Power-to-X Technologies using Hydropower in Greenland

Unlocking Greenland’s Renewable Energy Potential: A Techno-Economic Assessment of a Power-to-Ammonia Case Study Using the SpineOpt Optimization Framework

Master thesis defense

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Agenda

(1) Introduction

(2) Literature review

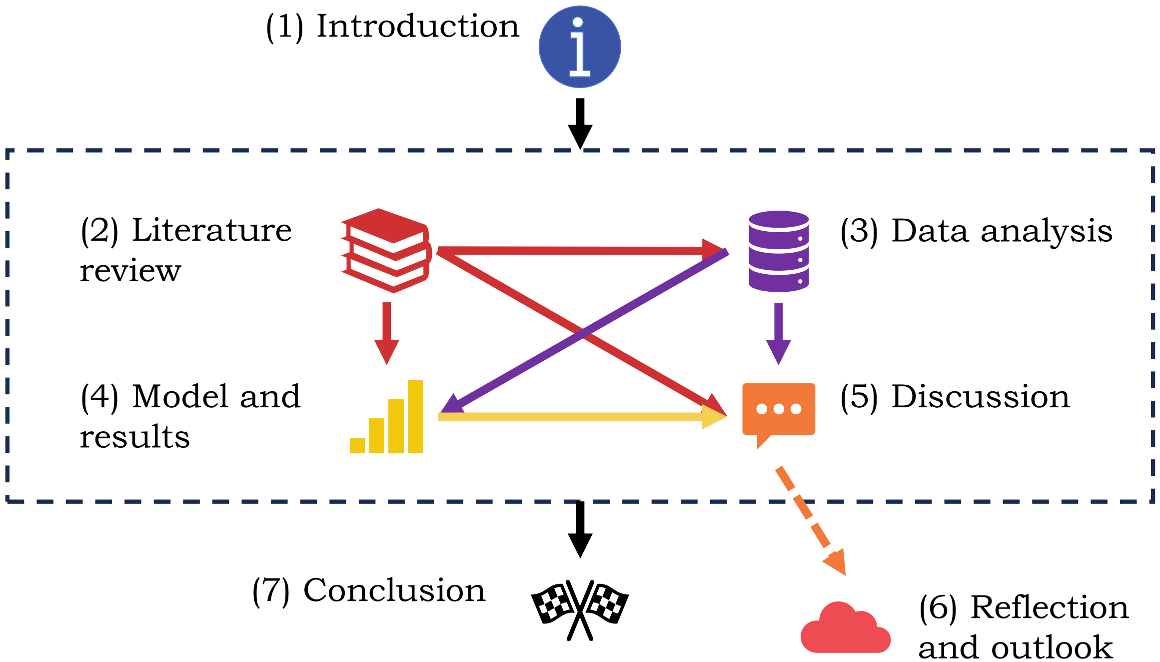
(3) Data analysis

(4) Model and results

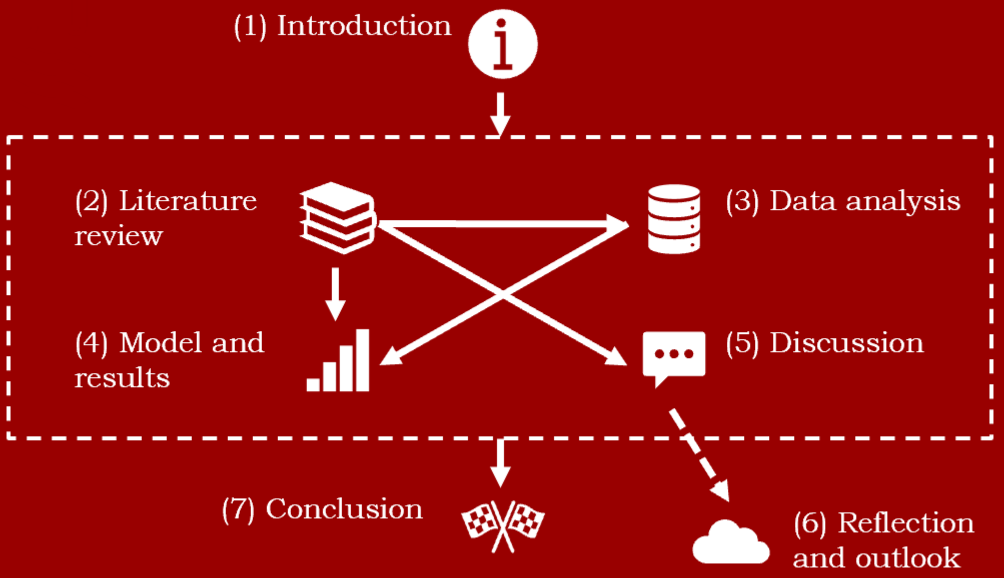
(5) Discussion

(6) Reflection and outlook

(7) Conclusion



(1) Introduction



The Greenlandic government issued several tenders for yet unexploited hydropower resources with 7e lake Tasersiaq as the largest

Renewable energy sources such as wind, solar and hydropower offer promising opportunities to mitigate climate changes

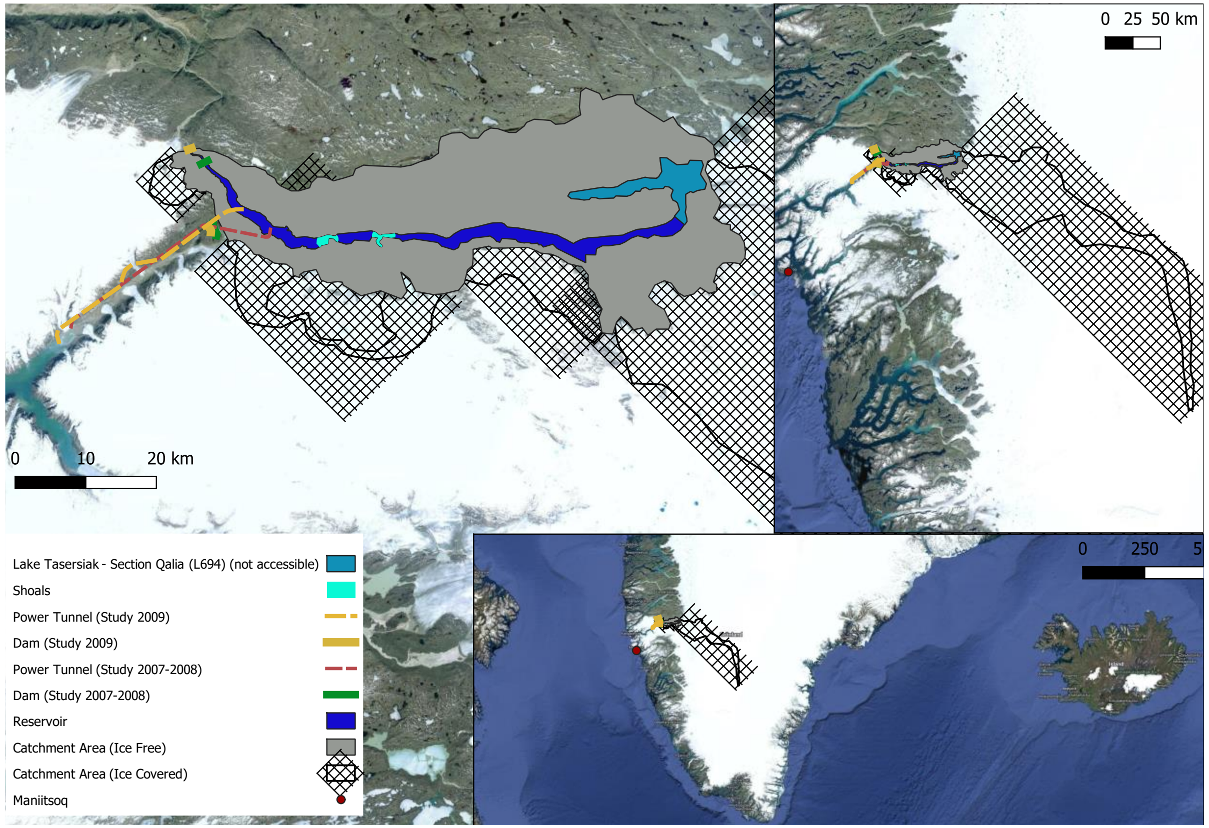
Advantages of hydropower	Challenges of hydropower
Installation of large capacities with relatively low levelized cost of electricity (LCOE)	High upfront investment
Stable energy production	Long construction times
Long lifetime	Complexity of managing unique project requirements

- ❑ Greenland has significant unexploited hydropower resources
- ❑ Power-to-X technologies as solution for energy storage and transport
- ❑ Carbon sourcing difficult – Power-to-ammonia as solution

- ❑ Greenlandic government recently issued several tenders for the development of hydropower resources in West Greenland
- ❑ Remarkable hydropower resource 7e Lake Tasersiaq as largest to be tendered

Objectives of the tender

- ❑ Ensuring an adequate and substantial financial return for Greenland
- ❑ Responding to unique characteristics of Greenland and promotes its development.
- ❑ Providing long-term environmental, climatic, economic and social benefits

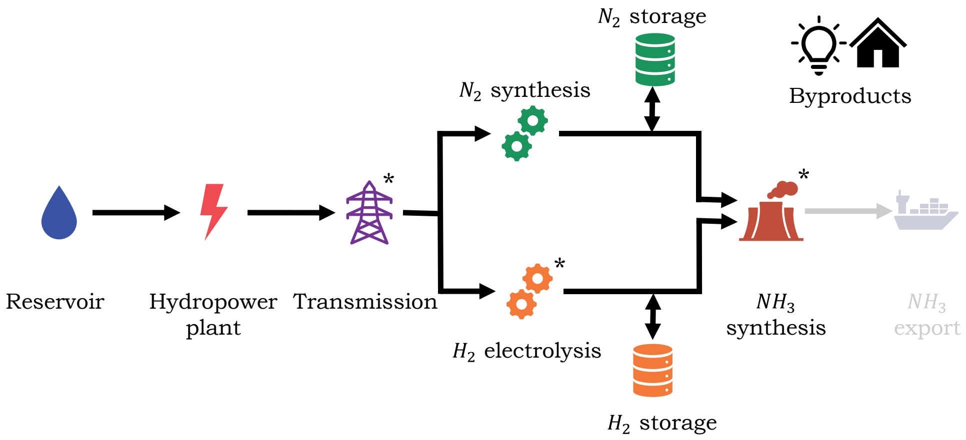


Due to its unique characteristics, the potential P2A system must undergo a thorough techno-economic assessment

