Master Thesis

TIL5060

Decentralized off-grid PV hydrogen production based on small-capacity electrolyzers

Determining the System LCOH - a case study for 6 kW electrolyzers

by

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Executive Summary

Hydrogen is emerging as renewable energy carrier as plausible means to decrease the global dependency on fossil fuels [1]–[3]. Various production routes are known for hydrogen. Hydrogen production based on renewable energy and electrolysis is a technically mature and well-researched production process. The processes based on large electrolyzers result in varying and relatively high (up to ± €14/kg) levelized costs of hydrogen - attributable to high electrolyzer and electricity costs [4]–[11].

Most recently, a study determining the levelized cost of hydrogen (LCOH) of PV-electrolyzer based hydrogen on a 100-200 MW electrolyzer by TNO, estimated electrolyzer costs at €3050/kW. The found LCOH was €13,68/kg - of which ± €7,50/ kg was attributable to electricity costs, of which nearly a third is due to the electricity grid tariff [11]. Thus reducing the electrolyzer and electricity costs can bring the LCOH to a more market-competitive range.

A lower electrolyzer cost can be realized when mass producing small-capacity electrolyzers, this has been evaluated by Zero Emission Fuels (ZEF) throughout their development process of a 6 kW alkaline electrolyzer. The expected electrolyzer costs are anticipated between €440-500/kW [12]. The electrolyzers are designed to be directly coupled to solar panels, eliminating the need for grid connection. These characteristics are the motive for this research. In this research, the potential of an off-grid and photovoltaic powered green hydrogen farm that is based on multiple small-capacity electrolyzers, is evaluated. The 6 kW electrolyzer that is directly coupled to solar panels are used as hydrogen production component.

The potential of such a hydrogen farm is evaluated by verifying the technical feasibility of the small-capacity electrolyzer incorporated in a complete hydrogen production farm setup, and by calculating the LCOH of resulting hydrogen farms. To this end, a water supply system and hydrogen outflow system is designed. Different designs are made in this research, where design choices are dependent on the farm location and size in order to answer the main research question:

*What system **size** and **geographical location requirements** are necessary to achieve a **market-competitive** Levelized Cost of Hydrogen for an off-grid, photovoltaic and 6 kW electrolyzer hydrogen production process?*

As an initial evaluation of the potential of an off-grid PV and small-capacity electrolyzer based hydrogen farm, the scope is limited to obtaining water from the water source, distribution across the farm to electrolyzers, production of hydrogen and collection hereof to a centralized point on the farm, with the possibility of compression and storage on the farm. The scope is limited to including mature technologies that are available on the market. The evaluation is limited to three farm sizes, namely 50 MW, 150 MW and 1,5 GW, and to two plausible farm locations: Ínsua, Portugal and Al Buraimi, Oman. For all farms, a lifetime of 30 years is assumed.

Simplifications and assumptions have been made regarding the PV-electrolyzer components. A set number of solar panels (10) is used per electrolyzer, no solar irrandiance and subsequent fluctuation of production is quantified and incorporated - though mentioned for some design aspects such as piping. The assumption of 600 Watt effective energy per solar panel is used alongside an average daily production based on the equivalent sun hours (ESH) of the location. Production quantities of the electrolyzer are assumed as 0,125 kg of 50 bar hydrogen per ESH per electrolyzer as given by ZEF and done in previous studies regarding this electrolyzer [12], [13].

To answer the main research question, the methodology of this research follows the order of three sub-questions which inquire the possible alternatives for a water supply system, a hydrogen outflow system, and the resulting LCOH of resulting farm configurations. Thus, first alternatives for a water supply system are designed. The same is done separately for hydrogen outflow systems. Resulting alternatives are then combined with the PV-electrolyzer element of the farm for final LCOH calculation. Designing of the water supply - and hydrogen outflow systems is based on qualitative evaluation including expert input as well as it is based on qualitative cost-related assessment.

The water supply system design consists of a water source, transport of (sufficient) water to the farm, water treatment, and distribution to electrolyzers. For both locations, water grid and water from waste water treatment plants (WWTPs) resulted as water sources with highest scoring availability and least water treatment required. When using water from the grid at both locations, reverse osmosis is required as water treatment. Urban wastewater of Ínsua requires fine screening. ultrafiltration and reverse osmosis, while Al Buraimi's urban and industrial wastewater requires only ultrafiltration and reverse osmosis. All water sources require electrodeionization and a mixed bed filter to result in demineralized water [14].

To obtain water to the farm, due to the constraint of market availability, no technologies that could avoid a pipeline for water transport - by e.g. generating water on-site - are considered. This causes the farm to include a grid-like structure: to no longer be fully off-grid. Distribution across the farm can be done with minimal diameter size PVC pipelines, no intermediate pumping required throughout the farm. The pressure losses are within the pressure holding capacity of PVC (16 bar), and result in water between 2 and 5 bar pressure to be delivered at every electrolyzer [15]. To obtain water to the farm, due to the constraint of market availability, no technologies that could avoid a pipeline for water transport - by e.g. generating water on-site - are considered. As all farms demand volumes of water that are only possible to acquire through pipeline transport, tis causes the farm to include a grid-like structure: to no longer be fully off-grid. Energy for the water supply system is supplied with additional PV on the farm - possibly using a battery for backup and redundancy though this is excluded from the research scope.

Results of the water supply system design choices show that for both locations, the 50 MW farms perform best when using grid water - which is a higher water cost per m3 to obtain, but requires less water treatment equipment and thus investment. The larger farm sizes can spread the investment costs for additional water treatment across higher water volume demands which allows them to benefit from lower water costs for water from WWTPs. The qualitative assessment used for selecting the water source was based on several criteria which each received equal weight [16], [17]. It is suggested for further research and/or project development to assign weights that better represent i.a. local policies and importance, etc. Cost estimates of the system are based on literature and are supported by quotations from suppliers and expert validation. For pipeline transport specifically, one estimate was used for all farms which is certain to overestimate the costs for especially the smallest farm sizes, possibly for the 150 MW farm size as well [16]. This estimate was used as no other reliable quotes were found. Overall, due to being a centralized system with equipment that provided benefits in terms of economies of scale, the water supply system favours larger farm sizes in terms of costs/m3 water.

For the hydrogen outflow system the on-site collection network is designed to be made of welded carbon-steel in a ring pipeline layout (to improve system redundancy). Based on pressure loss calculations, it is possible to achieve both minimal diameter pipeline sizes while also maintaining minimal pressure losses - and allowing for up to mass flow rate of at least five times the production [18]–[20]. The pipeline allows for intermediate storage of produced hydrogen as well. Hydrogen compression is achievable when utilizing two piston compressors installed in serie - it is the best performing technology in terms of maturity, flow management and compression range [21], [22]. Furthermore, it provides flexibility in operations as it has a full turndown ratio [23]. Hydrogen storage with aim of export from the farm is only possible using type IV hydrogen cylinders. The numbers of tanks required for even the smallest farm size is difficult to achieve from a practical and logistical perspective. It is only considered for the 50 MW farm size [24].

Compressing to 700 bar is common for hydrogen usage in the transport sector. However, the purity of hydrogen that is produced is at 99.5% , and thus too low for the transport sector (requiring a purity of 99.9%). Due to time limitations this research does not include a purification step, or assessment to compress to other pressures - though compression to 500 bar will require equal equipment investment and energy requirements will change insignificantly.

For LCOH calculation, the PV-electrolyzer element of the farm is first determined for each farm size, of which the CAPEX includes land costs, transport, installation, etc. Next all designed systems were combined to result in a total of seven farm designs per farm location:

- Water system and hydrogen collection (50 MW, 150 MW, 1,5 GW)
- Water system and hydrogen collection with compression (50 MW, 150 MW, 1,5 GW)
- Water system and hydrogen collection with compression and storage (50MW)

The initial LCOH calculation shows LCOHs ranging from €2,15-5,10/kg. Farms includes less system components in the hydrogen outflow system, result in a lower LCOH. Farms in Al Buraimi, due to a higher average running hours, result in more production, which is reflected in lower LCOHs for each respective design option.

The emerged water supply system favours larger farms; so does the hydrogen compression system. The on-site collection of the hydrogen system increases with farm size - favouring smaller farms sizes. The influence of these systems is minimal compared to that of the main cost contributor: the PV-electrolyzer system and more specifically, the electrolyzer costs. These account for at least 85% of the LCOH, of which 85% is attributed to electrolyzer costs. As this systems costs scale linearly with the farm size, benefiting smaller farm sizes, the final system shows lowest costs for the smallest farm size of 50 MW.

Critical factors are introduced to the respected system to account for simplifications and underestimations. The water supply system was multiplied by a factor of 2, the hydrogen supply system by a factor of 3 for smaller farm sizes and by 4 for the largest farm size (due to its novelty and scale) and PV-electrolyzer costs were increased by 20%. With critical factors implemented, the water supply - and hydrogen outflow system remain to take up at most 13% of the total farm costs. The lowest LCOH is realised in Al Buraimi for the 50 MW farm including on-site hydrogen collection only: **€2,92/kg**.

This research shows that even with limited running hours, the low cost per kW of the electrolyzer in combination with the relatively low costs of water supply and hydrogen outflow system, the off-energy-grid PV and 6 kW electrolyzer farms can lead to an LCOH that forms only ± 20% of the calculated LCOH for a centralized and grid connected PV-electrolyzer process [11]. This is further facilitated due to the electricity costs being as low as €0,013-0,007/kWh (Ínsua - Al Buraimi) and no additional energy grid related costs.

