KTH ROYAL INSTITUTE OF TECHNOLOGY

Biogas production potential in the Nordic countries and its impact on land, water, energy and climate systems

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Nordic energy WP1: Final seminar 18 February 2022

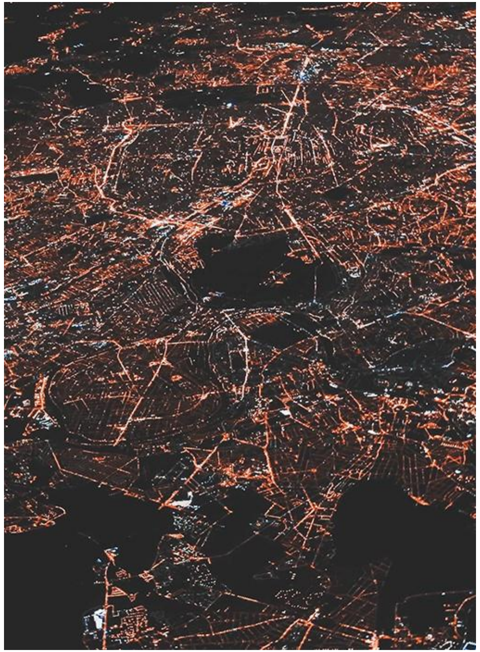
KTH – division of Energy Systems

https://www.energy.kth.se/energy-systems

Our research is based on a **broad system perspective,** where energy technology, innovation, and policy are linked to **sustainable development.**

We carry out **qualitative and qualitative analyses regarding the impact of policies on the transition to a sustainable society.**

Also, synergies and trade-offs between the 169 Targets of the 2030 Agenda's **17 Sustainable Development Goals** are carefully analyzed.



Research Areas – Division of Energy Systems

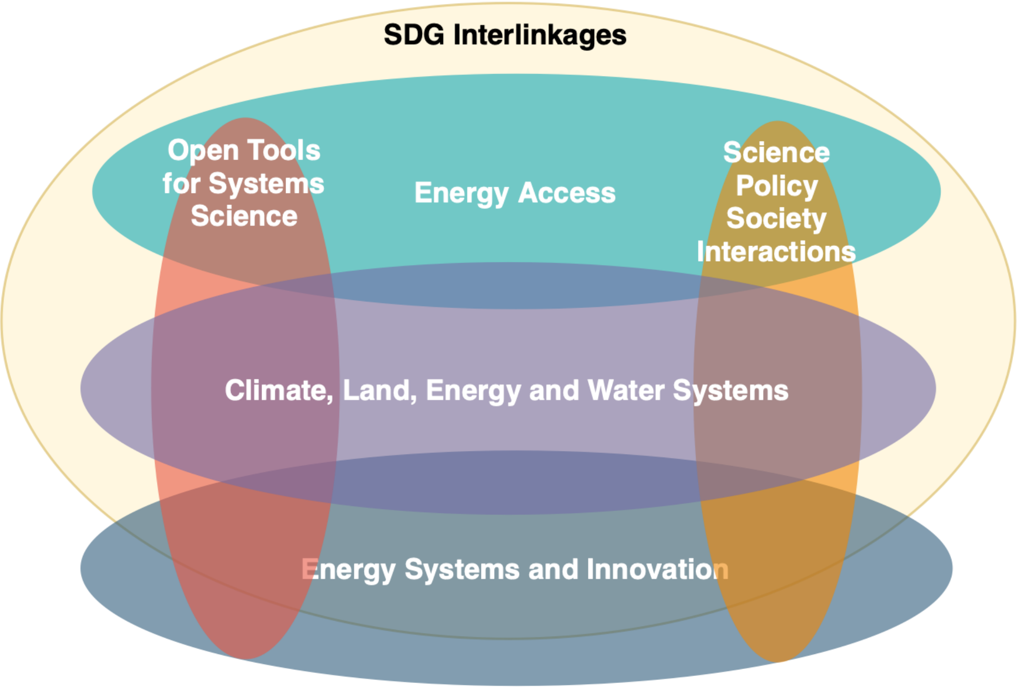
KTH VETENSKAP OCH KONST

OSeMOSYS
Open Source Energy Modelling System

OnSSET
Open Source Spatial Electrification Tool

BeWhere

Climate
Land
Water
Energy



SUSTAINABLE DEVELOPMENT GOALS

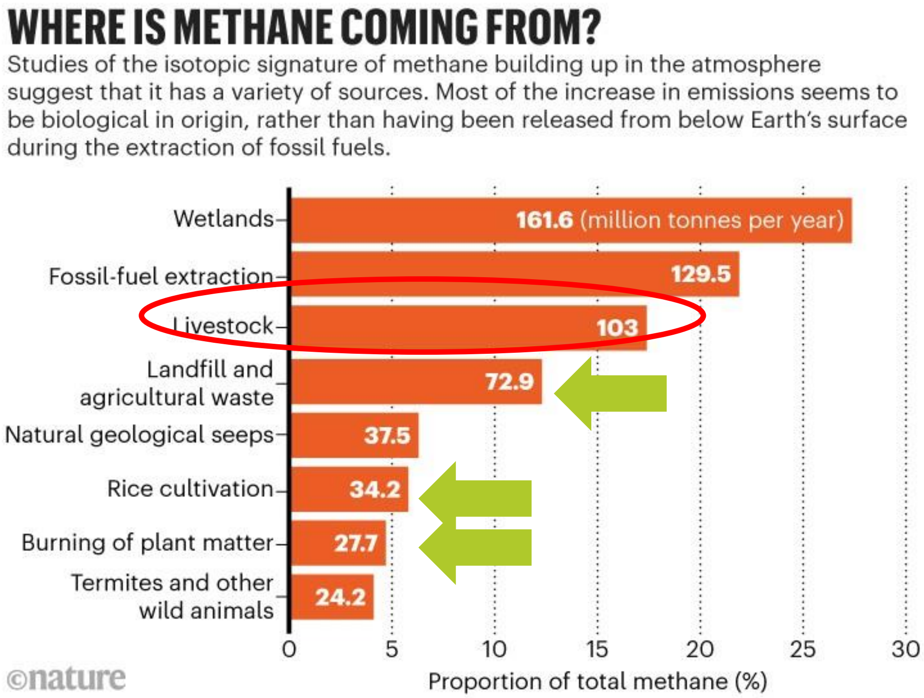
7 AFFORDABLE AND CLEAN ENERGY

Project Objectives and Research Questions

- The main objective of this study is to explore the biogas production from the agriculture sector (agricultural residues and livestock manure) and identify the nexus with water-land-food-climate-energy systems.

- Key Research Questions:
  - What is the production potential of biogas from agriculture residues and livestock manure in the Nordic Countries?
  - What are the sustainability aspects (emissions, water use, and fossil/mineral consumption) in the production of biogas?
  - How can biogas systems be integrated into the existing energy systems model and its role in net-zero and/or 100% renewable energy (develop scenario for biogas in the region by 2050)?
  - How biogas from agriculture sector can be promoted in an integrated climate-land-energy-water nexus approach, while maintaining the ecosystems services
  - What is the role of production and use in the National Energy and Climate Plans (NECPs)