Tender

- ❑ Open to dialogue: broad and non-specific
- ❑ Lack of clear decision-making framework
- ❑ Need for thorough techno-economic assessment of the hydropower resource 7e lake Tasersiaq

System under Study



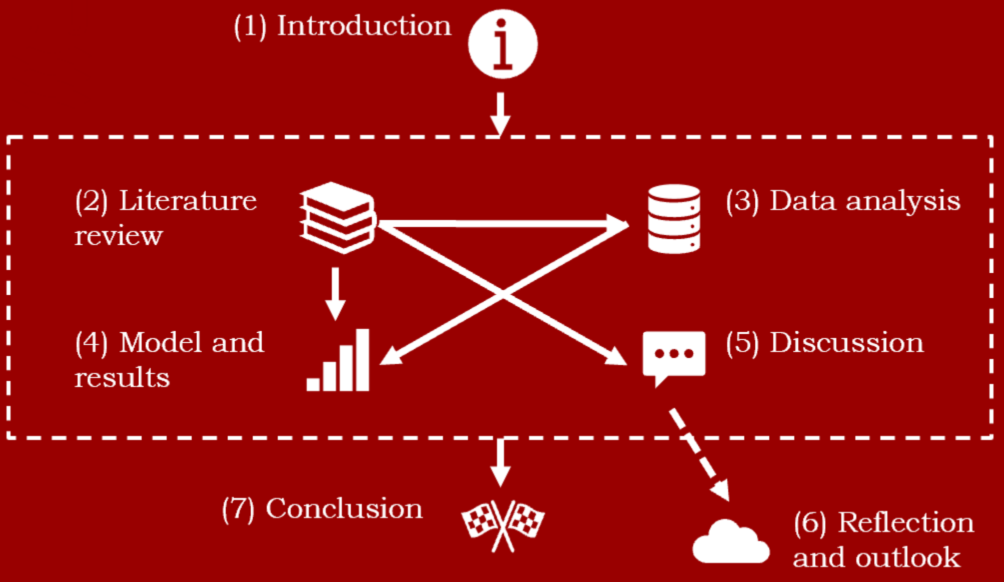
Novelty

- ❑ Applying the generic SpineOpt energy system modelling framework
- ❑ Assessing feasibility of a large-scale P2A system using hydropower as an energy source
- ❑ Off-grid and remote environment in the arctic region

What is the optimal scale and energy system setup of a financially feasible P2A system using the hydrological resource 7e lake Tasersiaq in West Greenland?

- ❑ What are the operational implications of the optimal setup?
- ❑ What is the impact of the project based on the triple-bottom-line (TBL) approach?
- ❑ How is the financial feasibility impacted by the volatility and uncertainty of future water inflows?

(2) Literature review



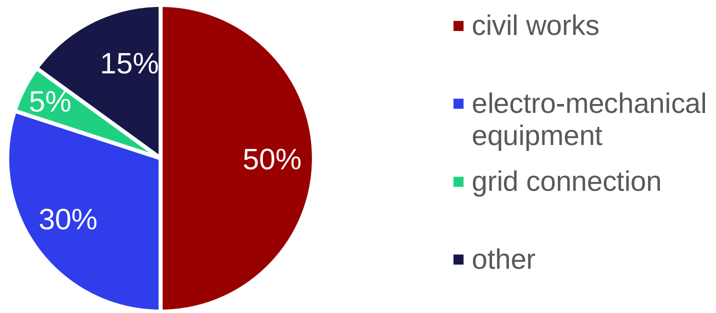
The literature review highlights the novelty of the study

Renewable energy system models

- Wide range of objectives for energy system modelling (investments vs operations, price- vs demand driven)
- Different types of hydropower plants require specific models tailored to their characteristics
- Concerns about oversimplifying hydropower in terms of flexibility (e.g., ramping up and ramping down).

Hydropower plants

- Frequently studied example is the Skellefte river in Sweden as frequently studied case of run-of-river systems, due to availability of public data

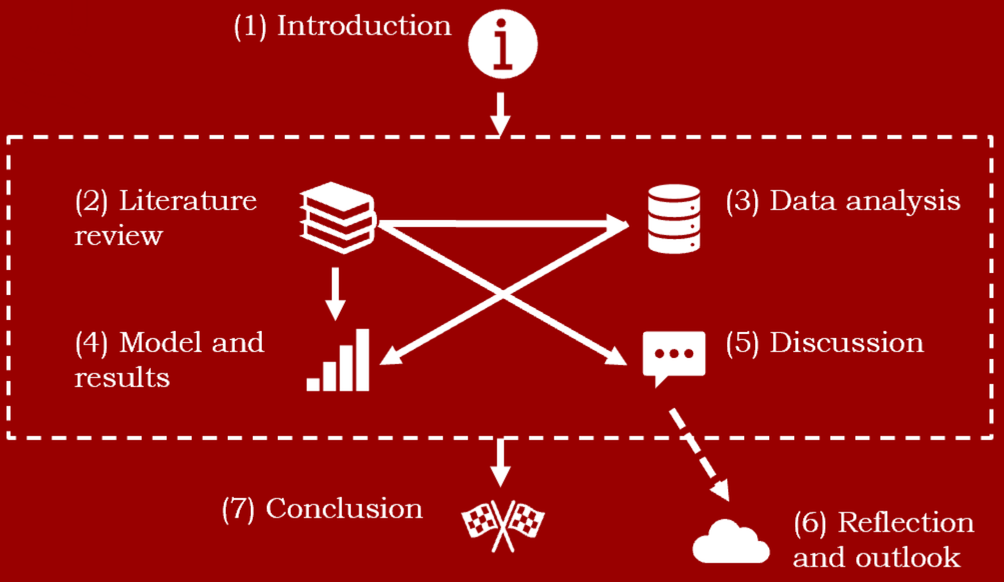


Adapted from: International Energy Agency (IEA). Hydropower Special Market Report - Analysis and forecast to 2030. Tech. rep. IEA, 2021.

Power-to-Ammonia plants

- Hydropower + Power-to-Ammonia common in 20th century. Ca. 30% of worldwide ammonia production facilities based on electrolysis in 1930
- Rjukan plant in Norway as 1st large renewable ammonia plant production capacity of ca. 300 tNH_3/day and decommissioned in 1971
- Renewable ammonia plant with a capacity of 1.2 million tonnes per year is currently being built in Saudi Arabia. First plant of its kind on such a large scale to reach GW capacity

(3) Data analysis



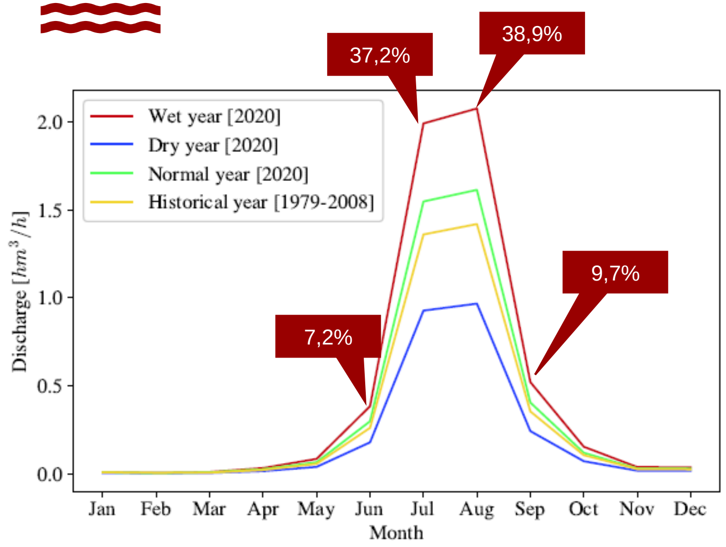
Data collected were validated and found to be of high quality for the case study, as assessed by a data analysis framework

Data analysis framework

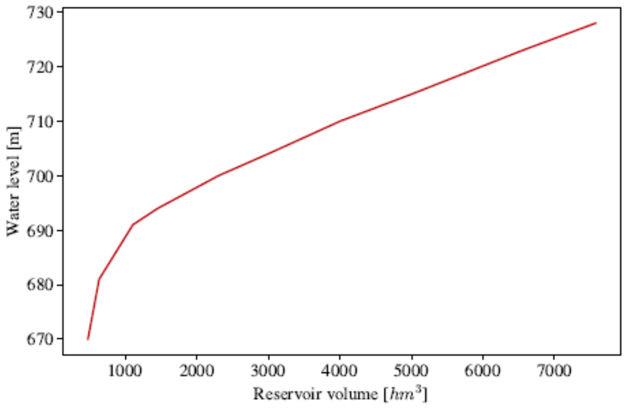
- ❑ Reliability
- ❑ Applicability
- ❑ Resolution
- ❑ Timeliness
- ❑ Transparency

- ❑ Applicability & Reliability: applicable data of PFS for hydropower resource. Data from DEA neglect arctic environment
- ❑ Resolution: Water inflow only available on monthly resolution, still sufficient for model due to high storage volume
- ❑ Transparency: data sources and underlying assumptions of PFS and DEA are provided

Hydrology and reservoir



Series	Discharge volume [$hm^3/year$]
Historical [1979-2008]	2.702
Dry [2020]	1.840
Normal [2020]	3.070
Wet [2020]	3.950



- ❑ Funnel shaped reservoir demonstrates non-linear storage increase

Data collection and analysis

Applicable hydropower plant data (PFS)