To conclude, there is technical and market potential for off-energy-grid PV and 6 kW electrolyzer farms. Their critical advantages are the low electrolyzer and low electricity costs. Even with limited running hours, and the electrolyzer cost taking up most of the total costs, the addition of a water supply and hydrogen outflow system do not jeopardize the market-competitiveness of the resulting LCOH.

Preface

The master Transport, Infrastructure and Logistics offers much flexibility in specialization and combination with other fields. As BSc Life Science & Technology, I tended to the direction of sustainability within chemical engineering and biochemical processes - writing my thesis on Sustainable Aviation Fuels and production processes hereof. It seems as though regardless of the faculty or field of study, I remain drawn to the evaluation of emerging sustainable energy carriers or technologies.

The TIL master provided a new set of design angles to approach upcoming technologies or logistical processes. It has been a broadening and challenging experience to methodologically combine all angles of interest - inevitably some aspects as optimization were left out. Nevertheless, it has been extremely engaging and rewarding to apply design theory with more 'creative' and investigative freedom.

It has been enjoyable to engage and discuss with experts in the fields, from technical experts to sales experts and project officers. I would like to thank Pim Reuderink, Peter Cloos, and Ted Wildenberg for their efforts and input, which have been extremely helpful. Learning about current hydrogen projects and exchanging intermediate findings

I would like to express deep gratitude to Jaap Vleugel, my main supervisor for being exceedingly supportive of my study interests, to help set up this thesis project, and to be flexible throughout the process. To Kenneth Bruninx, for valuable feedback and the adding alternative perspectives to the research. To Zofia Lukszo for supporting and facilitating this research of unconventional methodologies as chair, and to Ad van Wijk for encouraging this project into realisation.

I would like to thank Hessel Jongebreur for the opportunity to perform an evaluation based on the 6 kW ZEF electrolyzer in its final development and testing stages. The ease and readiness to provide input and support for the research is greatly appreciated.

Finally, I would like to thank all family and friends for their support and encouragement - for keeping me going through the process.

Content

1 Introduction 1

1.1 Supplying the hydrogen market . . . 1
1.2 Exploration of small-capacity electrolyzers . . . 1
1.3 Hydrogen production farm completion . . . 2
1.4 Problem statement . . . 4
1.5 Research goal . . . 5
1.6 Research questions . . . 5
1.7 Structure of the thesis . . . 5

2 The 6 kW electrolyzer 6

2.1 Solar power . . . 6
2.2 Hydrogen production . . . 6
2.3 Technology readiness level (TRL) . . . 7
2.4 Differences from literature . . . 8

3 Literature review 9

3.1 Solar to hydrogen technologies . . . 9
3.2 Water supply systems . . . 11
3.3 Hydrogen outflow systems . . . 12
3.4 Levelized cost of hydrogen (LCOH) . . . 14
  3.4.1 CAPEX and OPEX . . . 15
  3.4.2 Levelized cost of electricity (LCOE) . . . 15
  3.4.3 Overhead costs . . . 16
  3.4.4 Hydrogen yield . . . 17
3.5 Discussion . . . 17

4 Methodology 19

4.1 Design Goal . . . 20
4.2 Design Conceptualization . . . 21
4.3 Design Selection and Evaluation . . . 21
4.4 Design Evaluation based on LCOH . . . 21

5 Water Supply System Design 23

5.1 Design Goal . . . 23
  5.1.1 Water source requirements . . . 23
  5.1.2 Water quality and quantity requirements . . . 24
  5.1.3 Infrastructural requirements . . . 26
  5.1.4 Energy and transportation requirements . . . 28
  5.1.5 Requirement overview . . . 29
5.2 Design Conceptualization . . . 32
  5.2.1 Water source . . . 32
  5.2.2 Water purity . . . 33
  5.2.3 Water pressure . . . 38

5.2.4 Water quantity . . . 39
5.2.5 Infrastructure . . . 41
5.2.6 Energy . . . 51
5.2.7 Morphological chart . . . 52
5.3 Design Selection and Evaluation . . . 54
5.3.1 Water source . . . 54
5.3.2 Water purity . . . 58
5.3.3 Water pressure . . . 60
5.3.4 Water quantity . . . 60
5.3.5 Infrastructure . . . 61
5.3.6 Energy . . . 62
5.3.7 Transportation . . . 65
5.3.8 Discussion - critical design components, system redundancy and flexibility . . . 67
5.3.9 Data validation and calculation verification . . . 68
5.3.10 Cost estimation - CAPEX and OPEX . . . 70
5.4 Conclusion . . . 76

6 Hydrogen Outflow System Design 77
6.1 Design Goal . . . 77
6.1.1 On-site hydrogen collection requirements . . . 77
6.1.2 Hydrogen compressing requirements . . . 78
6.1.3 Hydrogen storage requirements . . . 79
6.1.4 Requirement overview . . . 80
6.2 Design conceptualization . . . 83
6.2.1 On-site hydrogen collection . . . 83
6.2.2 Hydrogen compression . . . 90
6.2.3 Hydrogen storage . . . 93
6.2.4 Morphological chart . . . 94
6.3 Design Selection . . . 96
6.3.1 On-site hydrogen collection . . . 96
6.3.2 Hydrogen compression . . . 96
6.3.3 Hydrogen storage . . . 98
6.3.4 System design overview . . . 98
6.3.5 Discussion - critical design components, system redundancy and flexibility . . . 99
6.3.6 Data validation and calculation validation . . . 99
6.3.7 Cost estimation and discussion . . . 101
6.4 Conclusion . . . 104

7 Combined system evaluation: LCOH 105
7.1 Hydrogen farm designs . . . 105
7.2 CAPEX and OPEX for PV-6 kW electrolyzer system . . . 107
7.3 LCOH calculation . . . 108
7.3.1 Discussion . . . 108
7.4 LCOH sensitivity . . . 109

7.4.1 Discussion 111

8 Conclusions **112**

9 Discussion **115**

9.1 Limitations 115
9.2 Reflection on methodology 116
9.3 Recommendations for future research 117

10 Appendices **127**

10.1 Appendix I: Water supply system cost breakdown for all farms 127
10.2 Appendix II: Weymouth, Panhandle A, and Panhandle B equations 133
10.3 Appendix III: List of Assumptions 134
10.4 Appendix IV: Research Paper 135

List of Figures

1 Model ZEF electrolyzer and solar panels [12] 2
2 Schematically depicted off-grid small capacity electrolyzer hydrogen farm, for three electrolyzers, based on 620 Watt solar panels 3
3 ZEF hydrogen process schematically 7
4 Methodology and research for evaluation water sources for hydrogen production through electrolysis by Catarino et al. and Simoes et al [16], [17] 12
5 Overview of the methodology 19
6 Process tree methodology [63] 20
7 Design specification method [63] 21
8 Weighted objective method [63] 21
9 Coagulation-flocculation process graphically depicted [93] 34
10 Mixed bed system, graphicallu [97] 37
11 EDI schematically [97] 38
12 Schematic flowchart for the water supply system 41
13 Schematic farm layout. Separation of water treatment area and solar-to-hydrogen area 44
14 Example setup of trakcer-system by CHINT [33] 45
15 Schematically presented row sets for the water feed system on the hydrogen farm. 48
16 Depiction of elbows in main pipeline over the hydrogen farm 51
17 Selected water sources for farms in Ínsua and Al Buraimi 58
18 Filtering and demineralization methods to ensure water purity for the different water sources at both farm locations 60
19 Means for ensuring water pressure and all previously defined system functions for the water supply system 60
20 Selected means for water quantity and all other system functions. 61
21 Selected means for infrastructure and all other system functions for the water supply system. 62
22 Selected means for energy and all prior system functions of the water supply system. 65
23 Final overview of all selected designs and the means for their system functions. 67
24 Cost breakdown for the 50 MW farm in Ínsua for water grid and urban waste water 72
25 Cost breakdown for the 150 MW farm in Ínsua for water grid and urban waste water 73
26 Cost breakdown for the 1,5 GW farm in Ínsua for water grid and urban waste water 74
27 Schematic overview for the hydrogen collection pipeline system of an off-grid PV 6 kW hydrogen farm. Green lines indicate the column pipelines to which electrolyzers are connected, red lines are the row pipelines which are connected to all column pipelines and form a ring pipeline structure . . 85
28 Schematic overview of the an electrochemical compressor by Danghi et al., [22] 91
29 Means for the system functions of the hydrogen outflow system design selections 99
30 CAPEX and OPEX contribution to total costs per subsystem, for 50 MW farm sizes of Al Buraimi and Ínsua which include only on-site hydrogen collection as hydrogen outflow system. 109
31 CAPEX and OPEX contribution to total costs per subsystem including critical Lang factors, for 50 MW farm sizes of Al Buraimi and Ínsua which include only on-site hydrogen collection as hydrogen outflow system. 111
32 Cost breakdown for the 50 MW farm in Ínsua for water grid and urban waste water 127
33 Cost breakdown for the 150 MW farm in Ínsua for water grid and urban waste water 128

34 Cost breakdown for the 1,5 GW farm in Ínsua for water grid and urban waste water 129
35 Cost breakdown for the 50 MW farm in Al Buraimi for water grid and urban waste water 130
36 Cost breakdown for the 150 MW farm in Al Buraimi for water grid and urban waste water 131
37 Cost breakdown for the 1,5 GW farm in Al Buraimi for water grid and urban waste water 132
38 Weymouth, Panhandle A, and Panhandle B equations for pressure loss calculations, used in the LMNO calculator 133

List of Tables

1 Hydrogen production pathways utilizing solar energy [36]–[40] 10

2 Farm size, number of electrolyzers and average daily production of hydrogen calculated based on the 6 kW electrolyzer, molecular weight of hydrogen, and average running hours per day [12], [13] 20