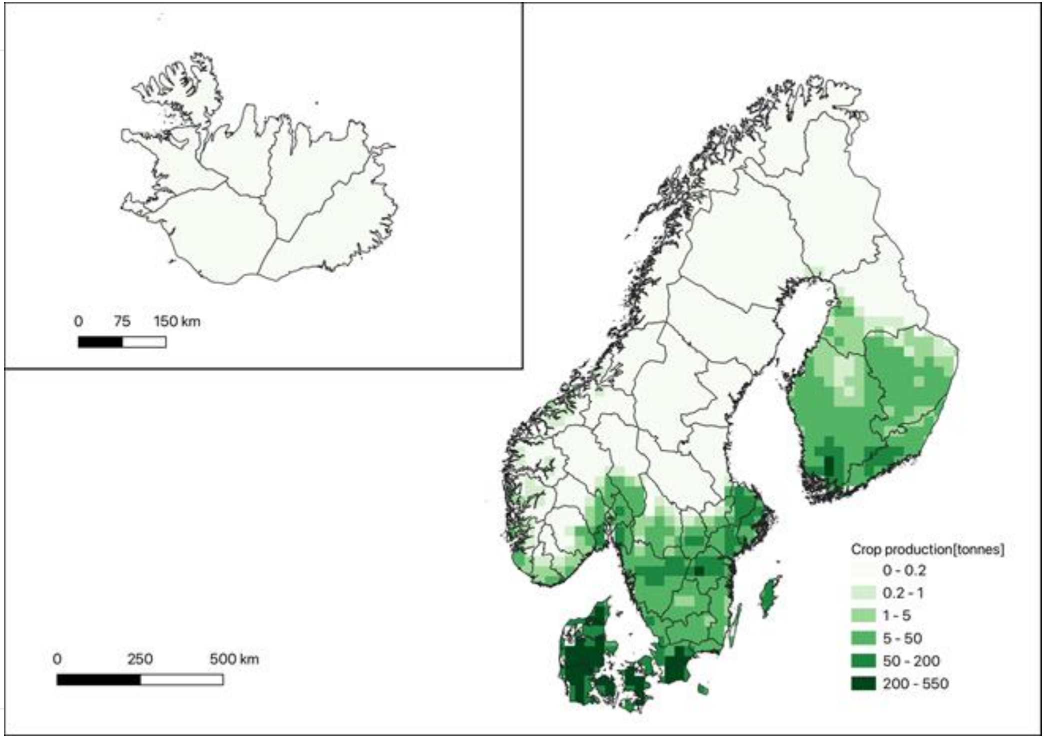
Research Contexts



- Global methane concentrations is increasing (over 1,900 parts per billion)
- At COP26 in Glasgow, over 80 countries signed the Global Methane Pledge to cut emissions by 30% from 2020 levels by 2030, including US and EU.

Tollefson, 2022

Research Contexts and Approach– Livestock and crop production in the Nordics



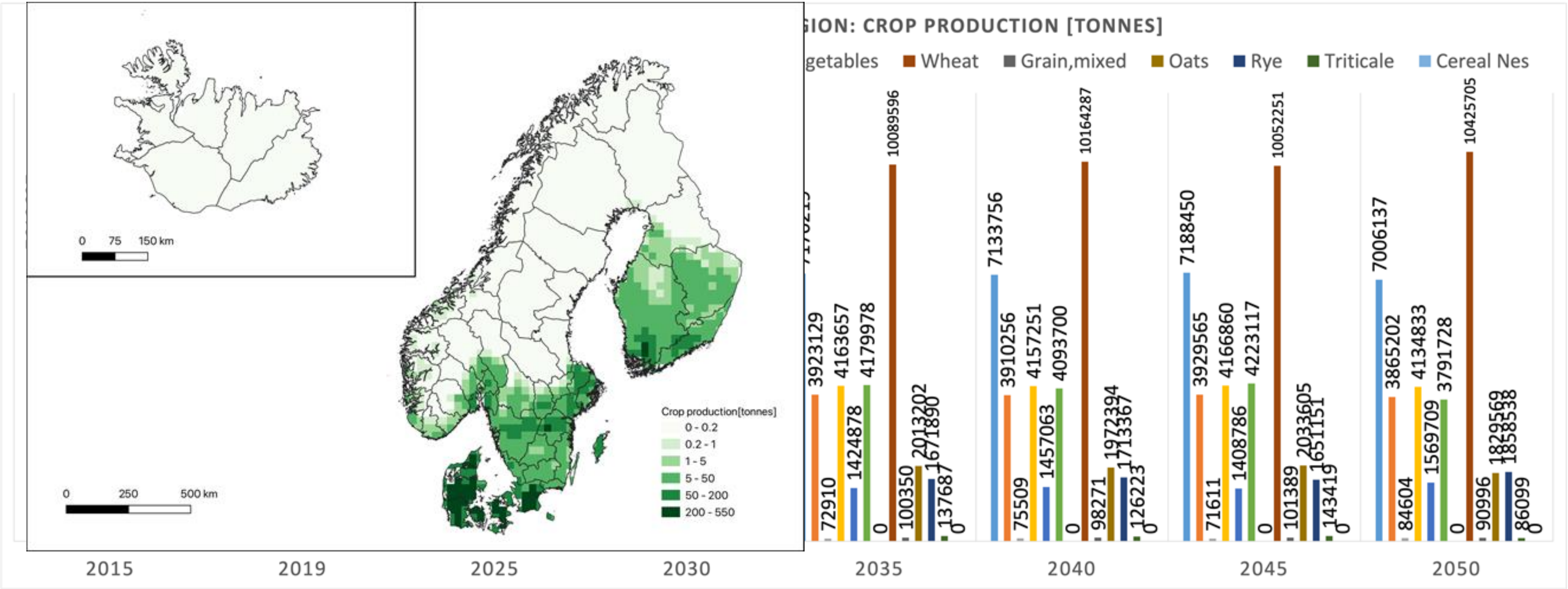
- Cattle, chickens, ducks, horses, goats, pigs, and sheep
  - Chicken represents the largest number of livestock (52% of the total livestock)
- The majority of the livestock concentrates in the southern Sweden and Denmark
- Major crops: wheat, barley, maize, potato & sweet potato, rapeseed, sugar beet, and “other cereals” (includes cereal, rye, oats, triticale, and grain mix)

Research Approach: Spatial Mapping of Feedstock for Biogas Production

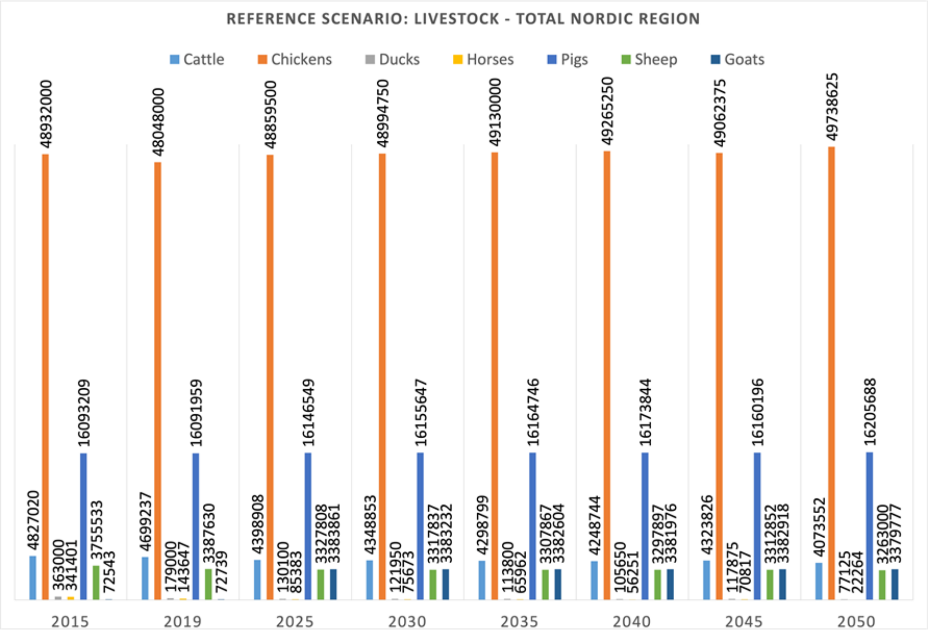
- QGIS to reproject data in the Nordic Countries
- 30 km x 30 km grid size
- Total of 1770 grids
- Data from FAO database on livestock distribution 2010 and agricultural crops 2015
- Projection of Feedstock Production in Different Scenarios (Validation with FAO dataset)
  - Gather data from the FAO datasets for **each crop** for the years: **2000, 2005, 2010, 2015 and 2019**.
  - Calculate the **average annual growth or decline for a 5 years' time span** (2000-2005; 2005-2010; 2010-2015 and 2015-2019).
  - Calculate the average **annual growth/decline 2000-2019** by averaging all the previous annual averages.
  - Assume that the same **annual growth/decline 2000-2019** for a 5 years' time span from **2020 to 2050** for each crop.