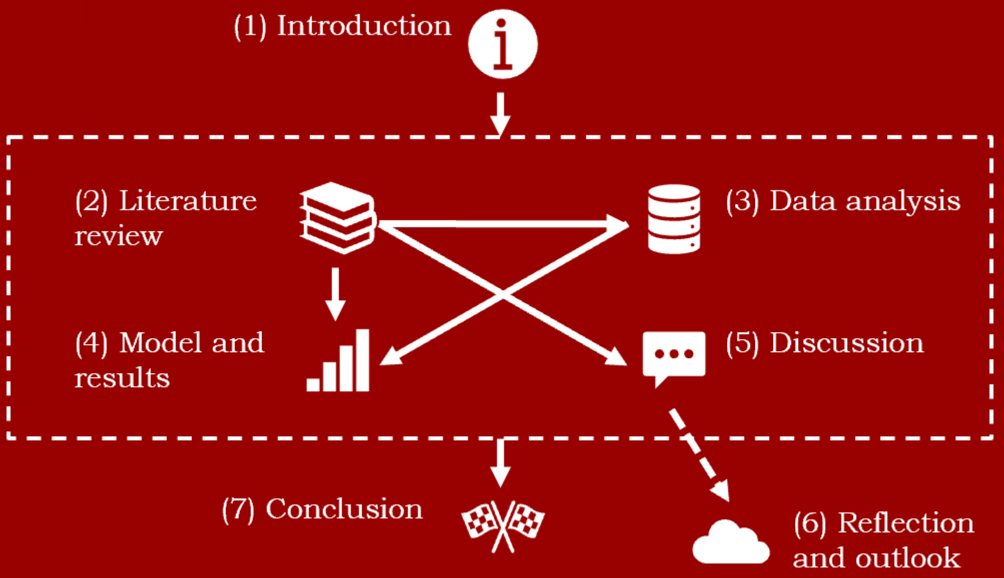
Category	Metric	Value
Water levels	Max operating level	714.0 m
	Min operating level	680.0 m
Headrace tunel	Length	26.6 km
	Diameter	8.0 m
Dam 1	Length	330.0 m
	Max height	55.0 m
Dam 2	Length	995.0 m
	Max height	27.0 m
Production devices	No. of turbines	5
	Max total output	595.0 MW

Power-to-ammonia data

Component	Parameter	Value (2030)
AEC	Cost p. capacity	662.000 $t€/MW$
	Conversion rate	48.540 MWh/tH_2
	Heat output	9.610 MWh/tH_2
Hydrogen storage system	Cost p. capacity	500.000 $t€/tH_2$
	Cost for compression	767.000 $t€/tH_2/h$
	Energy for compression	4.120 MWh/tH_2
ASU	Cost p. capacity	1.450 $mio€/tN_2$
	Energy for separation	0.250 MWh/tN_2
Nitrogen storage system	Cost p. capacity	12.437 $€/tN_2$
	Energy for liquefying	0.250 MWh/tN_2
Haber-Bosch unit	Cost p. capacity	7.300 $mio€/tNH_3/h$
	El. Energy usage	0.316 MWh/tNH_3
	Hydrogen conversion rate	0.180 tH_2/tNH_3
	Nitrogen conversion rate	0.840 tN_2/tNH_3
	Heat output	0.250 MWh/tNH_3
	Steam output	0.690 MWh/tNH_3

- ❑ Comparibly high cost for green Haber-Bosch unit in DEA compared to other sources
- ❑ High uncertainty in technological development of electrolysers. Comparably low cost in DEA

(4) Model and results



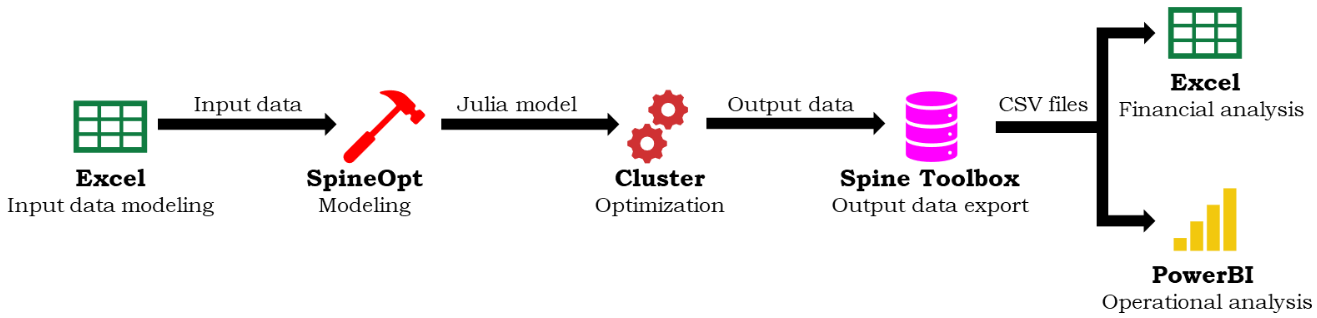
The generic structure of the open-source energy system modelling framework SpineOpt enables high adaptability and standardized results

Advantages of SpineOpt

- Generic energy system modelling framework ensures high adaptability
- Open source (highly relevant for academia)
- Validated through various case studies
- Fully flexible temporal structure
- Allowing scenario-based stochastic programming
- Standardized output generation
- Strong community

Modelling process

- Spine Toolbox: object-oriented visualization capabilities (parameterization, input data management)
- Spine Model: optimization of commodity flow models through modular building blocks translated into a Julia environment
- Price-driven optimization



Uncertainty and data scarcity require technological, operational and financial assumptions to ensure robust and feasible results

Technological

- Location of dams, tunnels and other infrastructure from the PFS are still applicable in 2030
- Efficiency of turbines and generators of the hydropower plant from the PFS can be used for the model
- System boundaries: modeling the hydropower plant & P2A system, that means from water inflow to ammonia output (excl. NH3 storage system)

Operational

- Year begins with the wet season on July 1st with an empty reservoir and ends on June 30th of the following year with an empty reservoir (cyclic condition)
- System operates entirely off-grid and is independent from external influences that could occur in a grid connected environment
- Water inflow to the reservoir in the model equals the measured reservoir outflows from the PFS. Historical data of the observed discharge 1970 to 2008 is used for the validation and sensitivity analysis of the model

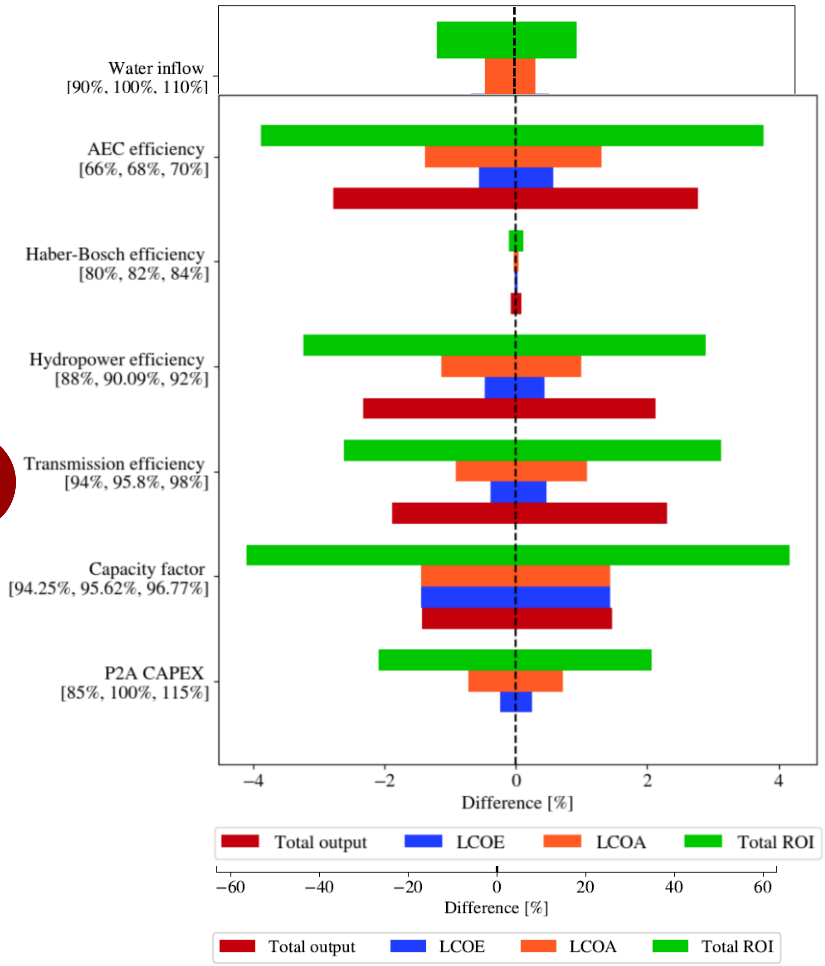
Financial

- Cost estimation for reservoir and infrastructure given by PFS and the model optimizes the reservoir capacity without concrete cost assigned to it
- The investment horizon of 25 years is equivalent to the lowest lifetime of components in the system
- Constant annuities to allow optimization of representative year

A high sensitivity towards the uncertain parameters of water inflow, WACC, ammonia price and capacity factor can be observed

- Iterative verification and validation of continuous model during development
- Sensitivity analysis for relevant parameters in range of uncertainty
- Aim: robust model, even if large sensitivities
- Base assumptions
  - WACC: 6%
  - Investment horizon: 25 years
  - Ammonia market price: 500€/tNH_3
  - Annuity €2015

Note the different scales across the different figures

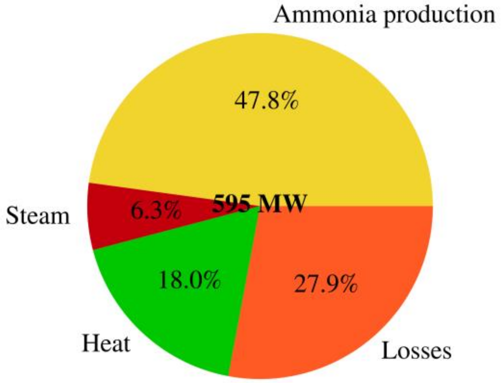


- High sensitivity for certain parameters can be neglected (transmission, hydropower)
- Water inflow, WACC, AEC efficiency and capacity factor have significant impact on LCOE, LCOA and ROI
- Ammonia price significantly impacts the total ROI

Financially feasible system with constant operations and an efficiency of 47.8%

Technological

- Overall satisfactory system efficiency of 47.8%

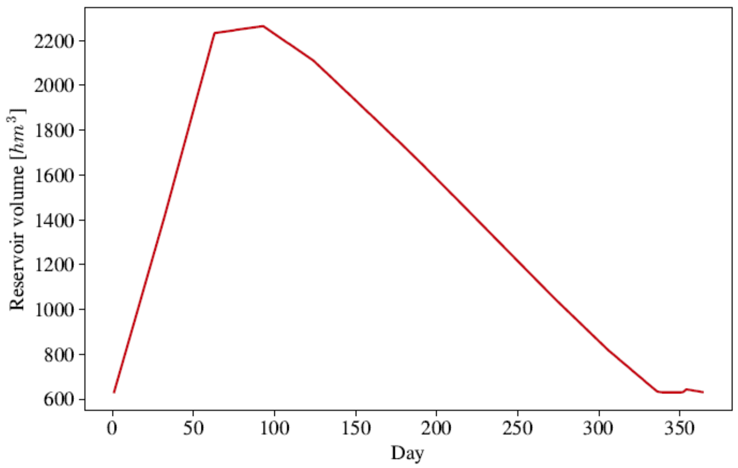


- The water flow through the tunnel and hydropower plant is constantly about 0.31 hm^3/h which is equal to 86.1 m^3/s