3 System functions and functional constraints for the water supply system 30

4 System functions and non functional constraints for the water supply system 30

5 System functions and functional objectives for the water supply system 30

6 System functions and non functional objectives for the water supply system 31

7 Plausible water sources for both farm locations 33

8 Water filtering methods and the pollutants each removes, average energy usage based on a centralized filtering system, water losses and waste production [16], [93]–[95] 36

9 Water demineralization method and average energy usage based on a centralizedfiltering system, water losses and waste production and efficiency [14], [94], [97] 38

10 Hourly water demand for different farm sizes depending on treatment process. 39

11 Daily water demand for different farm sizes and locations depending on treatment process. 40

12 Initial water storage tank sizes and costs as presented in Table 11 [16] 42

13 Initial water storage tanks required in case piping is used to supply water 42

14 Tank sizes and costs for the final storage tanks [16] 43

15 Estimated CAPEX in EUR for water filtering and demineralization methods, based on values by Simoes et al. and Puretec B.V [16], [96] 45

16 Dimensions for the three farm sizes, considering that one tracker table supports solar panels for 10 electrolyzers and has a length of 116 meters, and the distance between rows is 3 meters [33] 46

17 Flow rates required per farm size, using the flow rate per unit per hour of 1,082 L and 20% leakage losses throughout the pumping and piping distribution system. Values of usage for Ínsua have been used to derive the average water usage per electrolyzer row - this is equal value for the Al Buraimi farm (see water usage and ESH Al Buraimi of Table 12) 48

18 PVC pipes required per row set for the 50 MW farm, including the length of the PVC pipe covering the row set 49

19 PVC pipes required per row set for the 150 MW farm including the length of the PVC pipe covering the row set 49

20 PVC pipes required per row set for the 1,5 GW farm including the length of the PVC pipe covering the row set 49

21 PVC pipes required for the suction pipes of all farm sizes - note that the speed of 1,3 is used for the 1,5 GW farm as the largest standard PVC pipe available has a diameter of 315mm. 50

22 Pressure loss estimation for all row sets for all farm sizes 50

23 Overview of the water supply system functions and means. * only available for Ínsua ** only available for Al Buraimi 53

24 Non-functional objectives for water source selection and evaluation 55

25 Non-functional objectives and their corresponding criteria for the qualitative assessment of water sources by Simoes et al. [16] 55

26 Non-functional objectives and their corresponding criteria for the qualitative assessment of water sources by Simoes et al. continued [16] 55

27 Qualitative assessment of water sources for rural areas in Portugal by Simoes et al. - validated for Ínsua, Portugal [16] . . . 56
28 Qualitative assessment of water sources for Al Buraimi, Oman. . . . 57
29 Water costs depending on the type of water source and location [81], [82], [88] . . . 58
30 Overview of the initial and final storage tank sizes and costs for all farm sizes and both locations. . 61
31 PVC piping and installation costs for all farm sizes, based on quotes provided by Aqualeap B.V. (by Artechno group B.V) [15] . . . 62
32 Energy requirements for Ínsua and Al Buraimi when grid water is taken as source. Energy usage per system function derived from literature, technical reports and manufacturers. . . . 63
33 Energy requirements for Ínsua and Al Buraimi when wastewater is taken as source. Energy usage per system function derived from literature, technical reports and manufacturers. . . . 63
34 Solar panels and corresponding CAPEX and OPEX required to provide energy to farms utilizing grid water as water source for Ínsua and Al Buraimi. Calculation based on 600 Watt effective energy production per solar panel, average ESH per location, and provided CAPEX and OPEX per solar panel per farm location by ZEF. . . . 64
35 Solar panels and corresponding CAPEX and OPEX required to provide energy to farms utilizing wastewater as water source for Ínsua and Al Buraimi. Calculation based on 600 Watt effective energy production per solar panel, average ESH per location, and provided CAPEX and OPEX per solar panel per farm location by ZEF. . . . 64
36 Estimated CAPEX for water transport of source water to the farm, based on estimates found in literature, suggestions by experts at Aqualeap B.V., and quotations and estimates provided by pump supplier Van der Ende Group. . . . 66
37 Total CAPEX and OPEX estimations for two water sources per farm location, for all farm sizes, in euro (€). The water quantity is not discounted for this calculation. . . . 75
38 System functions and functional constraints for the hydrogen outflow system . . . 81
39 System functions and non-functional constraints for the hydrogen outflow system . . . 81
40 System functions and functional objectives for the hydrogen outflow system . . . 82
41 System functions and non-functional objectives for the hydrogen outflow system . . . 82
42 Farm dimensions and production quantities for all three farm sizes . . . 86
43 Resulting mass flow rate and velocities for plausible column pipeline sizes along the length of the 50 MW farm. . . . 87
44 Resulting mass flow rate and velocities for plausible row pipeline sizes along the length of the 50 MW farm. . . . 87
45 Resulting mass flow rate and velocities for plausible column pipeline sizes along the length of the 150 MW farm. . . . 88
46 Resulting mass flow rate and velocities for plausible row pipeline sizes along the length of the 150 MW farm. . . . 88
47 Resulting mass flow rate and velocities for plausible column pipeline sizes along the length of the 1,5 GW farm. . . . 89
48 Resulting mass flow rate and velocities for plausible row pipeline sizes along the length of the 1,5 GW farm. . . . 89
49 Pipeline lengths and sizes for all farms and the final pressure of hydrogen prior to compression. . . . 89

50 Calculation of carbon steel pipeline costs based on the price of €1/kg and production - (2), and installation factor including welding (1,5) [19], [20] 90
51 Total pipeline cost calculation for all farm sizes, based on the cost per km as determined in Table 50. 90
52 Characteristics of hydrogen compression technologies which are currently in use on the hydrogen market 92
53 Daily production quantities for all farm sizes in both locations determined with the average ESH, assuming complete compression (100% conversion) and the ideal gas law at a constant temperature of 25 C, required number of 994 L storage tanks are given for a daily and hourly rate according to the average ESH. 93
54 Tank costs for all farm sizes, based on the estimated €13.500 per type IV tank [18], [24], [111]–[113] 94
55 Morphological chart for the three system functions of the hydrogen outflow system. 95
56 Production flows for all three farm sizes on an hourly basis, quantities for compression. *hydrogen at 46 bar **hydrogen at 45 bar. 96
57 Compressor CAPEX and OPEX for all farm sizes as given by Siemens Energy [23] 98
58 Minimal amount of solar panels required to support compressors per farm size, based on 0,6 kW solar panels, average ESH and estimated energy usage of 5 kWh/kg hydrogen. 98
59 Discounted production quantities for all farm sizes based on a 5% discount rate. 102
60 Total CAPEX and OPEX for design selection one, for all farm sizes and both locations. 103
61 Total CAPEX and OPEX for design selection two, for all farm sizes and both locations. 103
62 Total CAPEX and OPEX for design selection three, for all farm sizes and both locations. 103
63 Hydrogen farm design configurations for LCOH calculations 106
64 CAPEX and OPEX for PV (including equipment) and electrolyzer cost (including BoP, installation and transportation) as determined in the previous TIL study and provided by ZEF. [12], [13] 107
65 CAPEX and OPEX for PV (including equipment) and electrolyzer cost (including BoP, installation and transportation) as determined in the previous TIL study and provided by ZEF. [12], [13] 107
66 LCOH calculation for all selected hydrogen farm design configurations for Ínsua. 108
67 LCOH calculation for all hydrogen farm design configurations for Al Buraimi. 108
68 LCOH calculation considering higher Lang factors for all selected hydrogen farm design configurations for Ínsua. 110
69 LCOH calculation considering higher Lang factors for all selected hydrogen farm design configurations for Al Buraimi. 110
70 Reference LCOH and LCOH including critical Lang factors for all selected hydrogen farm configurations. 113

1 Introduction

1.1 Supplying the hydrogen market

The Netherlands aims to be reliant on sustainable energy sources with little to no carbon emissions by 2050. One of the prospective means to this end is (green) hydrogen [1]. Plans for facilitating the transition to hydrogen usage include subsidies for producers, planning for a national hydrogen network – known as the hydrogen backbone – and providing infrastructure for hydrogen import. Initial hydrogen terminals are planned to be built by 2025, as it is estimated that a large portion of the hydrogen supply will be imported from various privatized producers [2], [3].

The leaders of the green hydrogen industry predominantly use solar and wind energy in combination with electrolysis for hydrogen production. Established green hydrogen suppliers use a form of renewable energy to operate large electrolyzers which can range from 10-200 MW in daily production capacity [25].

A less frequent path for large scale hydrogen production is by using multiple smaller electrolyzers. The usage of small capacity electrolyzers could prove cos-efficient in terms of smaller overhead installation costs and less safety risk in comparison to a large centralized electrolyzer [26], [27]. Zero Emission Fuels (ZEF) is a potential green hydrogen producer of this sort.

1.2 Exploration of small-capacity electrolyzers

ZEF is a start-up that focuses on zero emission solutions that require no energy grid and are based on solar panels for energy. Over the period of 2017 to 2024 ZEF has developed a microplant that converts air into methanol which is connected to solar panels and runs off-grid. The microplants consists of three subsytems: a DAC unit - which captures water and CO2 from air - an alkaline electrolyzer - which converts water into hydrogen - and a methanol reactor - which combines CO2 and hydrogen to form methanol. An alternative use for the alkaline electrolyzer is as standalone unit: producing off-grid solar hydrogen. The small-capacity electrolyzer (6kW) has a relatively lower production cost than that of industrial scale electrolyzers (price per kW) as results of mass production, novel production technologies, and integrated power control. Project realization costs can be limited by installing mass produced electrolyzers across a large surface area - compared to a large centralized electrolyzer unit and its corresponding installation costs. However, the thousands of decentralized electrolyzers each must now be supplied with water, and, must be provided with an outflow system for its produced hydrogen. There is thus a trade off between a decreased production (and installation) costs and complexity for the electrolyzer units, against an increase of complexity in water supply and hydrogen outflow system [12].

