to wastewater (brine) Source: Ramboll estimates og S.G. Simoes et al. 2021

CAPEX						
Main equipment		1) Feed water tank (not included) 2) Feedwater pumps 3) Sandfilter 4) tank 5) Pumps 6) High pressure pumps 7) Double pass SWRO (with energy recovery) 8) tank 9) Pumps 10) Degassing unit and electrode-ionization (EDI) 11) CIP facilities 12) Power + Controlling	1) Feed water tank (not included) 2) Feedwater pumps 3) Sandfilter 4) tank 5) Pressure pumps 6) Groundwater RO (with energy recovery) 7) tank 8) Pumps 9) Degassing unit and electrode-ionization (EDI) 10) CIP facilities 11) Power + Controlling 12) Product storage tank (not included)	1) Feed water tank (not included) 2) Feedwater pumps 3) Sandfilter 4) tank 5) Pumps 6) Pressure pumps 7) BWRO (with energy recovery) 8) tank 9) Pumps 10) Degassing unit and electrode-ionization (EDI) 11) CIP facilities 12) Power + Controlling	1) Feed water tank (not included) 2) Feedwater pumps 3) Sandfilter 4) tank 5) Pumps 6) UF 7) tank 8) Pressure pumps 9) BWRO (with energy recovery) 10) tank 11) Pumps 12) Degassing unit and electrode-ionization (EDI) 13) CIP facilities	For drinking water and brackish water: softening step of rawwater may be included (removal of $CaCO_3$) for protection of RO membranes

		13) Product storage tank (not included) 14) Handling and discharge of wastewater (not included) 15) Intake beach well and piping (not included)	13) Handling and discharge of wastewater (not included) 14) Groundwater well and piping (not included)	13) Product storage tank (not included) 14) Handling and discharge of wastewater (not included) 15) Intake piping (not included)	14) Power + Controlling 15) Product storage tank (not included) 16) Handling and discharge of wastewater (not included) 17) Intake piping (not included)	
Container size	ft	2 x 40	1 x 40	2 x 40	2 x 40	Expected size in container solution. Too compact systems shall be avoided
Price including container	Euro	2.013.024 - 3.757.645	1.207.815 – 2.415.629	1.744.621 – 3.220.839	1.476.217 – 2.818.234	Ramboll calculation based on market prices 2021-2022 in DKK. Exchange rate (DKK/EUR): 0,1344
Exp. Lifetime	Years (max)	25	25	25	25	Source: 2818234
OPEX						
Manpower	h/d	1	1	1	1	
Maintenance	Euro/y	101.993 – 190.566	60.391 – 120.781	87.231 – 161.041	75.153 - 139.570	5% of CAPEX. Exchange rate (DKK/EUR): 0,1344 Source: Ramboll recommendation
Electricity						

RO + pretreatment	KWh(e)/m3	2,5-6,5	0,5-1,5	2,5-6,5	1,6-3,6	
EDI	KWh(e)/m3	0,5-1,5	0,5-1,5	0,5-1,5	0,5-1,5	
Total	KWh(e)/m3	**3-8**	**1-3**	**3-8**	**2,1-5,1**	Source: S.G. Simoes et al. 2021 Electricity for other process equipment than mentioned above not included
Heat		Process operates at approx. 15 celc. and depending on rawwater temperature heat is required	Process operates at approx. 15 celc. and depending on rawwater temperature heat is required	Process operates at approx. 15 celc. and depending on rawwater temperature heat is required		

Table 10: Prices of raw water for Power-to-X production

Source	price directly from source *
Drinking water	0,92 euro/m3 (BEOFs price)**
Low-quality drinking water	0,13 - 0,27 euro/m3 (app.)
Storm water	0 euro/m3
Effluent Wastewater	0 – 0,13 euro/m3 (app.)
Seawater (Baltic Sea)	0 euro/m3

*These prices are directly from source, without expenses for constructions/pipes/pumping etc. Exchange rate (DKK/EURO): 0,1344