System component	Scale	Unit
Max water level (Dam height)	703.6	m
Hydropower plant	589.8	MW in
Transmission	530.2	MW in
Electrolysis	326,3	MWH_2 out
ASU	45.7	tN_2/h out
Haber-Bosch	285.3	$MWNH_3$ out

Operational

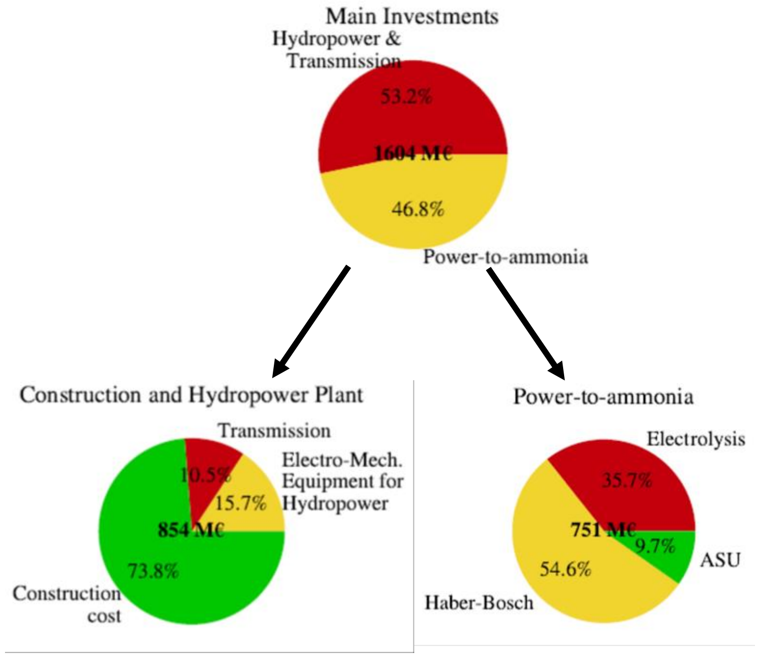
- Optimal solution proposes constant operations



- No intermediate hydrogen or nitrogen storage systems needed
- The reservoir volume suggested by the feasibility study is not fully used
- Scaling of energy system components solely depends on water inflow

Financial

- Cost distribution reflects literature findings



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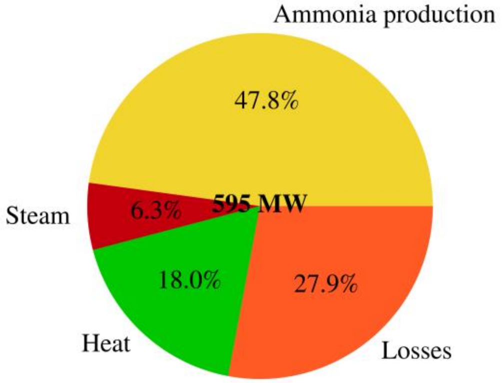

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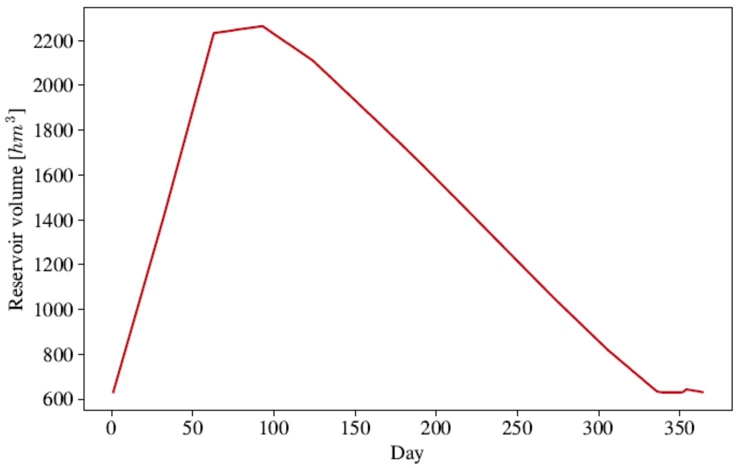

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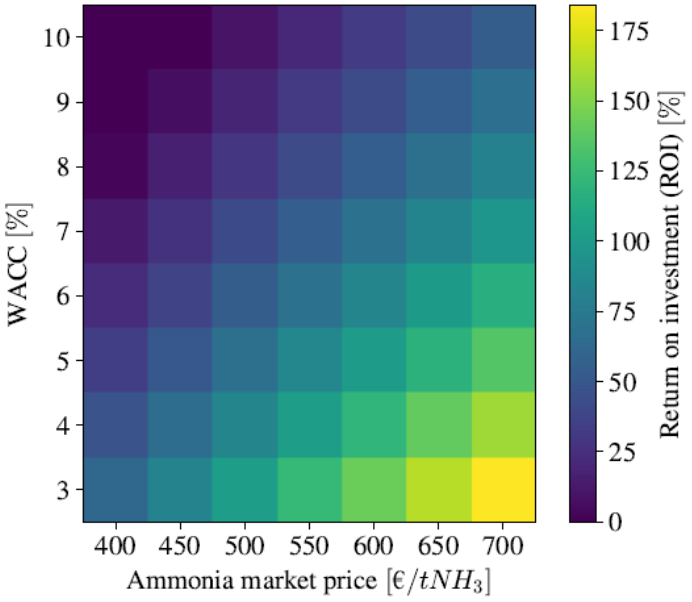
Financial

- Parameters of the investment methodology affect ROI significantly (e.g., investment horizon, construction time, WACC). Positive ROI.



To account for uncertainty, the model must incorporate derived water inflow scenarios in a stochastic manner

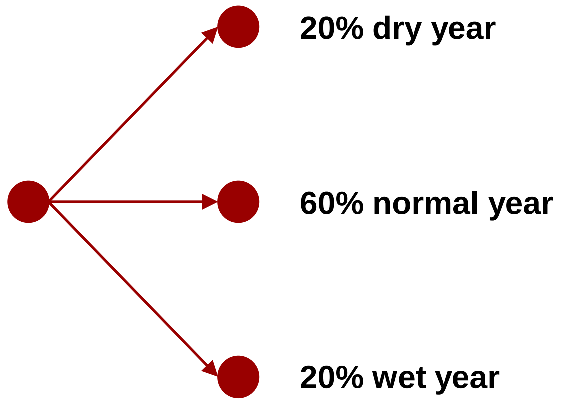
Basic model results (deterministic)

System component	hist. Year [1979-2008]	normal year [2020]	dry year [2020]	wet year [2020]	Unit
Max water level (Dam height)	703,6	705,9	696,3	709,7	m
Hydropower plant	589,8	670,7	402,1	862,9	MW in
Transmission	530,2	604,2	362,2	777,4	MW in
Electrolysis	326,3	371,3	222,6	477,9	$MW H_2$ out
ASU	45,7	52	31,2	66,9	tN_2/h out
Haber-Bosch	285,3	323,1	193,7	415,7	$MW NH_3$ out

- Sensitivity analysis has demonstrated water inflow as main driver of the system

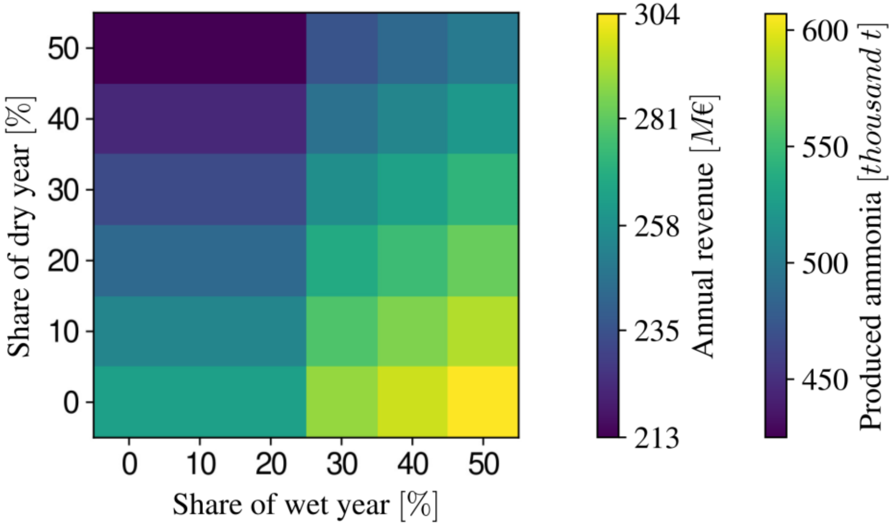
Model extensions (stochasticity)

- Including uncertainty by implementing stochastic programming
- Implementation of dry/wet/normal years in a stochastic tree by assigning the distribution to the 3 different water inflow series
- Example:



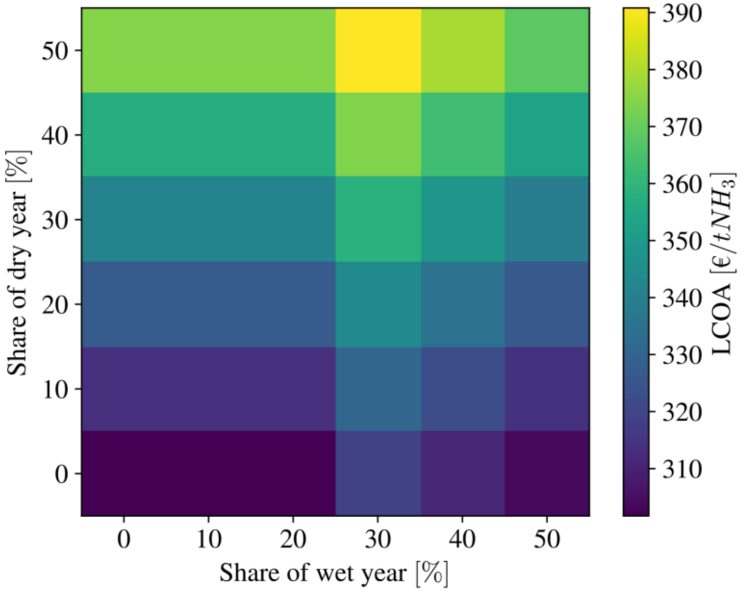
What is the optimal installed capacity based on the stochastic tree?