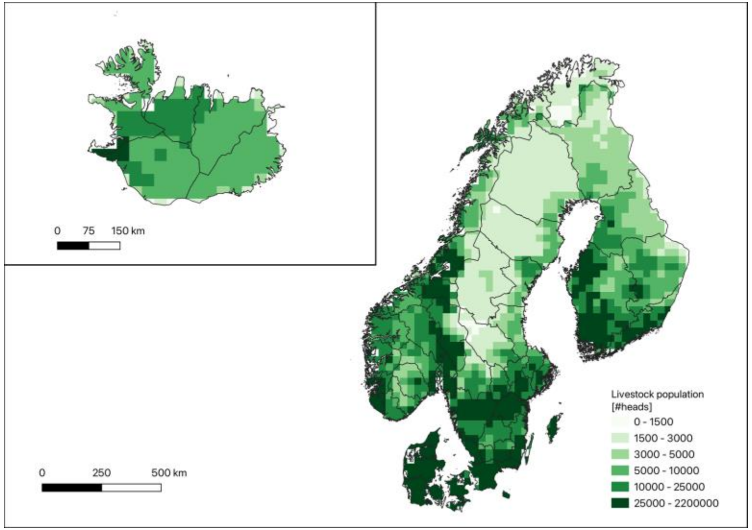
Food and Agriculture Organization of the United Nations

Projection of Crop Production in Reference Scenario



Projection of Livestock Population in Reference Scenario



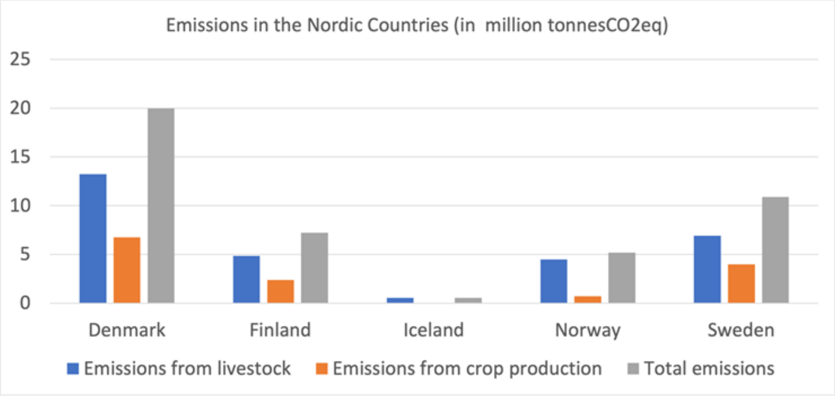


Emissions from Livestock and Crop Production

- Secondary data method to calculate the emissions from livestock and crop production.
- Crop production have higher emissions values, compared to livestock.
- In the Nordic Countries, the major contributor to the emissions provided by livestock and crop production is Denmark.

Uncertainties in accounting emissions:

- **For crops**: variances in the emissions due to energy, chemical/fertilizers usage, since they depend on the time, location and the agriculture farm.
- **For livestock**: the facilities have inherent spatial and temporal variability during the processes which produce the emissions.



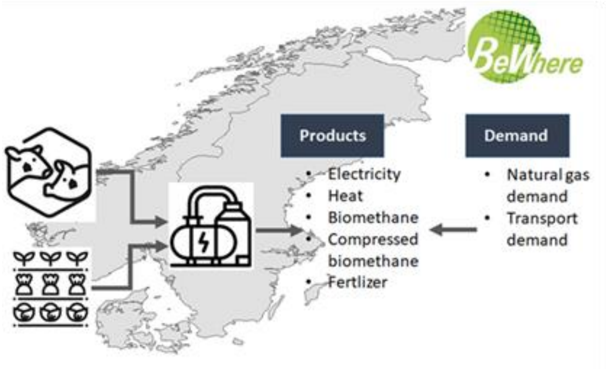
Land-use, Water, and Energy - Agriculture Sector

- 61% of the total land area of Denmark was being used for agriculture purposes
- Only 2% of the total land area of Norway, 6% in Sweden, 7% in Finland were being used for agriculture purposes
- Norway is the major water consumer for agriculture purposes (0.8449 billion cubic meters in 2004). Regarding energy usage, Finland is the major contributor (38603 TJ in 2020).
- On the other hand, Finland has the lowest water usage (0.05 billion cubic meters in 2007). While Iceland has the lowest energy usage (1833 TJ in 2019).

Countries	Water use [billion cubic meters]	Year	Energy Usage [TJ]	Year
Sweden	0.098[1]	2010	24367[2]	2019
Denmark	0.315[3]	2020	26376[8]	2019
Finland	0.05[5]	2007	38603[6]	2020
Iceland	0.07[7]	2006	1833[4]	2019
Norway	0.8449[9]	2004	25200[2]	2020

BeWhere Modelling Framework

(a)



(b)

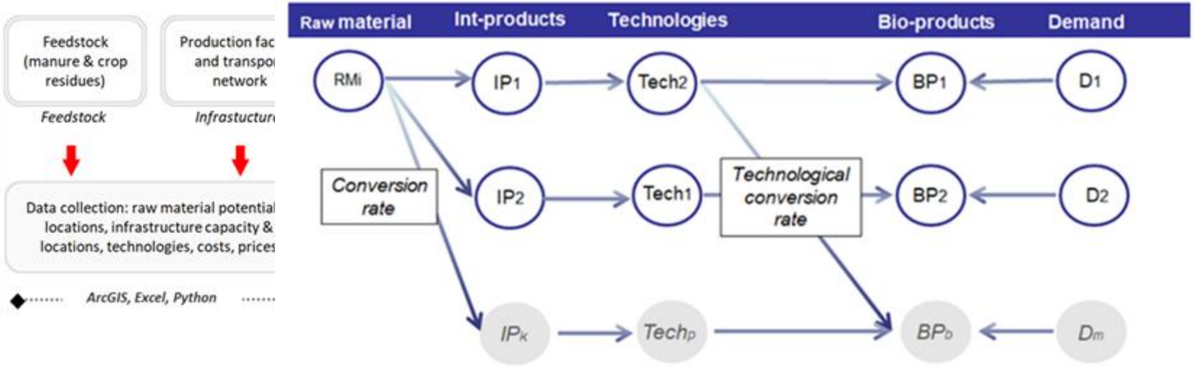
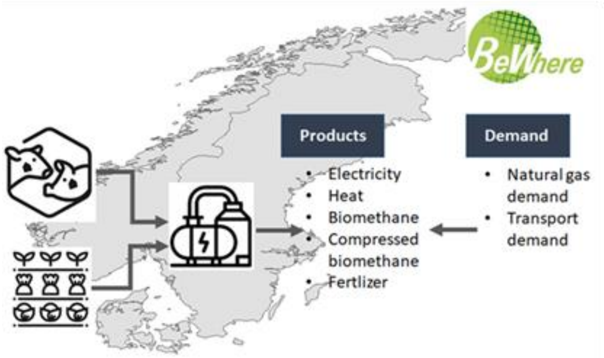


Illustration of biogas supply chain for BeWhere model configuration and modelling procedure in this study

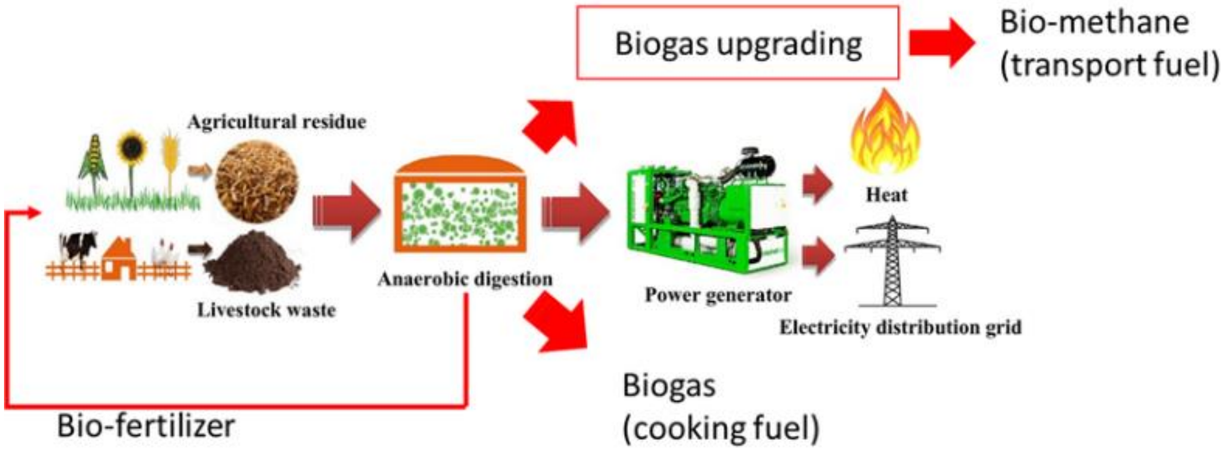
BeWhere Modelling Framework

Biomass supply/availability • Sustainable supply of biomass • Quality and quality of feedstock • Production scenarios	**Distribution and infrastructure** • Road, train network • Power lines • Power stations and energy grid
Production costs (techno-economic parameters) • Transport and distribution costs • Conversion efficiencies • Plant setup and operation & maintenance	**Demand projection/sites and targets** • Plans for expansion of infrastructure • Demand of energy • Goals, targets, and policy scenarios
Costs and price structure • Power/heat price • Fossil fuel use • Prices/costs of feedstock and renewables	**Environment** • Emissions (climate change) • Water loss • Biodiversity hotspots

(a)



Co-digestion of Agricultural Biomass for Biogas Production



Adopted with the modification from (Safieddin Ardebili, 2020).