** For consumption above 10.000 m3. BEOFs price is 0,40 euro/m3

1. **Drinking water:** The drinking water resources are very small on Bornholm – the total production is about 3 mio. m3/year – and the total resources are likely about 5 mio. m3/year. So, it is unlikely that the municipality will allow a reservation of good drinking water resources for P2X-production. At the P2X facilities, there has to be a drinking water supply for the employees, and this may also be at the water supply for electrolysis on short term, as a contingency. New wells for extracting ground water for electrolysis might be possible to establish near the cost, where production will not affect existing drinking water extraction or the flow-rate of the streams in the area.
2. **Low-quality drinking wate**r: Some of the wells on Bornholm is not used for drinking water production because the quality is too poor. In the vicinity of the energy island transformer area is pt. 3 wells that are not used for drinking water, primarily because of low quality. The most yielding well, DGUnr. 247.435, was formerly supplying raw water to Smålyngsværket, the largest waterwork on Bornholm. However, pollution with pesticides has done, that about 100.000 m3/year is pumped into the nearest stream to avoid the pollution to spread in the reservoir. Water from these wells may be used for electrolysis.
3. **Storm-water,** or surface water, may be collected in reservoirs, primarily in the winter season, but this will demand construction of huge and expensive reservoirs, eg. 1m x 500m x 500m for containing 0,25 mio. m3. Space requirements, construction cost, and availability of storm-water seems to rule out this source, though the low salinity is an advantage.
4. **Waste water**, outlet from WWTPs: The location of thew six major WWTPs on Bornholm and the yearly outflow is marked on the map. The largest source is Rønne WWTP, with about 3 mio. m3/year. The distinct seasonal variation of outflow is shown in table 11 below. The future structure of the WWTPs on Bornholm is currently reviewed, and one scenario is to replace the existings plants with one new large plant located in Boderne, near the Energy Island Transformers.

Table 11: Wastewater quantities

	Wastewater: Quantity - Seasonal (1000 m3/month) - 2021											
Source WWTP:	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Rønne	312	255	287	218	213	154	160	181	190	185	308	431
Nexø	145	122	124	87	84	43	64	67	75	77	158	200
Boderne	163	123	138	76	80	34	53	63	53	52	143	201
Tejn	114	68	87	50	57	31	54	45	35	47	76	137
Svaneke	80	54	62	40	48	19	29	27	31	38	63	95
Melsted	23	13	17	9	13	5	12	11	8	9	15	25
SUM	**814**	**635**	**715**	**480**	**495**	**286**	**372**	**394**	**392**	**408**	**763**	**1089**

Expences for upgrading raw water to electrolyzer quality

The Capex and Opex for upgrading different sources of raw water is shown in table 9. Outlet water from WWTPs is assumed to have a quality between drinking water and brakish water, and expenses for treatment much like brakish water, or slightly less.

Expenses for treating the brine is not included in the calculations, and different fractions may require different treatment, and have to be calculated in the specific case. If the recovery rate is 80% of the outlet flow, the content of salts and organic micropollutants in the outlet from WWTPs will be concentrated five times, and this excludes a direct outlet of the brine to the sea – the concentrations will exceed what is allowed. For Rønne WWTP this implies in average:

Table 12: Rønne WWTP

Outlet Rønne WWTP 2021	Average konc. in outlet	Average konc. In brine	Required removeal kg/year*	Saved outlet taxes euro/year**
Tot-N	4,5 mg/l	23 mg/l	1,158	44.769
Tot-P	0,5 mg/l	2,5 mg/l	10,551	27.157
BI5	0,36 mg/l	1,8 mg/l	69,492	9.814

Note: *Assuming that 20% of the inlet flow is left in outlet with the normal concentrations (2021). ** 4,26 euro/kg N. 23,40 euro/kg P. 2,34 euro/ kg BI5 - Exchange rate (DKK/EURO): 0,1344

The saved taxes sum up to app. 0,027 euro/m3, and of course the removal of 80% of organic matter and nutrients will be a great benefit for the environment/recipient (Baltic Sea)

Conclusions: It is an advantage, when considering GW-electrolyzer capacity, that the sea around Bornholm can be used as a nearby water source for electrolysis, and that the salinity is only 7-8 o/oo.

Among the different freshwater sources, the outlet from WWTPs constitutes a significant amount, but has a characteristic seasonal variation. Utilizing this source will have a positive environmental impact in form of reduced nutrient outlet to the sea. The different locations of WWTPs can be utilized if decentral P2X in smaller scale is considered.

Task 1.3 – Biogenic carbon (CO2)

In this task the availability of CO2 on Bornholm will be analysed. Both the baseline for CO2 availability on Bornholm and the possibility to increase the production of biogas will be investigated. Further the impact of new biomass fractions in the integrated energy system of the island is assessed. Lastly the possibility for methanization, from CO2 that is a by-product of purification, and H2 from the Powe-to-X plant.