When introducing uncertainty, it is recommended to invest in large-scale components if the share of wet years is ≥ 30%



<	Small		Large		Unit
Component	Scale	Annuity	Scale	Annuity	
Hydropower plant	670,70		862,89		MW in
Transmission	610,28		785,16		MW in
Electrolysis	372,92	134 M€	479,78	153 M€	MW out
ASU	52,21		67,18		tN_2/h out
Haber-Bosch	324,48		417,45		MW out

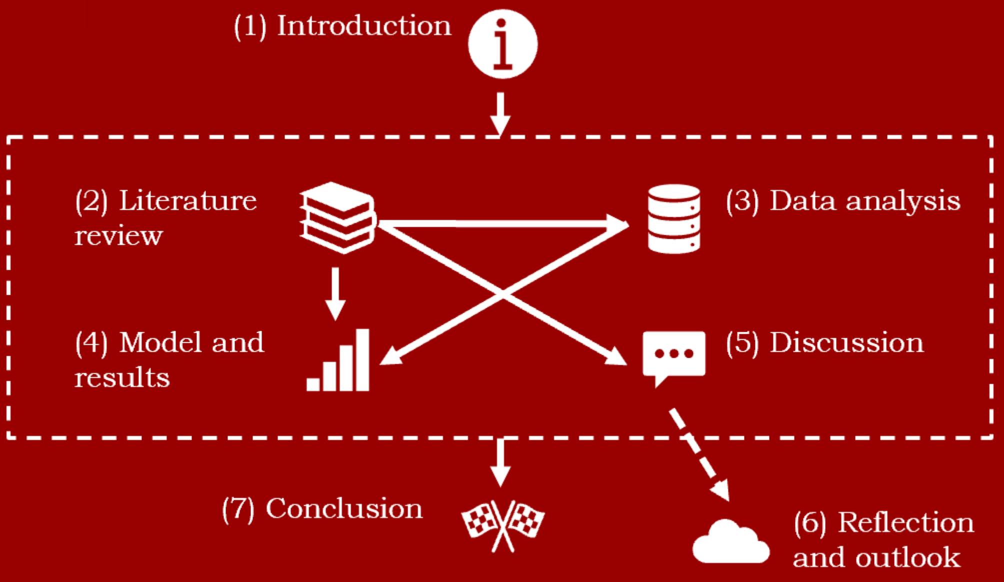
Distribution wet/normal/dry year	30/40/30	20/50/30	Difference
Annual Revenue	+243 M€	+268 M€	+25 M€
Annuity (Costs)	-134 M€	-153 M€	-19 M€
Annual Profit	109 M€	115 M€	+6 M€



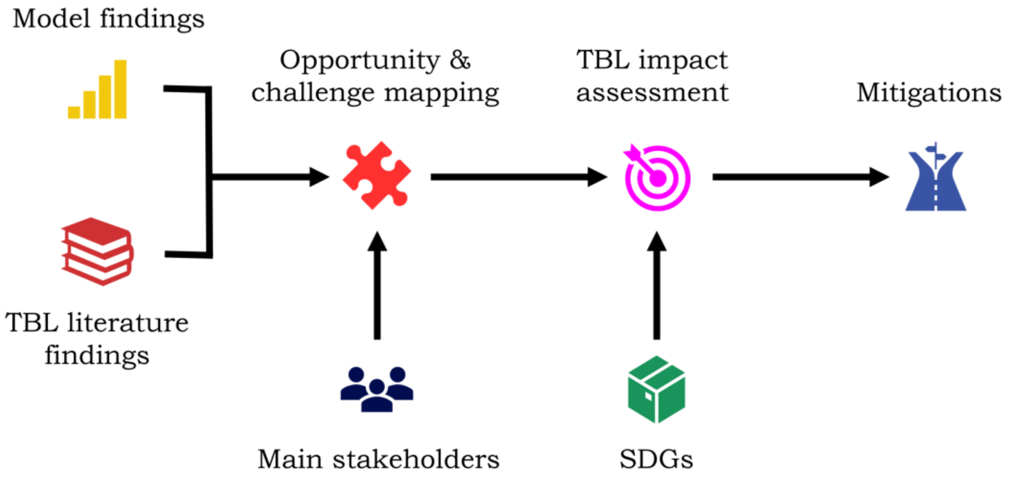
- ❑ Investment in large scale recommend for share of wet years ≥ 30%. Else small-scale investment
  - ❑ Absolute revenue increase overweighs $CAPEX_{Investment}$
- ❑ Competitive LCOA throughout all distributions

WACC: 6%
Investment Horizon: 25 years
Ammonia market Price: 500 €/tNH3
Annuity €2015

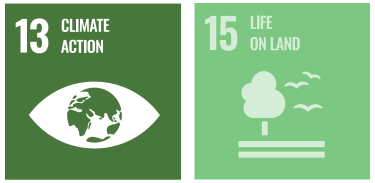
(5) Discussion



Triple-bottom-line impact assessment demonstrates potential benefits across all three dimensions

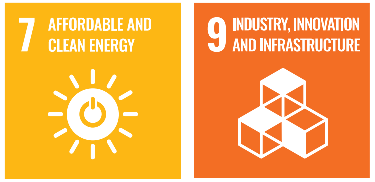


- Main stakeholders:
  - Project developer [DEV]
  - Public authorities in Greenland [PA]
  - Local/Greenlandic society [L/GS]



- Replacement of fossil fuels
- Environmental footprint during construction and decommissioning

- Knowledge transfer
- Tackling demographic challenges
- Increase wellbeing on local level



- Attract industries through available byproducts
- Local infrastructure

- Enabling further investments in Greenland
- Showcase attractiveness of green ammonia

- Life cycle assessment of the entire project for obtaining the real effects of the project on the environment
- Open dialogue with local communities and potential workforce to attract and retain skilled workers

Though the project is subject to large uncertainties, the robust model implies general feasibility & informed decisions about the system´s design

Weaknesses

- Reliance on a representative year, even with stochastic modelling
- System boundaries: Exclusion of storage systems and shipping of NH_3 within the system boundaries
- Although various financial assumptions cover the academic standard, they differ from project developer to project developer

Uncertainties and risks

- Uncertainty with the P2A system components (e.g., CAPEX, efficiency, arctic top-up factor)
- Uncertainty about the availability of components (supply chain)
- Uncertainty regarding future water inflow, (low time resolution of past inflows)

Benefits

- Robust model capable of assessing project profitability despite high uncertainty in CAPEX and water inflow
- General feasibility of the project, in conjunction with the feasibility study, providing cost quantification through the model. Feasibility demonstrated even with small water inflows
- Facilitating informed decisions on the establishment of systems, e.g., determining that H_2 and N_2 storage systems are not recommended

The methodology and model are generalizable with the results implying competitive LCOA of green ammonia for Europe and North America

Generalizable aspects

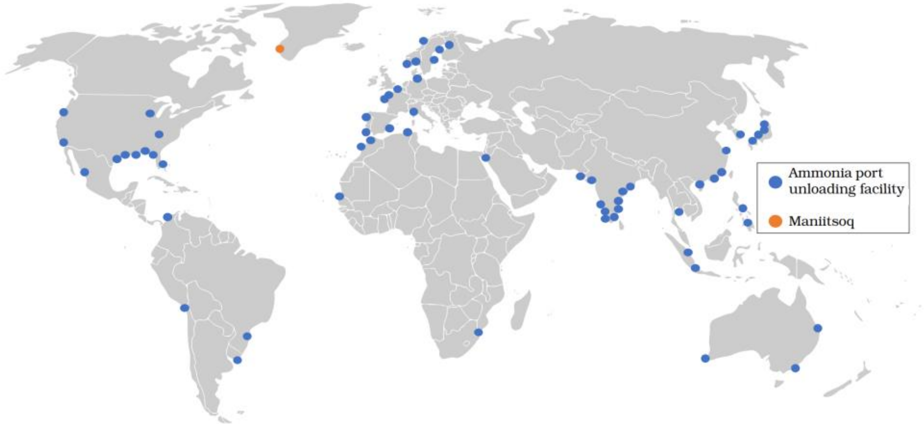
- ❑ Energy systems modelling methodology
- ❑ Model as a generalized reservoir hydropower plant with an off-grid power-to-ammonia system connected

Less generalizable aspects

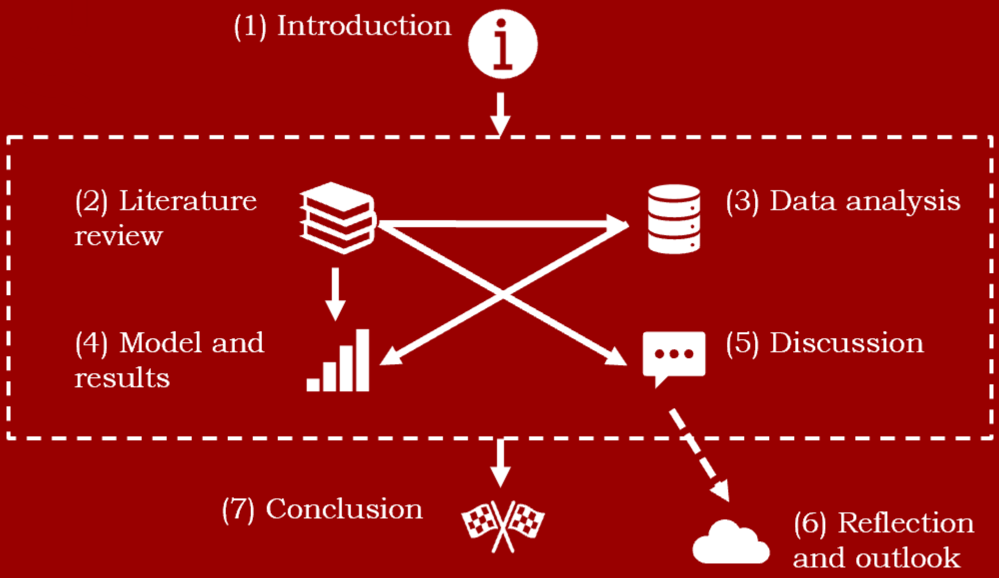
- ❑ Resulting recommendations for operations and scale of components
- ❑ Applicability of cost structure due to uniqueness and heavy reliance on the detailed estimations from the feasibility study