The developed 6 kW electrolyzer can be directly coupled to - and is powered by - solar panels. The solar panel and coupled electrolyzer system functions without connection to the energy grid, as a modular and mobile unit and requires no manual maintenance or on-site operational labor. A schematic model of the electrolyzer coupled to solar panels is shown in Figure 1.

Figure 1: Model ZEF electrolyzer and solar panels [12]

1.3 Hydrogen production farm completion

The off-grid, photovoltaic and 6 kW electrolyzer hydrogen production process will require a water supply and an on-site hydrogen collection system - including centralized storage of produced hydrogen of 99.5% purity at 700 bar and at 45 bar. This scope is depicted in Figure 2, with the to-be-designed systems in red.

Ideally, all systems of the hydrogen farm are in alignment with an off-grid approach. The initially intended method for obtaining water off-grid was through direct air capture (DAC). DAC is a technology where CO2 and vapor (water) are captured from the atmosphere. Water can in turn be used as feed for the electrolyzer to produce hydrogen.

However, DAC will not suffice as method for obtaining water for solely hydrogen production. This is due to the fact that CO2 is not required for hydrogen production. The required energy for the DAC to capture CO2 and vapor, separate the two from each other, and separate both from remaining pollutants in the atmosphere, is not used efficient if CO2 is simply released back into the atmosphere [12], [28].

Usage of DAC was tested by Solhyd, a company offering direct solar to hydrogen in the form of a hydrogen-solar panel. Solhyd initially started with DAC to supply a catalyst sealed membrane that produces hydrogen. Due to the inefficient energy usage, the process was altered to using moisture adsorbing materials, from which water could be derived. This process eliminates the role of CO2 for obtaining water. This technology however, does not supply enough water for an electrolyzer to run. The order of magnitude in production difference between a hydrogen-panel and panels connected to an electrolyzer coupled to 10 solar panels is a factor 10 (0,02-0,04 kg of hydrogen [28] compared to 4 - 8 kg of hydrogen [12]). Moreover, running the DAC on solar energy alongside the electrolyzer implies more system components and coordination required between these technologies - an increased complexity of the production process - as well as an additional amount of solar panels [12], [28], [29].

A novel method for off-grid water production is atmospheric water generation (AWG). AWG technology extracts moisture from the air through condensation, typically using refrigeration or desiccation methods [30]. It's particularly valuable in arid or remote regions where access to clean water is limited. The technology was deemed suitable and sustrainable in energy usage for supplying electrolyzers with sufficient clean water for hydrogen production by one recent study [31]. However, most overviews on AWG show that commercial deployment of AWG systems and AWG machines are still far due to high costs and lack of optimisation [30].

Commercial availability of systems required for the completion of the hydrogen farm is crucial for the scope of this research. Therefore, a system based on existing technologies on the market wherein sufficient water can be obtained without significant energy use and complexity for each individual electrolyzer will be designed for an off-grid, photovoltaic and 6 kW electrolyzer hydrogen production farm.

As for hydrogen outflow system, the following holds. Produced hydrogen is discharged by the electrolyzer. For it to form a tangible and manageable supply, the produced hydrogen must be combined in a safe and energy-efficient manner. Ideally, the on-site hydrogen collection structure coheres to the flexibility objective of an off-grid hydrogen farm as well. However, few methods and technologies on the market for hydrogen collection and compression adhere to these points. For safe collection and compression of the produced hydrogen, a hydrogen collection system will be designed based on existing technologies and equipment on the market.

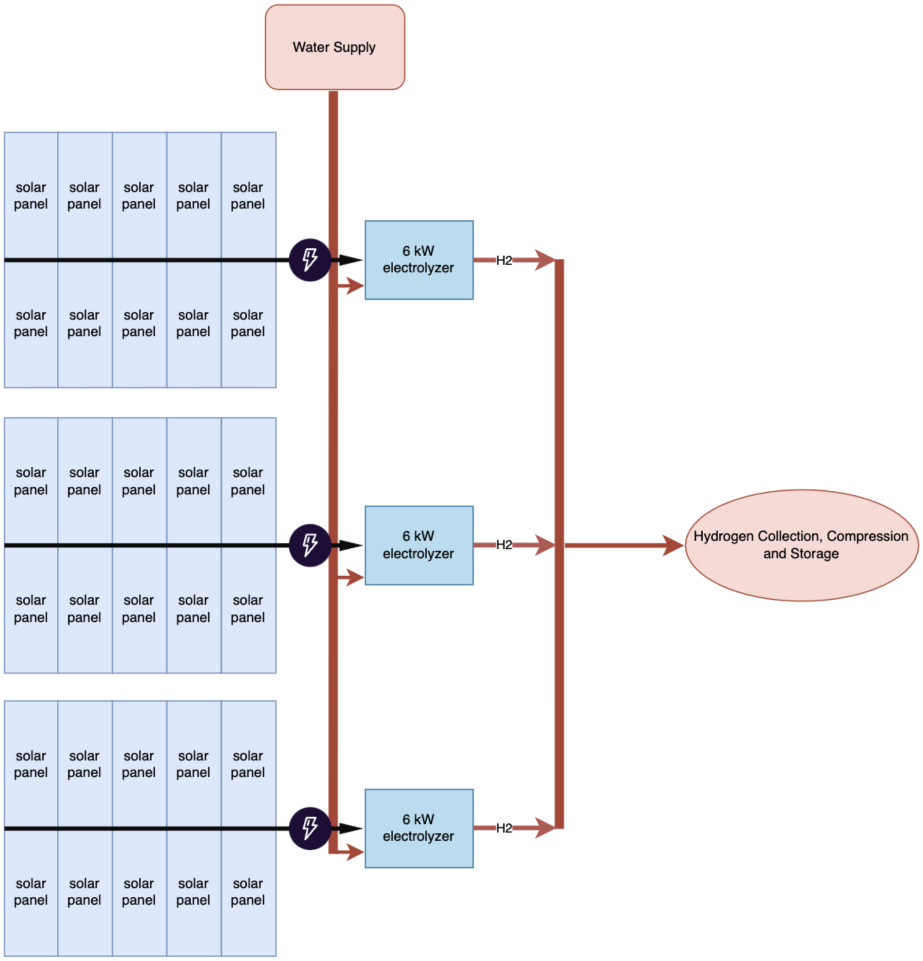


Figure 2: Schematically depicted off-grid small capacity electrolyzer hydrogen farm, for three electrolyzers, based on 620 Watt solar panels

System LCOH

The levelized cost of hydrogen (LCOH) is a value used to indicate the feasibility of hydrogen production under certain circumstances. It is not yet an established metric, but is used throughout literature and in practice for (potential) hydrogen production plants.

The LCOH is calculated as the cost per kg of produced hydrogen, which is determined by dividing the sum of costs over the hydrogen plant lifetime by the sum of hydrogen produced over the lifetime [4]–[10]. The system LCOH includes aspects that accompany the production process up until the system boundaries. In this research it will thus include production as well as on-site collection, with or without compression to 700 bar.

As mentioned above, the LCOH is dependent on the circumstances of the hydrogen production plant. The fact that the investigated production process is both off-grid and scalable due to its individual electrolyzer setup, provide flexibility of location and scale for the production plant. Location and scale of a production plant influence the production of the hydrogen farm through the equivalent sun hours and production capacity.

The LCOH is a metric that will be used to evaluate potential of an off-grid, photovoltaic and 6 kW electrolyzer hydrogen production process. The LCOH will be determined for the hydrogen production farm and corresponding processes up to the system boundary, i.e. including water supply system and hydrogen outflow system. This will be done for two potential farm locations - Portugal and Oman - and three farm sizes - 50 MW, 150 MW and 1,5 GW.

Relevance

The relevance of this thesis can be found in the originality and novelty of the hydrogen production process, the novelty of the supporting systems - water supply system and hydrogen outflow system - and the plausible insights for other off-grid scalable or small-capacity modular green hydrogen production processes in the future.

As mentioned, there are currently no known industrial scale hydrogen production processes using a multitude of small-capacity electrolyzers. Subsequently, no water supply systems or hydrogen collection are readily available, which supports the relevance of this research as well.

Furthermore, the 6 kW electrolyzer by ZEF offers hydrogen production at a significant low price, as will emerge from the following chapters. Evaluating the potential of hydrogen production farms based on smaller units in terms of total investments, flexibility in terms of location and scale and safety can provide meaningful insights for large or small scale hydrogen production as well as for hydrogen collection systems.

1.4 Problem statement

Hydrogen is a potential energy source to lower carbon emissions [1]–[3]. As hydrogen production method, electrolysis is one of the most mature and implemented technologies on an industrial scale. Green hydrogen production is predominantly based on wind or solar energy [25]. Current projects and literature evaluate centralized (green) hydrogen production processes. Techno-economic evaluations of such processes show a large variation in LCOH in literature, with various project reports confirming the higher ends of their findings [4]–[11].

A reduction of LCOH while maintaining the safety requirements of a hydrogen production process is sought after by i.a., potential hydrogen suppliers, various countries and literature [1]–[11]. Advances aside of other plausible hydrogen production processes are optimal production locations and production scales [4]–[10]. Thus far, no research has been found to evaluate a decentralized farm set-up for industrial scale production of hydrogen through electrolysis and powered by photovoltaics (PV).