- Biogas can be converted into different forms of energy
- The BeWhere model selects the optimal pathways (technology type and location of the plants), considering the modelling parameter and constraints

Estimating Biogas, Biomethane, Bioelectricity and Bioheat (1)

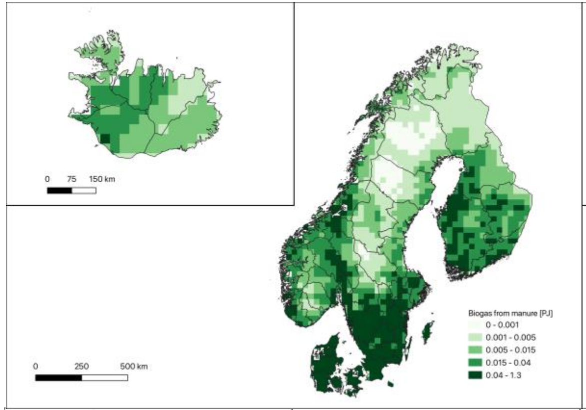
- The properties of each feedstock material is identified and tabulated and the biogas yield is calculated in each grid using the validated properties
- Calculations are done separately for agriculture residues and manure and summed up together in each grid
- Bioelectricity in the grid level is calculated considering the CHP plant efficiency as 30% and bioheat is calculated using the heat to power ratio 0.6

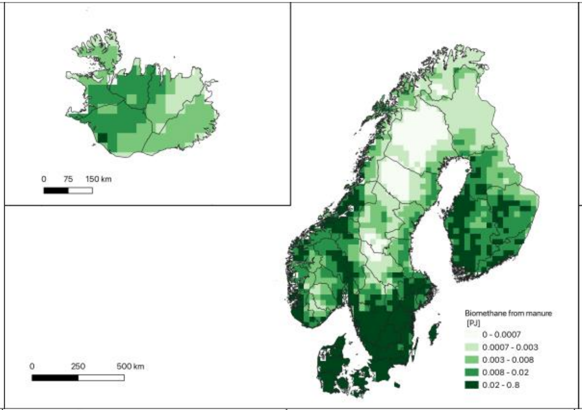
$$sum_{manure(i)} = Total\ number\ of\ head\ (i) \times Manure\ per\ day \times 365$$, it is the available total manure in a year

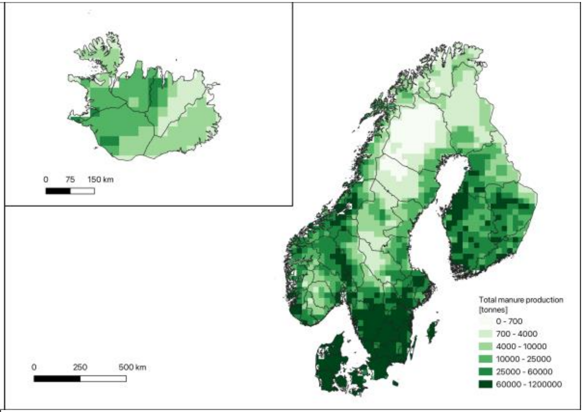
$$Theoretical\ Manure\ potential \left(\frac{MJ}{year}\right) = \sum_{i=1}^{n} (sum_{livestock(i)} \times Manure\ per\ day \times LHV(i)) * 365$$

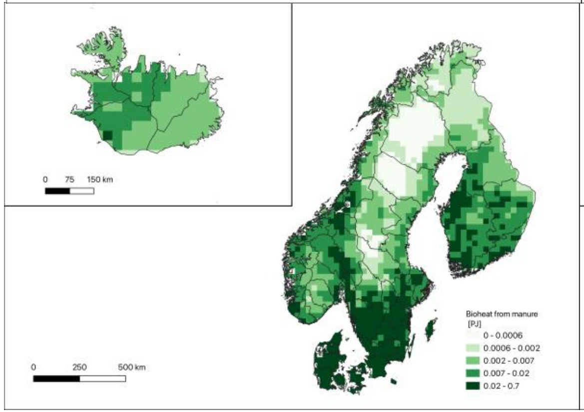
$$Biogas\ Yield \left(\frac{m3}{year}\right) = \sum_{i=1}^{n} [sum_{manure(i)} \times TS\%(i) \times VS\%(i) * Biogas\ yield(i) \left(\frac{m3}{kgVS}\right)]$$

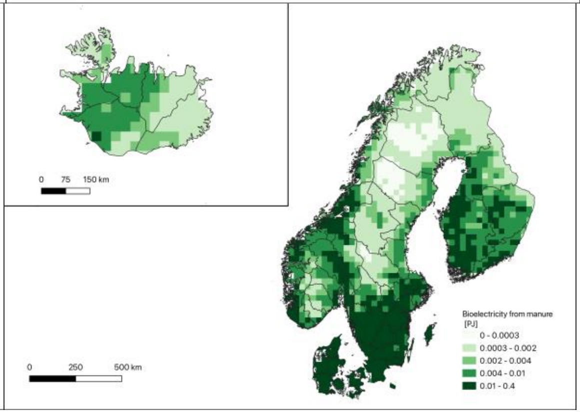
Manure Potential in the Region







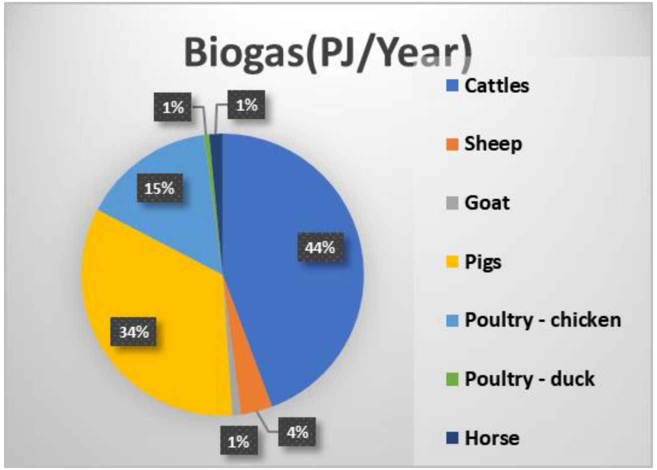




- ✓ It is observed that the biogas potential from manure is higher at the southern Nordic region

Estimating Biogas, Biomethane, Bioelectricity and Bioheat (2)

Livestock	Total number of Head (gridded FAO)	Biogas(PJ/Year)	Bio Methane production (PJ/year)	Bioelectricity (PJ/year)	Bioheat (PJ/year)	Theoretical Manure potential (PJ/Year) Direct combustion of manure
Cattles	4706747.062	33.13	19.876	9.938	16.56	94.882
Sheep	3648372.681	2.68	1.607	0.803	1.339	5.477
Goat	716738.788	0.75	0.449	0.224	0.374	2.112
Pigs	15862809.08	25.21	15.127	7.563	12.606	40.19
Poultry - chicken	42308614.313	11.39	6.837	3.418	5.699	24.941
Poultry - duck	1636231.008	0.44	0.264	0.132	0.220	0.965
Horse	306642.437	1.151	0.690	0.345	0.575	4.264
Total	69186155.3764	74.75	44.852	22.426	37.377	172.83



Estimating Biogas, Biomethane, Bioelectricity and Bioheat (3)