Leveraging significance

- ❑ Largest to date facility to combine hydropower with Power-2-X
- ❑ Demonstrating feasibility of a Power-2-X project in the arctic region
- ❑ Possible contribution to 10% of total ammonia imports in Europe or 13% in North America
- ❑ Green ammonia with competitive LCOA



(6) Reflection and outlook



The successfully applied framework shows overall financial feasibility, while additional data & the use of simulations likely lead to more certain results

Reflection

Challenges

- ❑ Missing industry knowledge in academia:
  More high-quality data (e.g., cost of components) would allow for more precise investment decision (e.g., MIP)
- ❑ Limited computational power forces the use of a representative year, cyclical conditions and feasible assumptions
- ❑ Put more focus on the Minimum Viable Product (MVP)

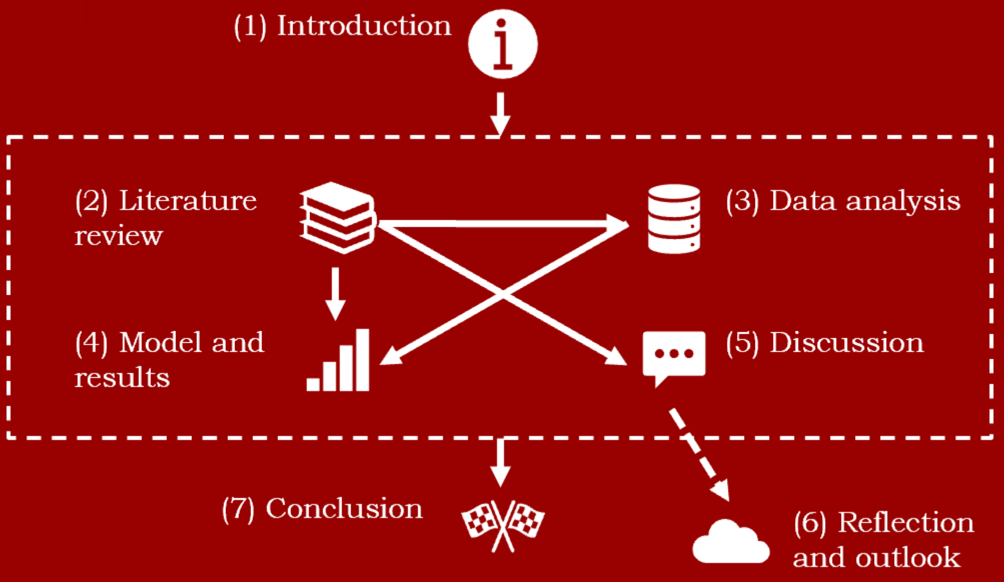
Successes

- ❑ Experience and knowledge of using (industry-specific) software such as Excel and Power BI in an academic context has proven to be highly advantageous
- ❑ Successful implementation of the relatively new SpineOpt framework
- ❑ Developed methodology demonstrates financial feasibility and provides guidance for the project

Outlook

- Detailed environmental study or life-cycle assessment
- Collecting of additional information on the cost impact of dam height to implement a stepwise investment strategy (MIP) to optimise the dam volume
- Running simulations over several years to validate the scaling parameters and to determine the optimal dam height & volume without using the cyclic condition
- Exploring different investment methodologies to demonstrate feasibility and impact on LCOE/LCOA

(7) Conclusion



Conclusion

Main findings

- ❑ Two system scales (670MW or 862MW hydropower capacity)
- ❑ Constant operations as optimal solution
- ❑ Water inflow as main driver of the system
- ❑ Financially feasible project
- ❑ No intermediate hydrogen and nitrogen storage systems needed
- ❑ Potential benefits in social, economic and environmental aspects

Appendix


7 AFFORDABLE AND CLEAN ENERGY
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
3 GOOD HEALTH AND WELL-BEING
4 QUALITY EDUCATION
13 CLIMATE ACTION
17 PARTNERSHIPS FOR THE GOALS
15 LIFE ON LAND

SpineOpt implementation

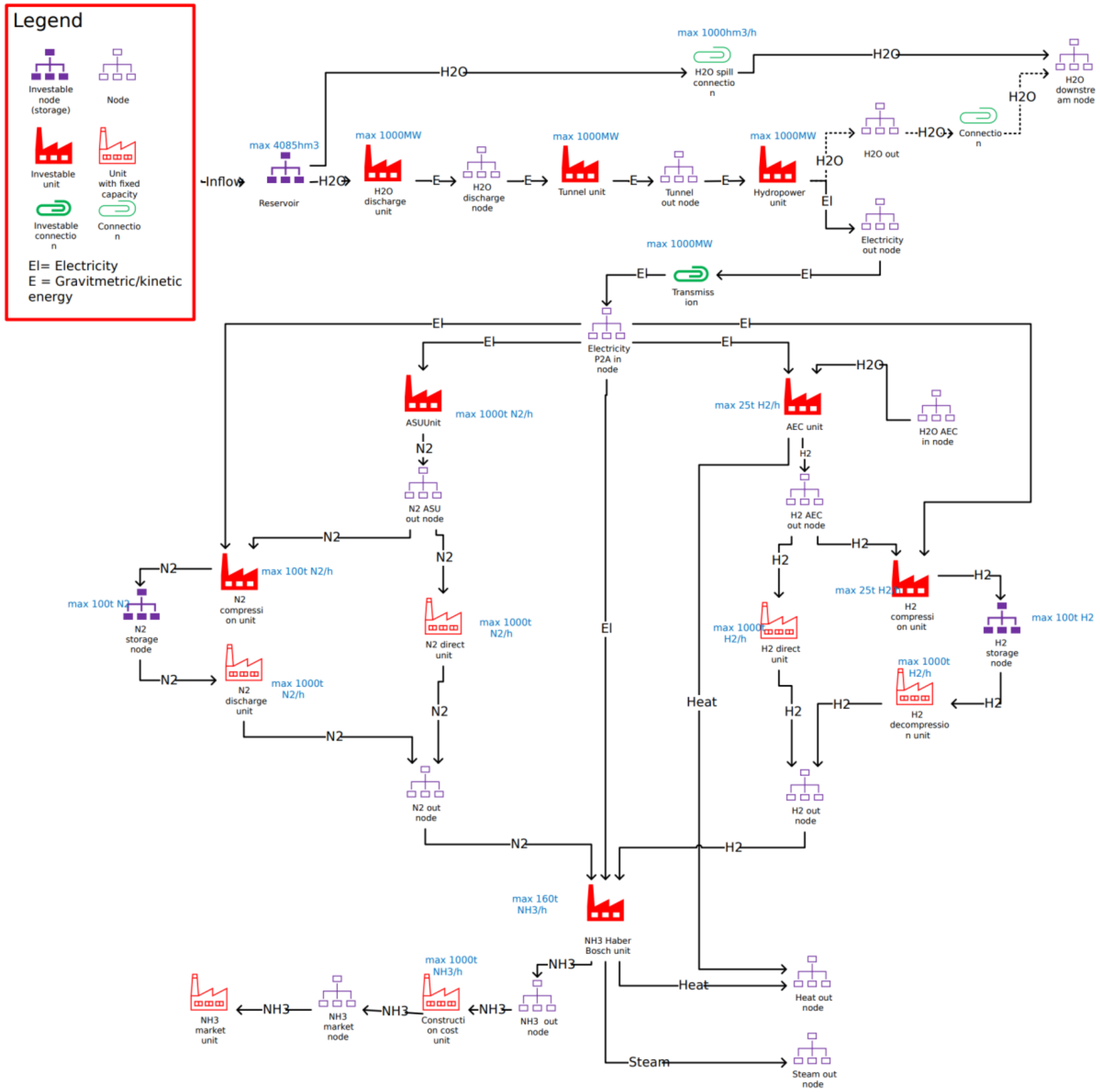


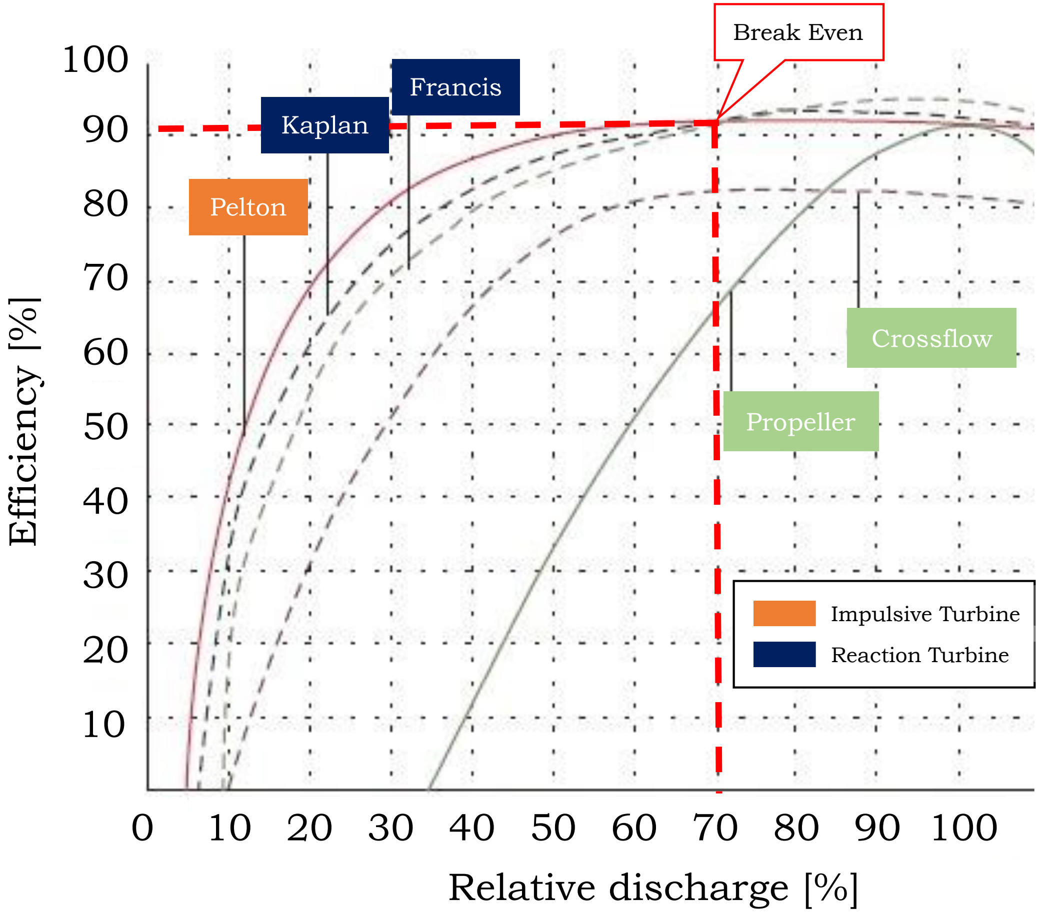
Figure A.1: Detailed illustration of the basic model implementation in SpineOpt