1.5 Research goal

This thesis aims to evaluate the potential of an off-grid and photovoltaic powered green hydrogen farm that is based on multiple small-capacity electrolyzers. The 6 kW electrolyzer that is directly coupled to solar panels will be used as hydrogen production component, as case study. The system boundary for this research is set at an on-site centralized storage point of the produced hydrogen at 700 bar and 45 bar. As solely the solar panel and electrolyzer component is established. The water supply system and the on-site hydrogen collection and compression system are to be determined. The scope for this research thus includes obtaining and distributing water to individual electrolyzers in a green hydrogen farm, collecting the produced hydrogen at a centralized point in the farm, with or without compression to 700 bar, and storage.

1.6 Research questions

The objective of this thesis is to evaluate and determine the farm size and geographical location at which the off-grid, photovoltaic and 6 kW electrolyzer hydrogen production process results in a minimal (market competitive) system LCOH. The scalability of the farm lies in the number of 6 kW electrolyzers. The research question is formulated as follows:

*What system **size** and **geographical location requirements** are necessary to achieve a **market-competitive** Levelized Cost of Hydrogen for an off-grid, photovoltaic and 6 kW electrolyzer hydrogen production process?*

In order to answer the above-mentioned research question, several sub-questions have been composed as follows:

1. What are the alternatives for a water supply system for a decentralized electrolysis-PV hydrogen production farm, considering different farm sizes and locations?
2. What are the challenges and alternatives for the hydrogen outflow system for a decentralized electrolysis-PV hydrogen production farm, considering different farm sizes and locations?
3. What is the LCOH of an off-grid photovoltaic 6 kW hydrogen production farm considering the possible configurations of water supply system and hydrogen outflow system for different farm sizes and locations?

1.7 Structure of the thesis

The structure of this thesis consists of providing extensive information regarding the 6 kW electrolyzer by ZEF (section 2) and evaluation of the current state-of art literature and project information available on electrolysis-PV hydrogen production processes (section 3). This basis is used to formulate the methodological framework for the design aspects of this research (section 4). The core of this research is the design of the water supply system as well as the hydrogen outflow system, which are carried out and evaluated individually in section 5 and section 6. These sections include qualitative evaluation of the system in terms of assumptions and requirements used for design selection, as well as quantitative validation of data and calculation verification.

The resulting designs for the respective systems are combined to form complete hydrogen farm designs, for which the LCOH is calculated as final evaluation in section 7. This section provides sensitivity analysis of the LCOH as well. The thesis is finalized with a discussion, conclusion and recommendations in section 9 and section 8.

As required in the TIL master, this thesis is compressed into a research paper. It is presented in Appendix IV.

2 The 6 kW electrolyzer

In this thesis the 6 kW electrolyzer as designed by Zero Emission Fuels (ZEF) will be used as basis for the hydrogen production process. This section gives an overview of the technical aspects of the electrolyzer, the development timeline, and remaining data including system costs. Additionally, this section shows the differences between a small-capacity electrolyzer hydrogen production system compared to that of a centralized large-capacity industrial size electrolyzer. It underlines why the components of the LCOH metric are not identical, and, why aside of theoretical calculations, practical aspects show even larger differences between small- and large-capacity electrolyzer hydrogen production farms.

2.1 Solar power

The hydrogen production process begins with power generation. For a 6 kW electrolyzer, 6 kW of solar energy is to be supplied using conventional solar panels of 620 Watt.

Depending on the Global Horizontal Irradiance (GHI) levels and the equivalent sun hours (ESH) of specific locations, the number of solar panels needed to produce 6 kW can vary. Oversizing the solar panels i.e., installing more solar panels per electrolyzer than strictly necessary, can be done as well. Oversizing solar panels increases the energy production - increases independence from the grid, possibility for energy storage in batteries and future-proofing -, decreases the efficiency losses of the solar panels and can stabilize the load management (due to an overproduction of energy) [32].

The yield of energy is can be optimized by the positioning of the solar panels towards the sun. To maximize solar energy generation, solar panels can be mounted on single axis trackers. Single axis trackers can improve the performance of photovoltaic panels between 25% and 30%. The tracker system shifts the orientation of the panels towards the sun which increases the energy conversion by the panel [33]. The lifetime of a solar panel is 30 years [12], [33].

For the scope of this research, optimization utilizing solar trackers is included and the effective yield per solar panel is considered 600 Watt - as was done in previous ZEF and TIL studies [12], [13]. Oversizing solar panels is not considered, and 10 solar panels per electrolyzer are considered as fixed parameter.

2.2 Hydrogen production

A 6 kW electrolyzer is responsible for hydrogen production in this research. As built by ZEF, the electrolyzer is an alkaline electrolyzer and is made up of stackable cells, produced by injection molding. The cells entail a cathode, an anode and potassium hydroxide (KOH) as electrolyte. The electrolyzer is equipped with a compressor so standard water pressure is acceptable at the inlet and pressurizes the water to 50 Bar after which it produces hydrogen at 50 Bar with a 99.5% purity factor. It does so at an average efficiency rate of 69%, which is well withing the range of assessed industrial alkaline electrolyzers (for which values between 50% to 77% are common) [12], [13], [34].

Direct coupling of the electrolyzer to solar panels implies that all power, when generated is directed to the electrolyzer. No additional systems such as power control, converters or inverters are required - the electrolyzer runs directly on DC produced by solar panels.

No power control or storage systems have another implication: dynamic production. There is no battery or power control to prolong the power supply for continuous production. The electrolyzers thus only operate during sun hours, when energy is generated. A schematical overview of the hydrogen only process is depicted in Figure 3.

The hydrogen production farm consists of many electrolyzers. Each electrolyzer must be supplied with water at the inlet, and, must have a form of hydrogen drainage at the outlet. Water must be distributed and hydrogen collected, across the farm. An overview with three electrolyzers was depicted as example in the introduction in Figure 2, the water inlet and hydrogen outflow components that are to be determined in this research are indicated in red. Note that this is a preliminary schematic overview as both systems are to be designed. Additional areas, processes and equipment are thus to be determined and added.

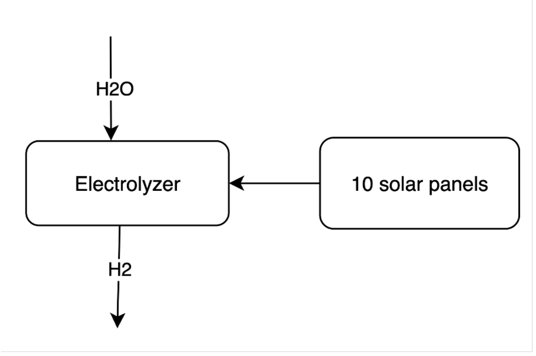


Figure 3: ZEF hydrogen process schematically

2.3 Technology readiness level (TRL)

This section briefly mentions the status of the built electrolyzer and its developments to circumstantiate its technology readiness level.

The 6 kW electrolyzer - including internal compressor unit - has undergone 250 hours of testing in an experimental setup in a bunker (safety purposes). The electrolyzer tested consisted of 20 cells, which corresponds to 60 Watts. The final electrolyzer will consist of about 200 cells (208 specifically) which corresponds to 600 Watt. The bunker testing has been done for continuous production using power from the energy grid. As water supply, demineralized water (demi water) was required and used. This is required to preserve the stacks and electrolyte of the electrolyzer, i.e. prevent undesirable side reactions or contaminate KOH, the electrolyte.

In the testing phase, the amount of produced hydrogen was measured and evaporated. The electrolyzers' technical feasibility of producing 6 mols of hydrogen per hour has been proved. Its TRL is therefore estimated between 4 and 5 after this stage of testing was completed. TRL 4 indicates that the technology is validated in the lab and level 5 is reached when the technology is validated in a relevant environment.

Currently, the 200 cell electrolyzer is undergoing testing under discontinuous production (simulated solar panel energy profile) with demineralized water.

Upon completing the testing hours, the estimated TRL increases to level 6-7. Level 6 indicates that the technology is demonstrated in a relevant environment and level 7 indicates that a system prototype is demonstrated in an operational environment.

The 6 kW electrolyzer is anticipated to have either 5.65 or 7 sun equivalent running hours per day on average depending on the location, each producing 60 mols of hydrogen per hour. This converts to ± 120 grams of hydrogen per hour per electrolyzer and ± 680 to ± 850 grams of 50 Bar hydrogen at 99.5% purity per electrolyzer per day on average, respectively [12].

2.4 Differences from literature

This section highlights the main differences of an off-grid (energy), photovoltaic and multiple small-capacity electrolyzer based hydrogen production process from large-capacity electrolyzer green hydrogen production processes based on solar energy. Literature from section 3 is used to support these commonalities and differences.

The off-grid photovoltaic 6 kW (alkaline) electrolyzer hydrogen production process entails solar energy in the form of PV panels and an electrolyzer. Solar PV is a relatively well-established and researched technology with high TRL and subsequently has led to an increase in affordability of solar panels. Usage of solar panels forms an advantage compared to less established green energy generation methods.

The small-capacity electrolyzer production route builds on the known PV- electrolyzer route. It directly couples a (small) dynamic electrolyzer to a set of PV panels. By doing so, the issue of power control is reduced (DC-DC), and, operating hours are limited as they are dependent on the ESH.

The drawback for the electrolysis technology is the cost-ineffectiveness of electrolyzers: higher costs to be covered in relatively little running hours (especially under discontinuous operation). Having limited operating hours, this drawback must be counterbalanced by the decrease in cost due to less components of the electrolyzer and economical electrolyzer stacks by using injection molding.