	Residue to product Ration (RPR)	Sustainable Recovery Rate (SRR)	LHV (MJ/kg)	TS (%)	VS (% of TS)	Biogas yield (m3/kg VS)	Methane yield (m3/kgVS)
Wheat	0.8-1.6	40%	13.9-19.5	94%	86.80%	0.4	0.24
Barley	0.8-1.3	40%	17.5-19.5	90.50%	94.30%	0.3817	0.229
Maize	0.9-1.2	50%	13.8-17.6	82%	97.50%	0.583	0.35
Potato & sweet potato	0.2-0.75	40%	16	25%	95%	0.685	0.411
Rapseed	1.4-2	50%	17.1	90.00%	92%	0.4	0.24
Sugarbeet	0.25	50%	15.5-17.7	17%	79%	0.5617	0.337
Other cereals(oats)	0.9-1.4	40%	8.8-19.5	86%	97%	0.6467	0.388

$$Practical\ agriculture\ residue\left(\frac{kg}{Year}\right) = PAR = \sum_{i=1}^{n}(crop(i)_{production} \times RPR(i) \times SRR(i))$$

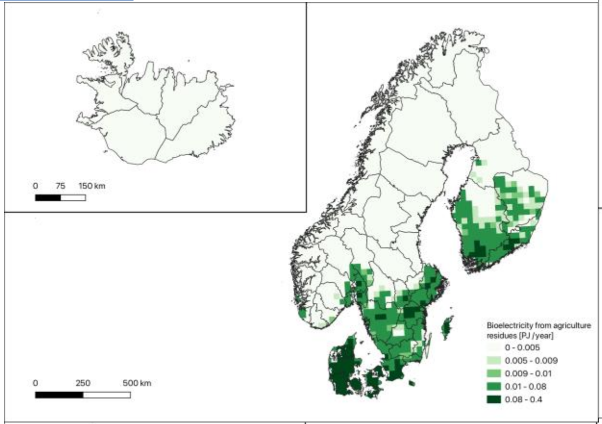
$$Theoretical\ Biomass\ potential\left(\frac{MJ}{year}\right) = \sum_{i=1}^{n}(crop(i)_{production} \times RPR(i) \times SRR(i) \times LHV(i))$$

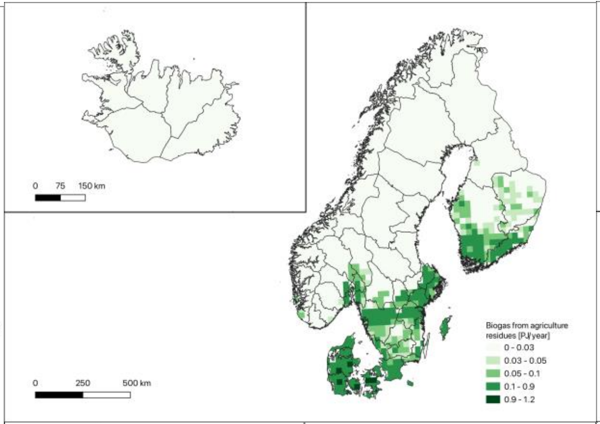
$$Biogas\ Yield\left(\frac{m3}{year}\right) = \sum_{i=1}^{n}[PAR(i)\left(\frac{kg}{Year}\right) \times TS\%(i) \times VS\ \%(i) * Biogas\ yield(i)\left(\frac{m3}{kgVS}\right)]$$

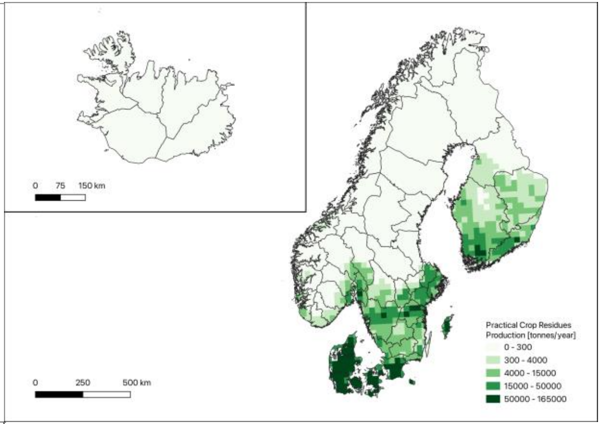
Sustainable removal rate:

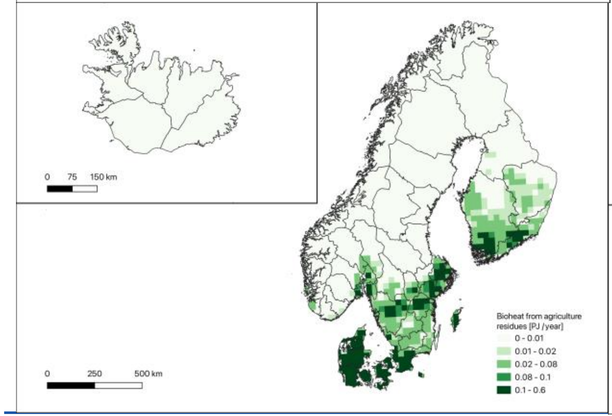
- Agricultural residue removal must be managed carefully to be sustainable, and spatial and temporal variability
- Excessive residue removal can degrade the long-term productive capacity of soil resources.

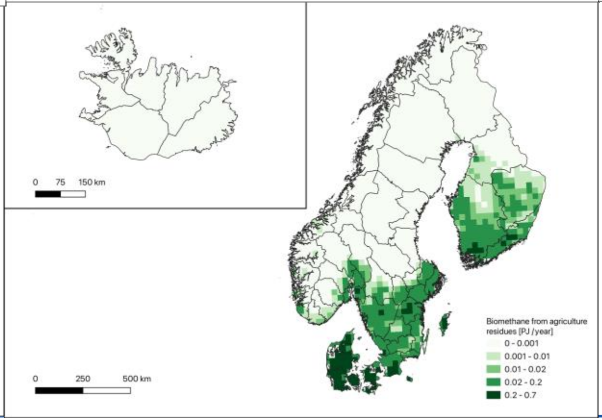
Crop Residue Potential in the Region







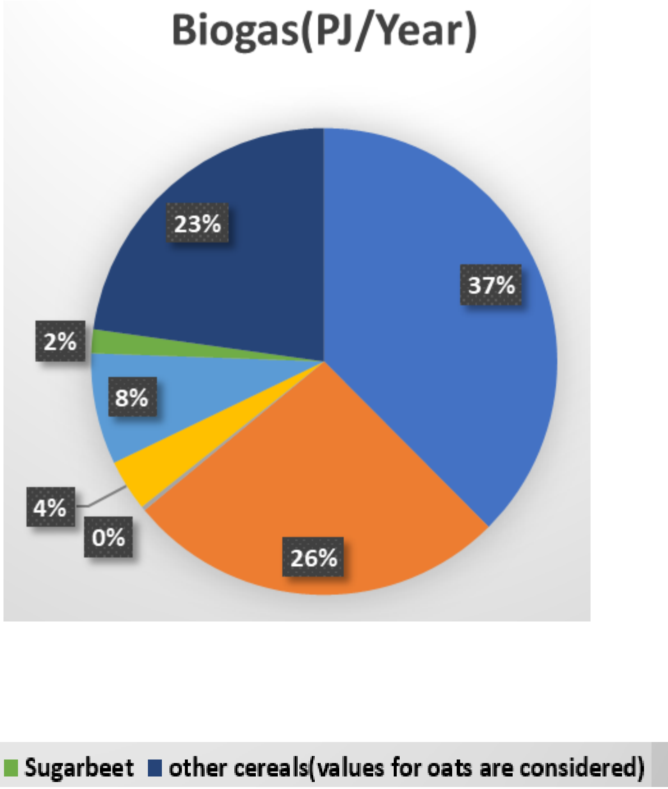




- ✓ It is observed that the biogas potential from crop residue is also higher at the southern Nordic region

Estimating Biogas, Biomethane, Bioelectricity and Bioheat (4)