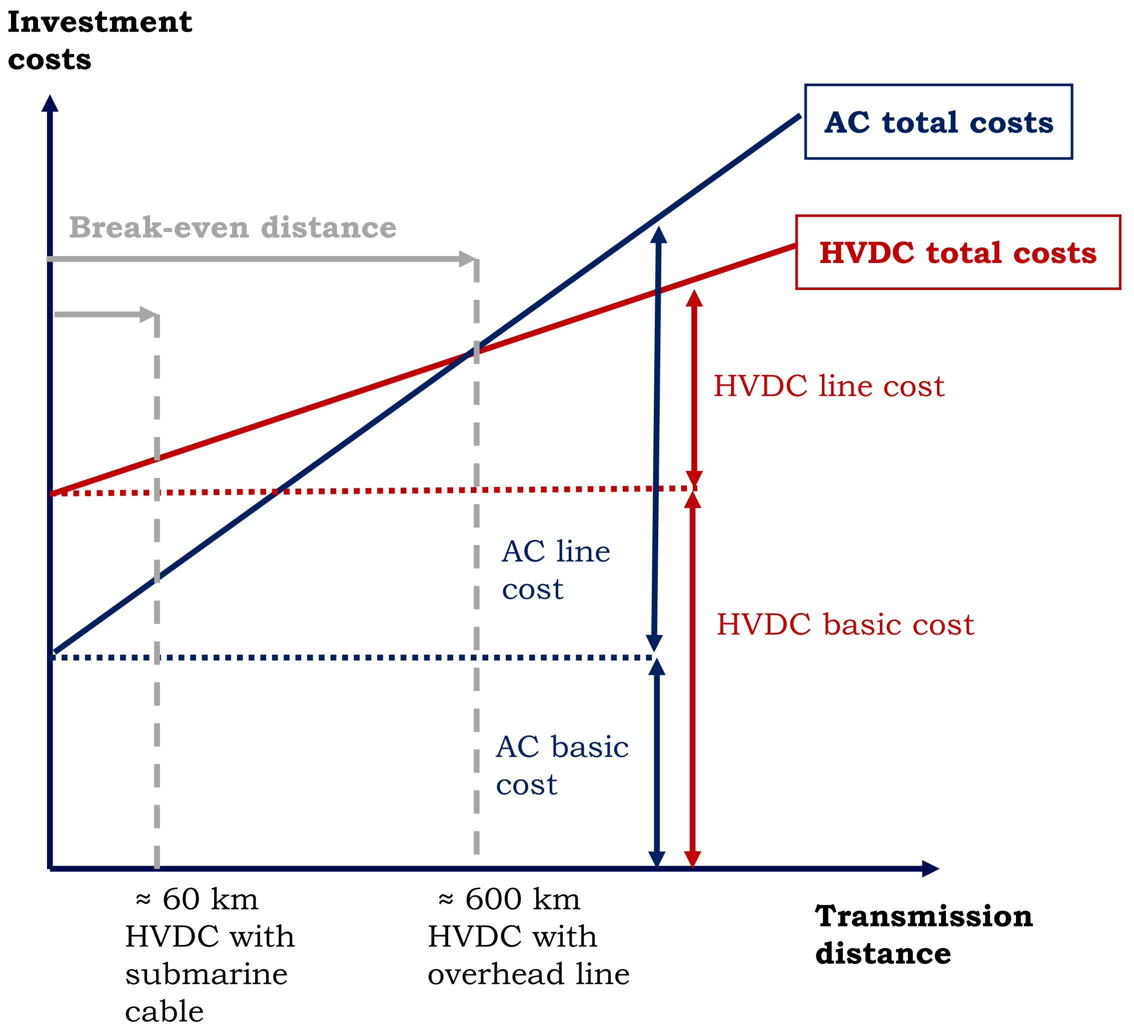
Cost estimations in the feasibility study

Table A.1: Fixed cost distribution in the PFS [63]

Category	Description	Cost [$ 2015]	Cost [€ 2009]
Direct Cost	Architectural works	474,981	311,944
	Port facility	4,050,016	2,659,848
	primary roads construction	45,875,129	30,128,491
	Civil works related to powerhouse, Tailrace tunnel and Surge tunnel	42,329,062	27,799,611
	Civil works related to power tunnel	130,717,844	85,848,944
	Dams and spillway	32,288,698	21,205,602
	Electrical Works	35,132,187	23,073,064
	Mechanical+electrical Works	120,575,844	79,188,186
	Architectural works	5,497,800	3,610,680
Indirect Cost	Temporary construction facilities	8,595,590	5,645,154
	Construction services	65,047,197	42,719,747
	Construction equipment, tools & supplies	74,738,361	49,084,419
	Material transportation	25,105,518	16,488,049
	Construction camp	107,729,334	7,075,124
	Insurance, taxes, permits, fees	25,871,461	16,991,082
	Miscellaneous	34,785,789	22,845,567
	EPCM Home Office	12,338,831	8,103,527
	EPCM Field Office	54,170,000	35,576,148
	Contingency	120,933,738	79,423,232
Transmission Line	Transmission line	93,900,000	61,668,825
	Substation	21,600,000	14,185,800
	T-line contingencies	11,500,000	7,552,625
Total		**1,073,257,380**	**704,861,784**

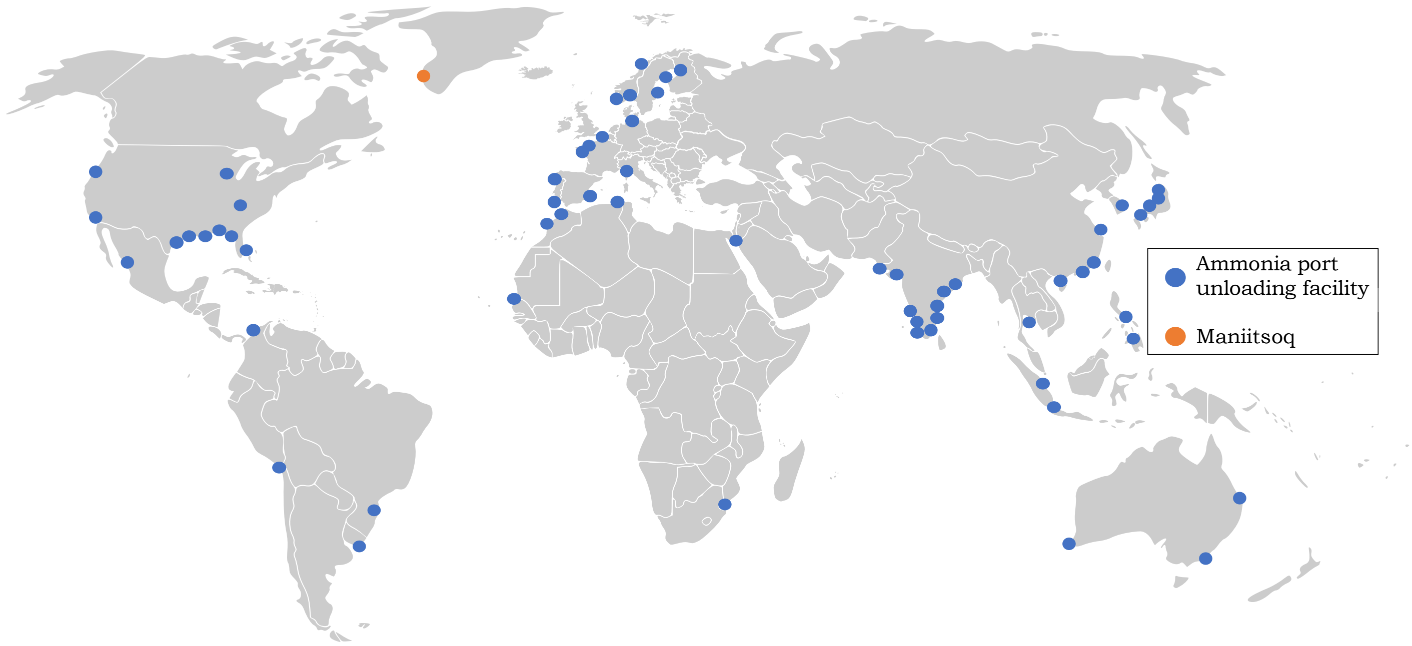
Choice of hydropower and transmission equipment





A growing population and energy transition increases the demand of green ammonia

- Need to reduce the high CO2 emissions associated with conventional ammonia production has underlined the growing importance of green ammonia
- Ammonia has many applications, with more than 70% of its production used for the fertiliser industry
- Promising developments are expected in the use of ammonia as power, heat or transport fuel. The maritime sector in particular is one of the key areas which is poised for significant market expansion
- 80% increase oft he worldwide ammonia production from 183 MtNH3 in 2020 to 2050 in a 1.5°C scenario
- European Union, India, and the United States emerge as principal importing regions and countries, collectively accounting for a significant portion of global ammonia imports, with shares of 24%, 14%, and 13% respectively
- cost of renewable ammonia is expected to be lower than that of conventional ammonia production due to CO2 pricing mechanisms