By coupling PV to an electrolyzer directly, the production process becomes less comparable to the industrial production process that consists of power generation and hydrogen production as two separate subsystems. In most other production processes, the power generation is separate from the hydrogen production system at first, so that the generated electricity can be valued, traded, sold, or stored before using it for hydrogen production. The proposed direct PV-electrolyzer coupled process does not allow for any of these options as the generated power can only directly be used by the electrolyzer. The levelized cost of electricity (LCOE) which makes up part of the LCOH in most studies, is expected to be lower for the non-electricity grid connected hydrogen production system. Additionally, the cost-effectiveness of an industrial size electrolyzer differs largely from the costs made by ZEF to produce (and install) a 6 kW electrolyzer. The production costs is significantly lower due to expected mass production, material -, and, design specific choices.

When mass-producing the 6 kW electrolyzers, at a rate of 10.000 per year, it is expected the stack is accountable for approximately two-thirds of the overall cost. The cost of the rest of plant is kept low through keeping a relatively simple design (original housing, etc.) by usage of low cost electrodes and a novel in-house developed crossover sensor which is a key innovation to drive down costs. The production cost for 10.000 electrolyzer units (including estimated installation costs) is €2.600 - 3.000, equivalent to €433 - 500 /kW [12], [13].

Industrial size electrolyzers tend to be estimated within the range of €500–3.000 /kW [5], [11], [35]. As mentioned, NREL has reported that these costs are much higher due to the current TLR and additional costs for installation. In reality, the cost of the 6 kW electrolyzer including installment will be much lower than that of large-scale production plants.

Plausible advantages of a small-capacity electrolyzer based hydrogen production farm include the elimination of power control drawbacks, avoided grid (connection and usage) costs, and lower electrolyzer costs per kW. Moreover, the design of the electrolyzer was aimed to allow for durability of the stack while encountering power fluctuations. Furthermore, utilizing small-capacity electrolyzers could offer more flexibility in location as well as in the configuration of the hydrogen production farm. The differences between the direct coupling of the PV panel to an electrolyzer and the cost-effectiveness of the electrolyzer and an industrial large-scale process for PV-electrolyzer hydrogen, may lead to differences in LCOH.

3 Literature review

In this section, a literature review is performed that covers solar to hydrogen technologies, water supply - and hydrogen outflow systems, LCOH methodologies, and influences of LCOH. Both scientific literature and project reports are used throughout the review. Though most green energy based hydrogen production processes discussed could be done without connection to the energy grid, this varies per source found. Various studies for green hydrogen production produce enough green energy to power their production process, yet include connection to the energy grid for stability in availability of power.

3.1 Solar to hydrogen technologies

Hydrogen production methods are classified by energy source, production method and starting materials. The primary energy sources are electrical, thermal, photonic, biochemical and combinations of these. An overview of the methods for hydrogen production that include solar energy is given in the table below [36]–[40].

Table 1: Hydrogen production pathways utilizing solar energy [36]–[40]

Method	**Brief description**	**Material resources**
Photovoltaic electrolysis	PV panels generate electricity to drive electrolyzer	Water
Photo-catalysis	Catalysts or molecular devices with photo-initiated electron collection are used to generate hydrogen from water	Water
Photo-electrochemical method	A hybrid cell is used to generate photovoltaic electricity, which drives the water electrolysis process	Water and biomass
Bio-photolysis	Biological systems based on cyanobacteria are use water to photo-generate hydrogen	Water
Photo-fermentation	The fermentation process produces hydrogen and is facilitated by light exposure	Biomass
Artificial photosynthesis	Chemically engineered molecules and associated systems to mimic photosynthesis and generate hydrogen	Water and biomass
Thermolysis	Concentrated solar heat generates ultrahigh-temperatrue steam and water molecules decomposes thermally	Water
Thermo-catalysis: H2S cracking	H2S extracted from sea or derived from other industrial processes is cracked thermo-catalytically using concentrated solar heat	Hydrogen sulfide
Thermo-catalysis: biomass conversion	Thermo-catalytic biomass conversion to hydrogen using concentrated solar heat	Biomass
Thermochemical processes: gasification	Biomass converted to syngas using concentrated solar heat; hydrogen extracted	Biomass
Thermochemical processes: water splitting	Chemical reactions are conducted cyclically with overall result of water molecule splitting using concentrated solar heat	Water
Thermochemical processes: fuel reforming	Liquid biofuels converted to hydrogen using concentrated solar heat	Biofuels
Thermochemical processes: H2S splitting	Cyclical reactions to split the hydrogen sulfide molecule driven by concentrated solar heat	Hydrogen sulfide

Though there are other energy inputs available for hydrogen production, solar energy is distinguishable as it is freely and abundantly available and reduces the environmental impact of hydrogen production. The trend of solar energy usage has paved the way for hydrogen production based on solar energy to now be well-established methods with a relatively high technology readiness level (TRL). This is the case for photochemical and PV-based hydrogen. On the contrary, extensive research is required to improve the performance of biological hydrogen production and bio-photolysis methods. Another advantage of solar energy as input for hydrogen production is its natural capability to supply processes requiring temperatures between 200 – 2000 °Celsius [36].

Disadvantages of solar energy is the intermittency and variation in the intensity of solar radiation which can lead to a discontinuous energy supply. Energy storage systems can be used to overcome this fluctuation but lead to more components required.[41] As solar energy is relatively far in development compared to other (renewable) energy sources, such energy storage systems are further in development as well. Drawbacks for less developed technologies are yet to be researched and their solutions developed. Nonetheless, the exergy efficiency of a solar collector of PV panel are critical parameters for the energy supply and thus for hydrogen production (for complete off-grid systems). A hydrogen production system coupled to both solar and another source of (renewable) energy is a possible solution, though again, it requires more system components [36] It should be noted that PV hydrogen production is considered a green hydrogen production method, even though the production of PV panels has negative impact on the environment.

As far as hydrogen production methods, most consist of breaking or splitting water into hydrogen and oxygen. Water is the main reactant in almost all hydrogen production reactions. Water electrolysis is the most common production method with a subsequent high TRL. This lead can be traced back to this method's full renewability and closed hydrogen cycle together with flexibility in local applications and distribution, and, its land requirements. Gas reforming is considered less environmentally friendly yet is a commercially accepted method for hydrogen production as well [36], [37]

When looking at recent comparisons for hydrogen production, nuclear thermochemical cycles could be promising technologies to further invest in due to the continuous energy supply and its capability to support high temperature reactions. This is said especially as it will be more market competitive than wind and solar electrolysis, as it does not require energy storage or additional power control components. Additionally, nuclear thermochemical cycles do not require an electrolyzer, which is a large costs component for hydrogen production through electrolysis [37]. However, nuclear hydrogen production routes require large capital investments, which makes its market competitiveness uncertain. Furthermore, nuclear thermochemical cycles are considered a renewable energy source, it remains to have negative environmental implications [36], [37].

3.2 Water supply systems

Water supply is not yet incorporated in the proposed off-grid photovoltaic 6 kW electrolyzer hydrogen production process. The water supply and water sourcing reviews have been done specifically for green hydrogen production research through water electrolysis. The following section presents the found options for water supply in hydrogen production systems. The general water supply options for water supply for hydrogen production are surface water, industrial wastewater, urban wastewater, seawater, water grid, cooling towers and rainwater [16].

Catarino et al. proposed a sustainable value approach to balance qualitative performance as well as cost to determine a sustainable value indicator. This indicator can support water source decision making for hydrogen production. The qualitative performance regards assessment of the water sources based on social, technical, and environmental and circularity criteria. The costs include abstraction, collection, pumping, transport, treatment, storage, cleaning and disposal. Decision-making is then based on the qualitative performance with regards to the overall cost per water source. In this way the quality and reliability of water sources, treatment needs, complexity of the permitting process, and associated costs are all included [17]. A graphic depiction of the method and research is depicted below in Figure 4.

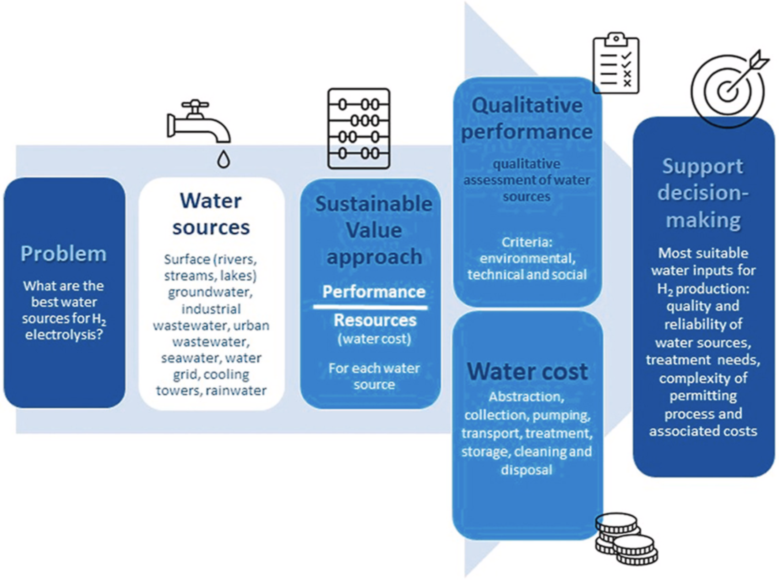


Figure 4: Methodology and research for evaluation water sources for hydrogen production through electrolysis by Catarino et al. and Simoes et al [16], [17]

The sustainable value approach can be used to determine the optimal water source for a set location for hydrogen production. Simoes et al. found that for hydrogen production sites located close to a port and more inland in Portugal, that the preferred available option for both cases is public grid water. The main factors for this decision are the high levels of water purity requirements, low supply risk of grid water and low complexity in permitting process and costs of grid water (including building infrastructure for transport to the hydrogen farm). The purity requirements differ per electrolyzer. In case water of a lesser purity level is allowed, industrial – and urban wastewater is a viable source as well, especially considering circularity criteria. Additionally, the use of grid water currently has no lesser sustainability value due to the policies effective at the location of the production sites. It is recommended to consider the water sources available for the set hydrogen production site, that the scale is included (as the permitting process and costs will decrease relatively to the production plant), and that future policies are considered to assess the environmental performance of each water source [16], [17].