Crop	Production [kg]	Biogas (PJ/Year)	Biomethane (PJ)	Bioelectricity (PJ/year)	Bioheat (PJ/year)	Theoretical Biomass potential (PJ/Year)
Wheat	8614872006	29.15	17.49	8.75	14.58	69.06
Barley	6958081017	20.56	12.34	6.17	10.28	54.06
Maize	43433196.49	0.23	0.14	0.07	0.11	0.36
Potato&sweet potato	4151084572	2.77	1.66	0.83	1.39	12.62
Rapseed	982758099.1	5.98	3.59	1.79	2.99	14.28
Sugarbeet	6302634602	1.28	0.77	0.39	0.64	13.08
other cereals(values for oats are considered)	3302792945	17.70	10.62	5.31	8.85	21.50
Total	30355656438.243	77.67	46.60	23.30	38.84	184.96

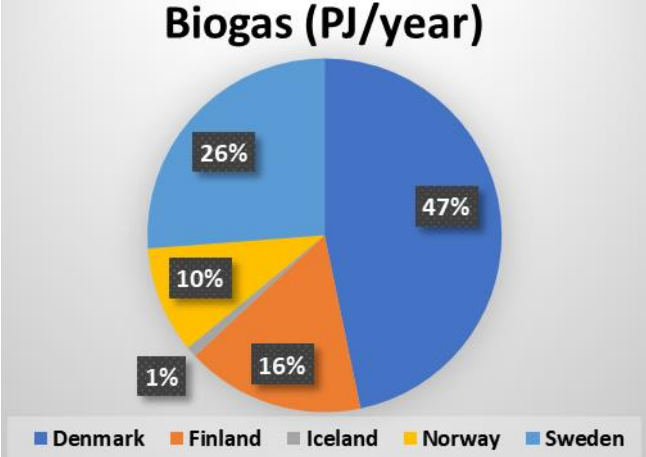


Total Biogas Production Potential in the Nordics

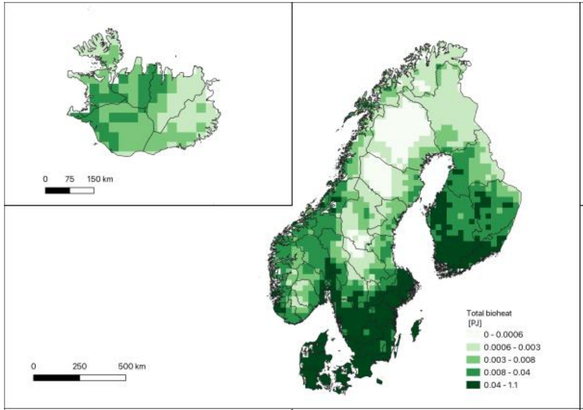
Country	Agriculture residue and manure (million tonne/year)	Biogas (PJ/year)	Biomethane (PJ/year)	Bioelectricity (PJ/year)	Bioheat (PJ/year)
Denmark	38.88	70.91	42	21.27	35.46
Finland	14.83	24.72	14.62	7.42	12.36
Iceland	1.41	1.49	0.9	0.45	0.75
Norway	13.57	14.84	8.84	4.45	7.42
Sweden	23.90	39.74	23.48	11.92	19.87
Total	92.58	151.7	89.83	45.5	75.85

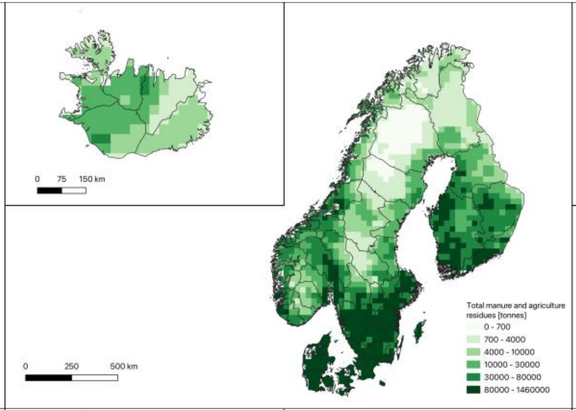
Country	Our study in PJ Year: 2021	Data from IVL study in PJ
Denmark	89.74	160-180 in 2020
Norway	9.37	9-19.8 in 2019
Sweden	56.9	50.4-79.2 in 2021

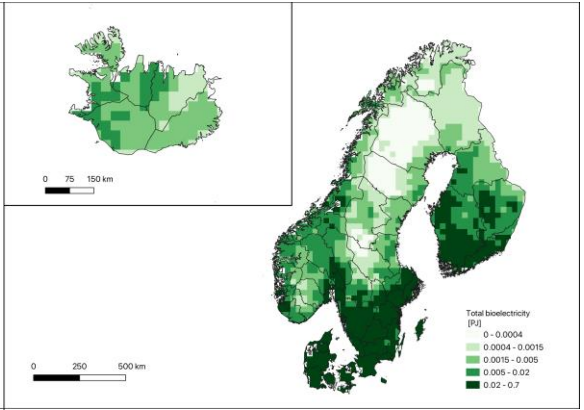
Technologies and energy production Potential of Nordic in total		PJ	TWh
AD plant	Biogas	151.7	42.14
Upgrading plant	Biomethane	89.83	24.95
CHP plant	Bioelectricity	45.5	12.642
	Bioheat	75.85	21.069

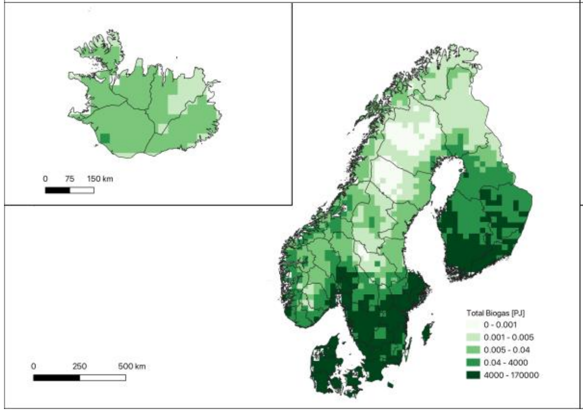


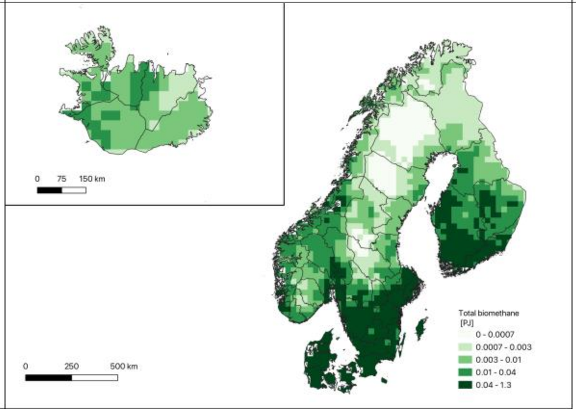
Biogas Production Potential in the Region











✓ It is quite obvious that the total potential is higher at the southern Nordic from the previous slides

The Role of Biogas in Decarbonizing the Nordic's Energy Sector

Total biogas energy potential (From our calculation)	Current biogas production in 2019	Power Consumption in 2020	Natural gas consumption in 2020	Transport fuel consumption in 2020	Energy consumption in district heating in 2020	Cooking fuel consumption in 2020
PJ	PJ	PJ	PJ	PJ	PJ	PJ
151.7	25.2	1386.504	187.4981	860.0144	528.2504	55.907
The share of biogas /biomethane/bioelectricity		3.3%	47.9%	10.4%	14.4%	36.9%

- Biogas can contribute in substituting fossil fuels in the region
- The estimates show that the Nordic countries have only harnessed around 17% of the total biogas potential

Energy Production in the Region, 2020

Hydro	Wind	Solar	Solid biofuels	Other renewables	Non renewables	Bioelectricity potential (Our calculation)
PJ	PJ	PJ	PJ	PJ	PJ	PJ
828	172.8	14.4	86.4	36	381.6	45.5

- The total bioelectricity potential is around 45.5 PJ, which can substitute 11.9% of the non-renewable energy in the region
- Around 11 % of fossil oil can be replaced by biomethane.
- The total diesel consumption in the Nordic countries was 626.5 PJ in 2020 and the corresponding emissions were 55.13 million tonnes CO2. Biomethane can substitute around 14.3% of the diesel consumption, thus reducing emissions in the region.