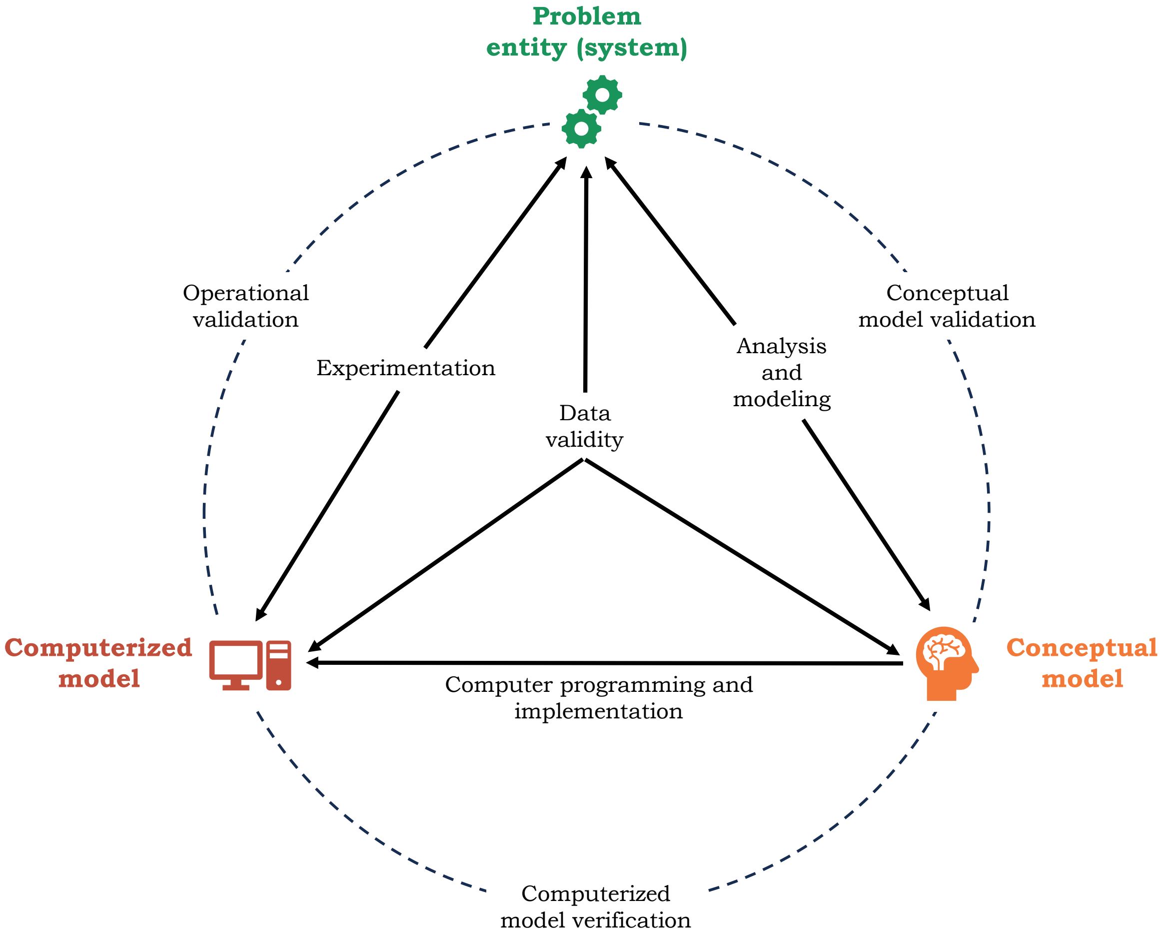


The model has been iteratively verified and validated

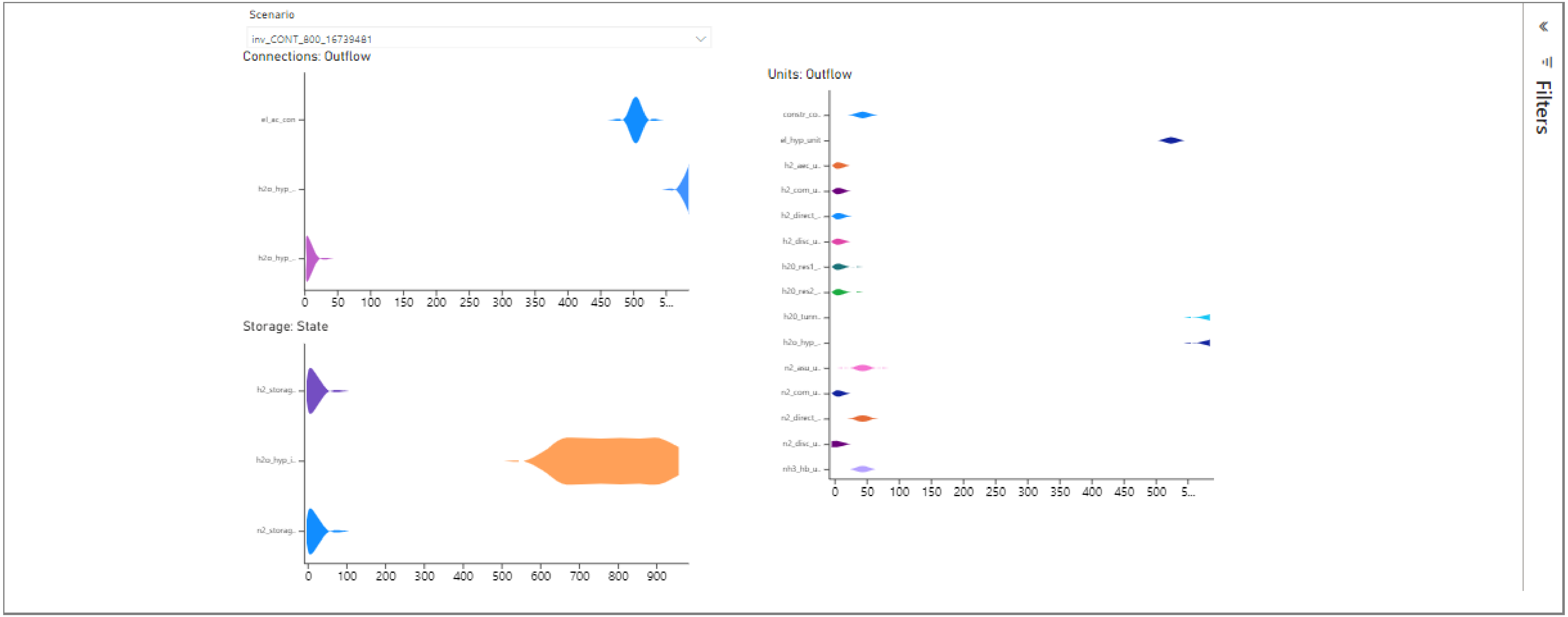
- Verification is a critical process that ensures that the implementation of a model accurately reflects the conceptual description of the model and the proposed solution.
- Validation, on the other hand, is the process of determining the extent to which a model is an accurate representation of the real world concerning the intended uses of the model.

- problem entity represents a real or proposed system
  - achieved through the conceptual model that is the mathematical representation
    - process of conceptual model validation involves ensuring that the underlying theories and assumptions are correct
  - conceptual model is created through an analysis and modelling phase. Then, the conceptual model is implemented on a computer referred to as the computerized model
    - process of operational validation involves assessing whether the model's output behaviour is sufficiently accurate for the intended purpose
    - modular programming; iterative implementation approaches, documentation to facilitate traceability and checking intermediate and final simulation outputs through tracing; animation through Power BI; extreme testing

  - data validity pertains to ensure that the data used in the model is reliable, representative and accurate



PowerBI Dashboard



TBL impact assessment

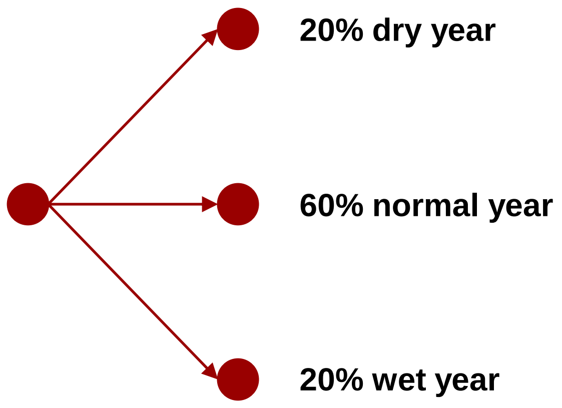
TBL	Impact	Connected opp. & ch.	SDG No.
Environ-mental	Fewer emissions through the replacement of energy from fossil fuels on local and global level.	[1][9]	13
	Footprint on the environment during construction, operation and decommissioning, e.g., through emissions.	[b][e]	13 [neg.] 15 [neg.]
Economic	Penetrate and showcase the attractiveness of green ammonia and enable investments in further renewable energy projects in Greenland.	[2][3][5][6] [a][h]	9 13 17
	Economic growth in the region. Distribute wealth across Greenland and enable more financial independence from Denmark.	[7]-[11] [g]-[i]	17
Social	Knowledge transfer.	[g][i]	4
	Tackling demographic challenges of an aging population.	[8][i]	3 4
	Increase wellbeing on local level through development of infrastructure, knowledge transfer etc.	[7]-[11]	7

Table 5.1: Opportunity mapping prior to impact derivation.

Opportunity			Challenge		
No.	Stake-holder(s)	Description	No.	Stake-holder(s)	Description
1)	[DEV]	Renewable ammonia production.	a)	[DEV]	Attractiveness of investment (profitability compared to other projects).
2)	[DEV]	High market share in the EU/USA for green ammonia.	b)	[DEV]	Safety.
3)	[DEV]	Incorporation of more sustainable practices in portfolio and its operations.	c)	[PA] [DEV]	Fulfil environmental standards (e.g., Water outflow, change of water level, ammonia leakage).
4)	[DEV]	Long time in operation compared to other renewable infrastructure projects.	d)	[PA] [DEV]	Minimize threats to flora fauna.
5)	[PA] [DEV]	Gain knowledge for tenders to provide framework for renewable energy projects (in Greenland).	e)	[PA] [DEV]	Minimize footprint in environment.
6)	[PA] [DEV]	Awareness of enabling large-scale renewable projects (especially in the arctic).	f)	[PA] [DEV]	Meet expectations of stakeholders and align actions (e.g., non-governmental-institutions (NGO) could harm more sustainable business practices).
7)	[PA]	Additional tax income.	g)	[PA] [DEV]	Inclusion of Greenland in project (e.g., local workforce).
8)	[PA] [L/GS]	Increase attractiveness of region.	h)	[PA]	Balance interests of foreign investors and greenlandic society.
9)	[PA] [L/GS]	Use of large scale renewable generated (by-) products (e.g., electricity, heat, oxygen) in e.g., Maniitsoq.	i)	[PA]	Attract workforce.
10)	[PA] [L/GS]	Expanding local infrastructure (e.g., accessibility, health care etc.).			
11)	[PA] [L/GS]	Boosting local industry and attract new industries (e.g., more opportunities for tourism such as hot swimming pools).			

Stochastic tree

- Run each deterministic scenario to obtain optimal scale
- Run “simulations” with given scales for each of the 3 water inflow series (no uncertain parameters anymore)
- Determine overall best scale for distribution of water inflow series based on weighted average



What is the optimal installed capacity based on the stochastic tree?