For most hydrogen production methods, the focus in most research lies in the choice of production pathway and (renewable) energy source. Water for the electrolyzer production process is seen as an abundant source - which is not always the case. Water sources tend to not be mentioned on producers' ends freely [2]. For European hydrogen projects with an electrolyzer process, the water source tends to be sea water that undergoes a desalination process when using offshore wind energy or solar energy close to the sea or ocean. This is only favorably in case the production site is located within close proximity to the sea and to the desalination plant [42].

3.3 Hydrogen outflow systems

This section provides known possibilities for on-site hydrogen collection, compression and storage at 700 Bar.

Hydrogen collection

Research on hydrogen farm construction for electrolysis based processes all include an industrial scale electrolyzer. Produced hydrogen is thus centralized and processed (i.a., compressed, liquefied, etc.) before being exported from the farm. Literature is limited for hydrogen collection systems.

The main concern for hydrogen being safety and perceived safety [43]. It is important to note that there is experience with hydrogen in pipelines. Throughout Europe, the US and currently still in China, town gas consists of up to 55% hydrogen [44]. For pipelines containing a higher percentage of hydrogen, increased safety measures are taken. Hydrogen poses fire and explosion risks for different reasons:

- Low ignition energy: hydrogen can easily ignite and is ten times easier to ignite than hydrocarbons; [45]
- High reactivity due to its particular chemical and physical properties; [45]
- Boil-off tendency: hydrogen can convert from a liquid state to a gaseous state quickly causing instant fire or explosion risks; [45]
- Wide flammability limits: hydrogen is highly flammable in air and can ignite at concentrations as low as 4%, very wide with respect to methane; [45]
- Deflagration-to-detonation transition: transition easily occurs and is often observed in the case of a high-scale system; [45]
- High burning velocity: the laminar burning velocity is significantly higher than that of many other fuels; [45]
- Hydrogen is colourless, odourless, and tasteless: detection instruments required, and additives cannot be easily added; [45]
- High reactivity with materials: difficult to contain without reacting with other materials, and easily affects the stability of other materials (embrittlement); [45]
- Low gas density and diffusivity: particular behaviour in the case of release, and it can stratified in the upper part of confined spaces. [45]

There are various protectives set up regarding safety with hydrogen production, storage and transportation such as the ISO 22734 and ISO 19880 by the International Energy Agency. Though not tailored to hydrogen collection, regulations and standards are given for the materials of hydrogen infrastructure. The protectives refer to secondary and tertiary safety measures within themselves [46]–[48].

In terms of materials, coated PVC can be used for short distance transport of hydrogen (no further than 200 meters) when combined with appropriate sensors for monitoring for leakage [18]. For hydrogen at pressures higher than 20 Bar, steel piping is used [18], [47].

Given the exhaustive nature of safety guidelines such as ISO and NEN standards, a qualitative research approach involving interviews with industry professionals and experts in hydrogen transport will be undertaken to find suitable infrastructure options.

Hydrogen compression and storage

Zhang et al. give a comprehensive overview on the available technologies for storing and transporting hydrogen [49]. Short term storage and transportation can be done for hydrogen in a gaseous state, liquid hydrogen or using hydrogen carriers. For long-term storage, gaseous storage in salt caverns or depleted oil and gas reservoir is currently being researched, but said to be possible [49]. Long-term hydrogen storage is possible through solid carriers, making hydrogen a solid state good. As the system boundary for this thesis is centralized storage at 700 Bar, only gaseous hydrogen is assessed further.

Gaseous hydrogen for short-term storage and transportation can be done with high pressure tube trailers or pipelines. For both methods, compression of hydrogen is required as it is a low-density gas [50]. Orlova et al. state that the costs for compression of hydrogen can be nearly as much as the production costs, depending on the total amount produced [51]. Zhang et al. says that piston compression is most cost-effective out of all compression technologies for pressures higher than 450 bar [49]. This is reinforced by Sdanghi et al. citing 2300 USD in piston compression costs per kg per day compared to up to 5000 USD per kg per day for diaphragm compressors [21].

Whereas just compression is required for tube trailers or hydrogen tanks, purity and specific pressures are required when compressing hydrogen for pipeline transportation and usage. Hermesmann et al. confirm that the compression requirements differ as plans for hydrogen pipeline infrastructure are yet to be finalized in countries and most importantly, throughout the EU. Depending on the points of insertion for hydrogen in such a backbone, it might be economically efficient to have hydrogen producers compress their product to an intermediate pressure and have larger compressor stations nationwide instead of having each hydrogen producer fully compress their product individually [50].

Pressure requirements and purity requirements for the so-called Dutch hydrogen backbone have not yet been published, though pipeline transport will not require hydrogen to have a pressure of 700 bar [2], [3]. What is clear is that compression forms a large cost component, and it is unclear who will cover these costs [2], [3], [50]. As the system boundary of this research is set at centralized hydrogen storage on the farm at 700 Bar, compression costs will be included in LCOH calculations.

Gaseous hydrogen tanks and tube trailers are easy to deploy and offer flexible relocation and routing. The disadvantages include a limited capacity, higher transportation costs w.r.t. pipeline usage and safety concerns. Pipelines offer a large capacity, low operating costs and reliable operation. However, it does require a high initial investment of infrastructure, has less flexibility in routing and reach and is susceptible to leaks and sabotage. This increases the maintenance cost for pipeline safeguarding [49]–[51].

3.4 Levelized cost of hydrogen (LCOH)

The LCOH is a cost calculation used for conducting techno-economic comparisons for hydrogen production [4]–[6]. LCOH is used for a variety of research goals: determining the (optimal) production process for hydrogen, determining (optimal) locations for hydrogen production, determining (optimal) production process configurations, etc [4]–[10].

There is not one standard formula for LCOH. The LCOH expresses the cost of hydrogen production in a monetary value per kg of hydrogen [52], [53]. Cost components corresponding to the hydrogen production technology are included in the capital - and operational expenditure (CAPEX and OPEX) calculation. In these calculations, aside of aspects as costs and maintenance, the lifetime of the elements, and discount rates are included. The cost for energy usage, the levelized cost of electricity (LCOE) - where the energy generation technology is offset to costs, maintenance, and load hours - is included in LCOH calculations as well.

LCOH calculations vary across research: not all research includes certain components of the hydrogen production process. Such components are the costs of water, the costs of obtaining water (pipeline/infrastructure required), land costs of the production facility, the cost of postproduction processing of hydrogen (i.e., pressurizing or purification). The majority of LCOH research does not include compression, additional purification, or other post-production processes.

Many sources even suggest that transportation should be included or offset to the LCOH as these costs have large impact on the reality of adoption hydrogen as renewable energy source [4], [5], [9]. The key aspects for LCOH calculations, as well as aspects considered overlooked in most LCOH determining studies: the CAPEX and OPEX, LCOE, overhead costs and hydrogen yield, are discussed further.

3.4.1 CAPEX and OPEX

CAPEX should cover all equipment costs of the hydrogen production process. OPEX costs should cover the operations and management cost for all processes in the plant. In most assessed papers, the scope for both CAPEX and OPEX is generally limited to the electrolyzer, PV costs, and the balance of plant (BoP) costs. The BoP costs cover all other systems requires for the hydrogen plant, such as inverters, transformers, substations, transmission lines, access roads, water supply systems, land acquisition, etc.

In most papers though, the water supply or water supply processes are more often than not excluded from LCOH calculations: nearly all evaluated sources of PV-H2 do not include water costs in the BoP section of the LCOH calculation, with the exception of Bhandari and Shah [35]. Most are yet to specify the water supply source used for the designed production site [4]–[10].

More than water costs, the distance to the water supply source has been showed to influence the LCOH. So does the type of water due to the potential need of filtering systems prior to electrolysis, as it increases the system components and so the CAPEX and OPEX [4], [5], [16]. Moreover, the distance to a water source influences the land costs for the industrial site [4]. The land costs have not been included in any of the assessed papers either.

Final processes as compression are expected to be integrated in the BoP costs as well. However, the pressure characteristic of the produced hydrogen tends to be left out in studies regarding the economic feasibility of hydrogen. At most, low pressures are mentioned, after which compression is left out of the equation as ‘hydrogen might not need further compression depending on its end use’ [35].

A review given by Orlova et al. on compression of hydrogen gas for energy storage and transport reveals that the costs for compression are high compared to hydrogen production, depending on the total amount produced. The review entails different possibilities for storage as well, and more specifically shows that requirements for compression differ depending on the storage time anticipated for the produced hydrogen. This review reaffirms the importance of considering compression when determining the LCOH [51].

For the elements that are included in the LCOH calculations, findings throughout literature indicate that the majority of the CAPEX (and OPEX) for a water electrolysis-based hydrogen production plant are the costs for the electrolyzer and costs of the solar panels, after which the BoP - of which the processes considered vary - follow [4], [5], [35], [54]. When a battery is included in the system design, this cost contributes to the CAPEX more than the other elements in the BoP [35]. OPEX costs cover the operations and management cost for all processes in the plant - which tend to be highest for the electrolyzer and the BoP costs [5], [35].

3.4.2 Levelized cost of electricity (LCOE)

The LCOE is taken into account for most LCOH calculations. The LCOE – LCOH ratio is in some cases considered to determine the feasibility of building both the renewable energy power plant and the hydrogen production facility [5]. The LCOE is compared to electricity costs in case the location of the production site has been determined and the choice in question is the coupling of a renewable energy plant or not [35], [55], [56]. A determinant for both

LCOE and LCOH is the operating hours of the hydrogen production plant: this influences both the amount of electricity required and the quantity of hydrogen that is produced.