Bio-digestate Nutrient Quality

- Bio-digestate = 85% of the total feedstock
- Total Solid content is 10%
- N is 8.8% of total solids
- P is 3.6% of total solids
- K is 5.9% of total solids

✓ The values are finalized based on different case studies on biogas plants in Europe

✓ 1ton Bio-digestate gives 8.8kg N

✓ 1ton Bio-digestate gives 3.6kg P

✓ 1ton Bio-digestate gives 5.9kg K

- **Ref: circular solutions for Biowaste;Horizon 2020**

Fertilizer Consumption in 2019 and Total Bio-digestate Potential

Particulars	Bio-digestate in tonnes (From our calculations) (kilo-tonnes)	Total fertilizer consumption, (kilo-tonnes) (FAO-STAT)	Comparison (Biofertilizer/Total Fertilizer Consumption)
N	692.5	671.6	1.03
P	283.3	111.2	2.55
K	464.3	187.9	2.47

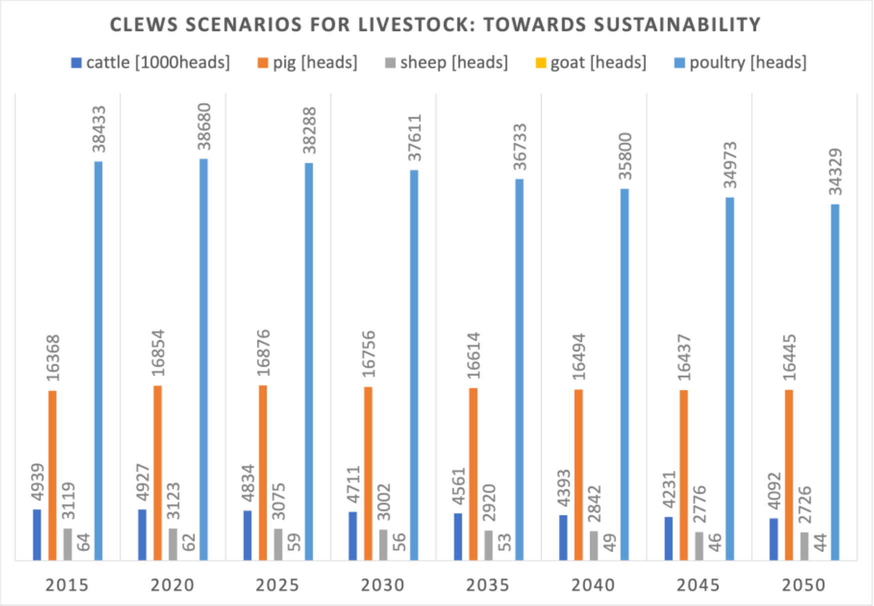
- The study finds that bio-digestate can replace the current fertilizer consumption.
- The nitrogen content in the available bio-digester is almost same as the current demand in 2019.
- Potassium and phosphorus are more than twice the demand.

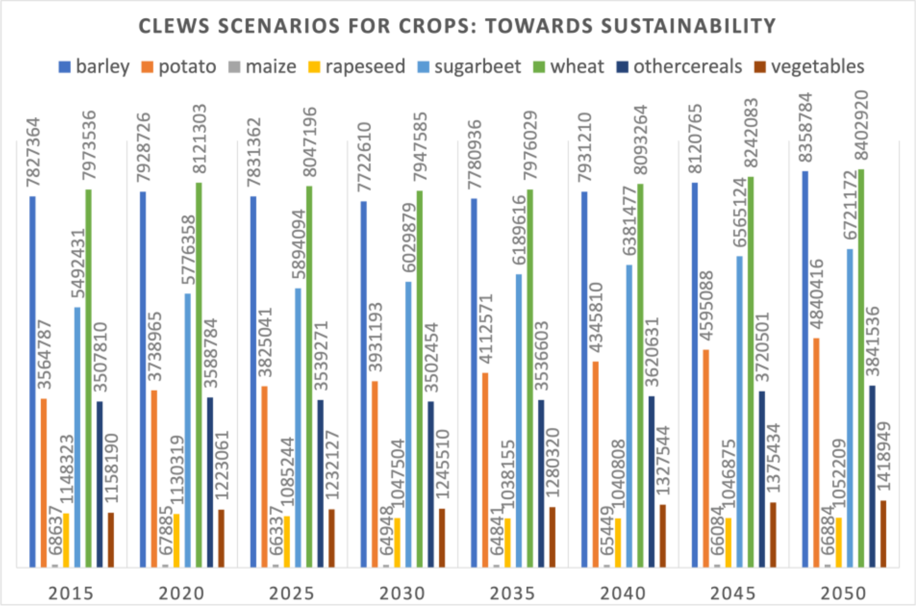
CLEWs Scenarios

Scenario	ppm	W/m^2	percent		°C
	CO2-eq Concentration	RCP	change in Co2 eq annual emissions in 2050 compared with 2010		2100 temperature change relative to average 1850-1900
			from	to	
Towards Sustainability (**sc1**)	580-650	4.5	-38	24	2.3-2.6
Stratified Societies (**sc2**)	>1000	8.5	52	95	4.1-4.8

Two scenarios were considered to input in the BeWhere Model the "Towards Sustainability" (best-case scenario) and "Stratified Societies" (worst case scenario) from the FAO database.

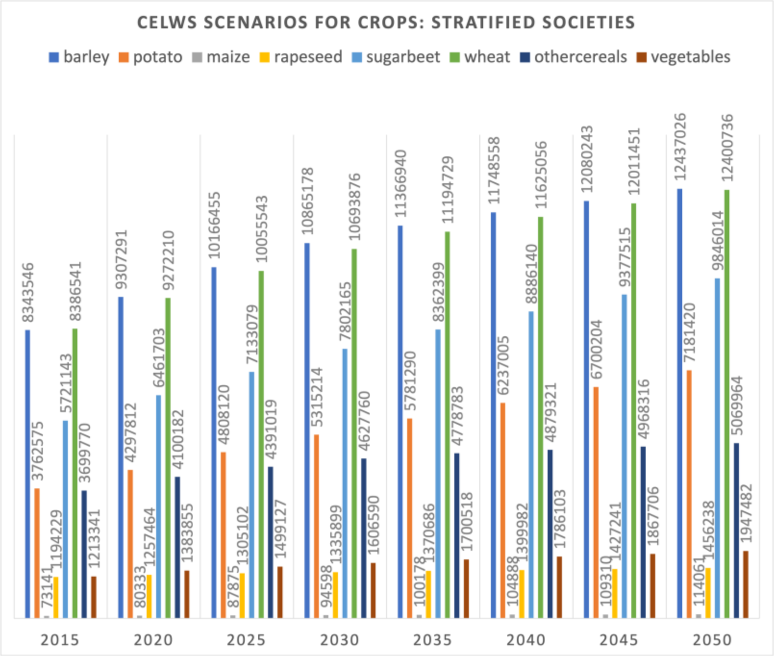
CLEWs Scenarios – Towards Sustainability (sc1)





- In the **sc1** the number of livestock decreases and the crop production increases slightly. Due to the **decrease in meat consumption** and the **environment conditions for crop production (temperature and CO2)**.

CLEWs Scenarios – Stratified Societies (sc2)



- In the **sc2** scenario both livestock and crop production have a larger increase, compared to the other scenario. Due to the **increase in meat consumption** and the **environment conditions for crop production (temperature and CO2)**.