The sources of biogenic CO2 on Bornholm are as follows:

1. The Biogasplant, Bornholms Bioenergi, owned by Bigadan A/S
2. The four heatplants owned by BEOF (Bornholms Varme A/S)
3. The CHP (Central Heat and Powerplant) on Rønne Harbor
4. The WWTP's (Waste Water Treatment Plants) on Bornholm

In table 13 the potential and utilized biomass is shown.

Table 13: Biomass

Biomass	Potential [tonnes/year]	Elsewhere utilized [tonnes/year]
Liquid manure	547.530	Fertilizer
Deep litter	29.700	Fertilizer
Sludge (dry matter)	2.400	Fertilizer
Seaweed (15% sand)	3.000	0
Wood chips	50.000	50.000
Landscaping	2.195	
Straw	88.480	44.000
Secondary crops	4.450	0
KOD	2.350	BOFA*
Wood waste	4.550	BOFA*
Garden waste	8.920	BOFA*
Total	743.575	
Note: *Biomass source is utilized by BOFA		

1. CO2 from the local

Biogas production (location: Rønnevej 48, 3720 Aakirkeby).
Today CO_2 is not separated form methane, and the biogas is burned in two generators, producing 3 MW electricity and a little more heat, where the surplus is sold to BEOF fore District Heating. Bigadan is currently planning to increase the production with a factor 3-4, by increasing the amount of manure supplied to the plant, but primarily by using large amounts of straw from the fields on Bornholm as biogenic carbon source.
The yearly CO_2-production af Bornholms Bioenergi is 2,5 – 3 mio. M3/year. The production is relatively stable.

Table 14: Quantities of CO_2 from biogas available for use in Power-to-X production

Source: Biogas	Quantity
Baseline in 2022	2,5-3 mio. m3/year = 4,700 - 5,600 tons/year *
Production in 2030	10 mio. m3/year = app. 19.000 tons/year **

** Source: Bigadan. As conversion from m3 to tons is used 1,87 kg/m3 (15 oC, 1 atm.) ** The quantities in 2030 is not yet known with certainty.*

2. The four heatplants owned by BEOF (Bornholms Varme A/S)

Table 15: Quantities CO_2 from Heat Plants available for use in Power-to-X production

Source: Heatplants	Quantity 2022
Nexø Heat Plant	21.000 tons/Year
Hasle Heat Plant (woodchips)	18.000 tons/year
Aakirkeby Heat Plant (woodchips)	7.000 tons/year
Østerlars Heat Plant (straw)	6.500 tons/year
SUM	App. 50.000 tons/year

The CO_2 production from the heat plants has a clear seasonal pattern because most heat is produced during winter. The heat plants are also scattered on the island (see map)

Table 16: CO_2 quantities

	Quantity - Seasonal (tons CO2/month) 2022											
Source	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Nexø	2800	2750	2500	2100	1350	750	650	800	1050	1600	2000	2850
Hasle	3200	2550	2400	2100	1050	50	200	200	950	1450	2250	2950
Aakirke.	900	800	850	900	550	150	0	0	20	650	950	1400
Østerlars	850	800	800	650	450	200	200	250	300	450	650	900

SUM	**7750**	**6900**	**6550**	**5750**	**3400**	**1150**	**1050**	**1250**	**2320**	**4150**	**5850**	**8100**

The quantity of CO2 from the heat plants is expected to decline, because it is one of the goals in the municipal energy strategy, to reduce the amount of biomass used in the heat and power plants – a plan for this has to be developed by 2025. Biomass for district heating production can be substituted by waste heat, or heat generated on electricity in heat pumps and electrical boilers.

3. The CHP at Rønne Harbor had an annual CO2 production of app. 68.000 tons in 2021 – a little more than the sum of heat plants. Production is primary coupled to the heat demand in Rønne, and it is shut down enterily for 6-8 weeks during summer. Thus, the quantities is quite low in the summer. Furthermore, waste heat from the Energy Island transformers and from eventual P2X production will reduce the available CO2 from Heat and Power plants to such a degree, that this is most likely not a reliable source in 2030.

4. WWTP's: The sum of CO2 emmisions is very low, less than 500 tons per year (see map) - so this source is too small.

Conclusions: In 2030 the most reliable and continous source of biogenic CO2 is from the biogas plant – Bigadan's plans of increasing the biogas production, and separate the CO2 from the methane, will increase this CO2 source from app 5.000 tons/year to app. 20.000 tons/year if the plans are succesful. The price of this CO2 is not known and must be negotiated, but hence it is a bi-product and easy accesed the price must be assumed to be low. The CO2 can easily be transported in tubes to the transformer area of the Energy island Bornholm, which is just 3 km south of the Biogas Plant.