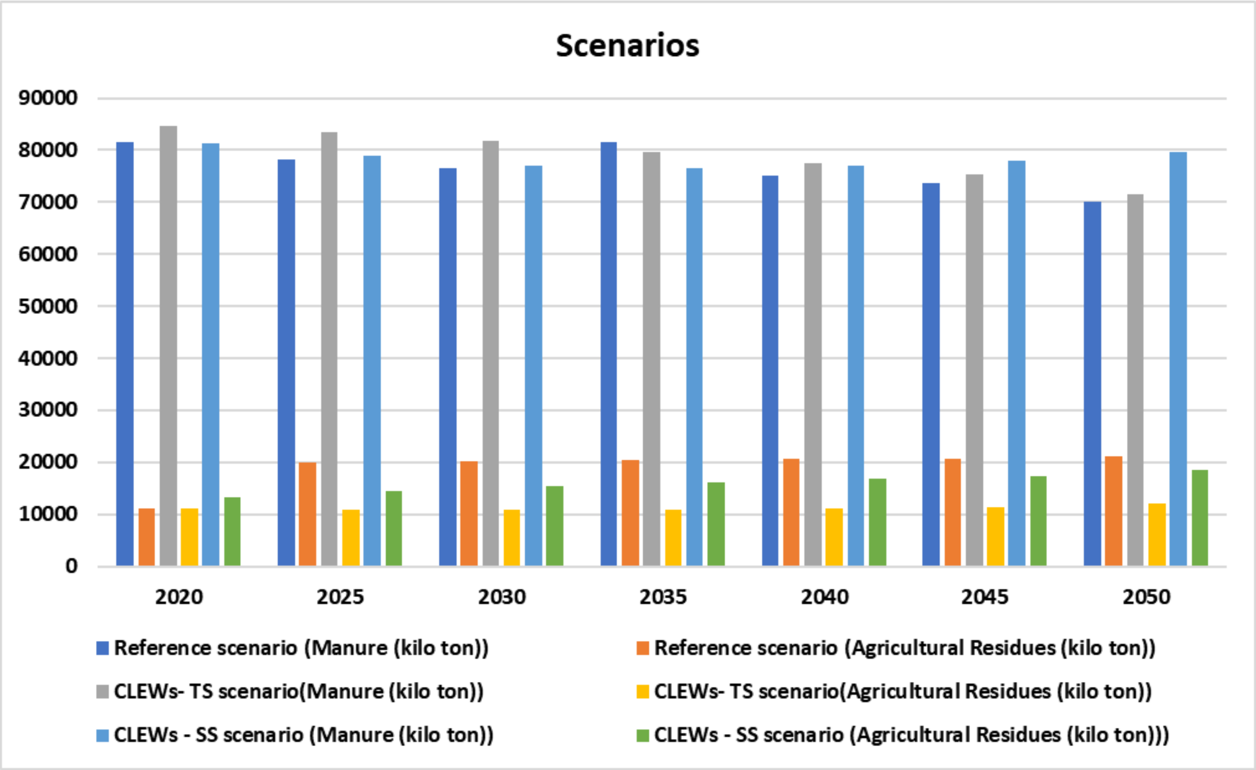
Scenarios and exploration of future biogas production

- Biogas production potential has been estimated in three scenarios

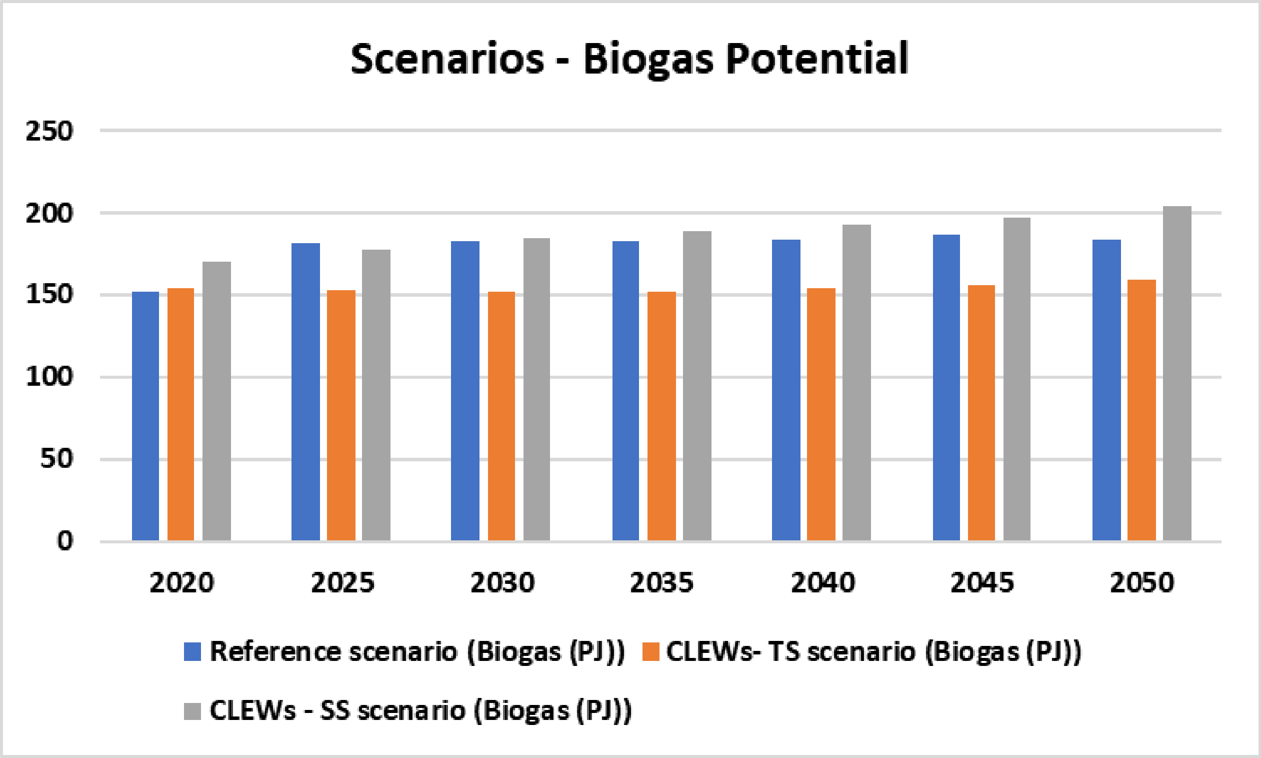
	FAOSTAT Reference scenario			CLEWs- TS scenario			CLEWs - SS scenario		
Year	Manure (kilo ton)	Agricultural Residues (kilo ton)	Biogas (PJ)	Manure (kilo ton)	Agricultural Residues (kilo ton)	Biogas (PJ)	Manure (kilo ton)	Agricultural Residues (kilo ton)	Biogas (PJ)
2020	81572.8	11011.5	151.7	84656.2	11036.9	153.8	81263.9	13332.3	170.1
2025	78090.4	19840.1	181.7	83500.5	10931.7	152.8	78998.8	14461.1	177.9
2030	76585.8	20077.0	182.2	81774.2	10824.9	151.8	77069.0	15407.3	184.4
2035	81572.8	20313.9	182.7	79684.8	10918.8	152.4	76633.5	16140.6	189.2
2040	75081.2	20550.8	183.2	77396.7	11138.4	153.8	77070.0	16752.2	193.1
2045	73576.7	20772.5	186.8	75276.3	11401.0	155.6	77881.3	17310.8	196.6
2050	70028.3	21033.7	184.1	71557.6	11974.6	159.6	79631.6	18493.0	204.1

- In the FAOSTAT scenario, the biogas potential has a significant increase from 2020 to 2025 and over the years, the potential is almost stable
- In the CLEWs TS scenario, the biogas potential is not having a significant variation over the years
- In CLEWs SS scenarios the biogas potential is keep on increasing over the years and has highest potential in 2050

Biomass over the years in the three scenarios analysed



Biogas Potential over the years in the three scenarios analysed



Total Energy Demand Projections in the Region

Year	Electricity Consumption in PJ	Natural Gas consumption in PJ	Transport fuel consumption in PJ	Cooking fuel consumption in PJ	District Heating in PJ
2020	1386.5	202.5	846.2	74.2	513
2025	1352.7	203.6	863.6	75	531.6
2030	1321.8	206.8	881	75.7	545.3
2035	1290.9	210	898.5	76.5	559
2040	1260	213.2	915.9	77.3	572.6
2045	1229.1	216.4	933.3	78	586.3
2050	1198.2	219.6	950.8	78.8	595.2

- From CLEWs-SS scenario – Biomethane potential is 122.46 PJ in 2050. Which can replace ~13% of the transport fuel consumption.

Or

- Biomethane can be fed into natural gas grid and can replace around 55.7% of natural gas consumption in 2050

Concluding Remarks

- 152 PJ of biogas can be produced from crops residues and manure in the Nordic countries. That amount can then be upgraded to biomethane or converted to 46 PJ of electricity and 76 PJ of heat
- 11 % of the fossil oil used for refining vehicle fuels can be replaced by biomethane, i.e. up-graded biogas, being produced in the Nordic countries.
- An increased production of biogas in the Nordic countries can also contribute to the long-term emissions targets for GHG emissions.
- Bio-digestate can replace the current fertilizer consumption, thus contributing to energy and climate gains in the region.
- There is a need of developing an integrated assessment framework for biogas production in the Nordics: Linking CLEWs aspects, while devising NECPs.