The LCOE is dependent on the technology chosen for renewable power generation: PV, wind, nuclear, etc., and subsequently on the location of the power plant. As example, Lehmann et al. show that the variability in power produced – which is dependent predominantly on the location of the plant – influence the LCOE and subsequently the LCOH [6].

Similar conclusions were found for a sunnier country as Egypt by Mohamed and Hamdy. They showed that LCOH can vary from 1 to 8 EUR/kg depending on the used power generation: PV, wind, or a combination. Due to the high level of solar radiation, using PV power plants lead to the lowest LCOH in Egypt [9].

A report by TNO for solar-electrolyzer based hydrogen in the Netherlands shows that the costs coupled to electricity - consisting of the price of electricity (€ 0,075/kWh), the electricity tax (€ 0,01 per kg hydrogen), and the electricity grid tariff (€ 2,31 /kg hydrogen) - amount to € 7,50/ kg hydrogen. This was calculated for hydrogen that is produced at 60 bar [11].

As the TRL of for renewable energy production is much further, the Lang factor for energy generation plants is about 1, meaning that the found LCOE in techno-economic analyses are more reliable and dependable compared to those of the electrolyzer CAPEX [57]. In case the LCOE is not used in the LCOH calculation, the electricity cost of the region is used [35], [50].

3.4.3 Overhead costs

Often overlooked and excluded from LCOH calculations are the project realization costs. It is estimated that these costs lead to an investment much higher than that of the equipment cost upon installation. Reports from the National Renewable Energy Laboratory and the EU on the actual costs for industrial electrolyzers state totals of €2000 – 3000 /kW [11], [26], [27]. These reports show that the costs required for installation are nearly double the costs of the electrolyzer: engineering, materials and services for civil engineering (foundations, earthworks for laying cables and pipes, surface mounting), assembly of the main components, process control technology (material and assembly), electrical engineering (material and assembly), approval, site equipment, construction and assembly monitoring, safety testing, quality control, commissioning, and other costs [26], [27].These costs are not included in the widely used €500 – 1000 / kW for most techno-economic analyses [58] [35][4][5]. Likewise and more recent, a study done by TNO for the LCOH of solar-electrolyzer based hydrogen production in the Netherlands found € 3050/kW [11].

Furthermore, the Institute of Energy Economics at the University of Cologne writes that an even larger sum can be required for initial investment. They state that the so-called Lang factor – a multiplier for the based on the TRL to determine the total cost of equipment and installation based on the purchase cost – of 6 for an electrolysis-based hydrogen production plant in 2030-2050. They also state that a large Lang factor will cause the subsequent operational expenditures to increase as well [57]. The Lang factor is used to calculate the total plant costs according to the following equation:

$$C_{T,i} = F_{lang} \sum_{i=1}^{n} C_{p,i}$$

Where $C_{T,i}$ is the total plant cost (for all plant components i); F_{lang} is the Lang factor and;$C_{p,i}$ is the sum of the cost of all purchased equipment (for all plant components i) [59].

The understatement of the equipment cost of electrolyzers should thus not be overlooked in papers using the estimate of EUR 500 – 1000 / kW for electrolyzers. Conclusions regarding the negligible influence of electrolyzers on the total LCOH, given among other by Bhandari and Shah, should be taken carefully as its influence might be larger or even the largest in reality [35]. In addition, when found that the CAPEX and OPEX of the electrolyzer takes up the majority of the LCOH estimation, this effect is likely to be even larger in reality [5], [57].

3.4.4 Hydrogen yield

As mentioned, the LCOH determines the total production cost per produced kg of hydrogen. There are two factors that have a high influence on this ratio. These are the efficiency of the electrolyzer and the operating hours of the electrolyzer or production plant. The efficiency of the electrolyzer expresses its ability to convert electrical energy into chemical energy - hydrogen. Efficiency rates for alkaline electrolyzers range between 50% to 77% [12], [13], [34]. A larger efficiency relates to both a larger production volume and less costs in terms of energy waste.

The number of running or operating hours of the hydrogen production plant influences the amount of hydrogen produced as well as the amount of energy required - and thus energy related costs. Electrolyzers are considered cost-ineffective compared to other hydrogen production methods, with respect to the hours they operate. Less operating hours tends to lead to higher LCOH costs [5].

3.5 Discussion

This section relates the influences on LCOH to the water supply and hydrogen outflow systems.

Common components of LCOH are the CAPEX, OPEX and LCOE. The BoP is a common component as well, however varies in the processes it includes. The electrolyzer takes up most of the cost aspect of the LCOH in terms of CAPEX and OPEX throughout literature, after which the cost of PV follows. Studies that have shown this consider an electrolyzer cost between €500–1.000 /kW [4], [5], [35]. Research also shows that the scale of the power generation site as well as the quantity of hydrogen produced has effect on the CAPEX, OPEX and LCOE as it can equalize large investment costs (including the land required for production) [5], [54].

The cost of water and obtaining water can be overlooked in LCOH studies but do influence the actual cost of hydrogen production. Even more, the type of water source might require additional system components to achieve clean water for usage. This subsequently influences the CAPEX and OPEX and so LCOH [4]–[10].

The final hydrogen characteristics such as pressure and purity influence the cost of hydrogen production as well. As these steps are subsequent to the actual production of hydrogen, there is debate whether to incorporate them into the LCOH. Nonetheless, many researchers suggest the cost to be included for evaluation of hydrogen production (economic) feasibility [49]–[51], [60]–[62]. Compressing and purification require process equipment and additional costs, their own CAPEX and OPEX.

Other than the CAPEX, OPEX and LCOE, the scale of the hydrogen production plant, the distance to water source and the final hydrogen pressure and purity levels influence the cost of hydrogen production as well. From subsection 3.2 and subsection 3.3 it is clear that some systems can only cover the investment costs when enough hydrogen is produced.

For water supply, grid water is favourable as no additional filtering or cleaning systems are required. It is however, not considered favourable in terms of renewability and water scarcity. Seawater is suggested for the latter reasons, but distance between sea-desalination plant and hydrogen production plant as well as production scale (minimal of 100 MW size plant in proximity to water source) is underlined as prerequisite to cover the costs for water treatment systems [16], [17].

For all processes hold that the project realization costs form large overhead costs depending on the TRL of the technology. LCOH estimations based on electrolyzer processes can vary from the true cost by up to a factor of 6 due as found by the Institute of Energy Economics, the National Renewable Energy Laboratory, and the EU [26], [27], [57]. Furthermore, the electrolyzer efficiency rate and total operating hours of the plant are inversely proportional to the LCOH. An increase in both efficiency and operating hours reduces the LCOH [5], [34].

All systems for water supply and hydrogen outflow have a point where scale and requirements as location and distance to water source lead to a market-competitive LCOH. Water sources influence the water costs, which are higher for water that has been purified (i.e., processed or grid water) than that of waste water which still requires treatment. Obtaining water at a lower cost will require investment in terms of water treatment equipment. Low water costs will only compensate for high treatment costs when larger amounts of water and thus hydrogen, is produced. Similarly, for the hydrogen outflow system, high equipment costs especially for compressors, can only result in a market-competitive LCOH in case a large amount of hydrogen is produced.

Aside of the practicality of the systems, these tipping points should thus be used to find a feasible design for the off-grid photovoltaic 6 kW electrolyzer based hydrogen production process. The objective of this thesis is thus to determine the scale and location characteristics at which this scalable hydrogen production process results in a minimal (market competitive) system LCOH.

4 Methodology

This section contains the design and evaluation methodology that will be used to answer the research questions of this thesis.

For the off-grid photovoltaic 6 kW electrolyzer hydrogen production process to be completed, both water supply system and hydrogen outflow system must be designed. For water supply, different systems are known and implemented on industrial scale for various industries including hydrogen production, as presented in the literature review. Hydrogen outflow systems, are less known throughout literature and in practice, and will require a unique approach based on literature, known guidelines, current projects and expert input. At this phase the inclination is to explore existing systems that can be annexed to the 6 kW electrolyzer production system rather than design self-made systems for water intake and/or hydrogen outflow. The novelty of the research lies in the dimensioning of existing systems to the requirements of a small-capacity electrolyzer and hydrogen farm.

The Delft Design Guide has been consulted to determine a suitable design method. All design methods include the following steps [63]:

1. Defining a design goal
2. Conceptual design
3. Design selection
4. Design evaluation

The following structure is adhered for this thesis:

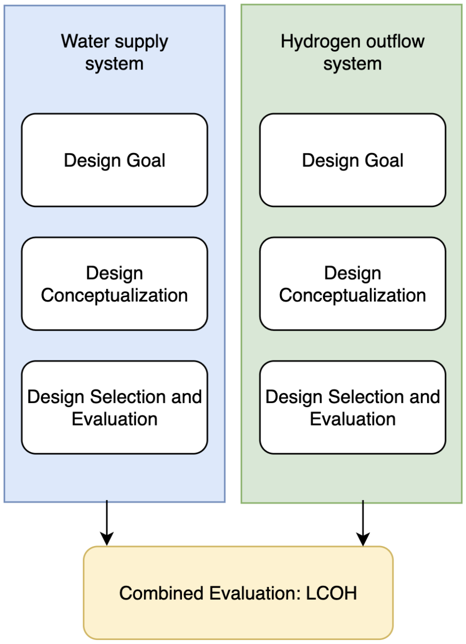


Figure 5: Overview of the methodology

As the research question indicates, design alternatives will be made for different farm sizes and farm locations. The scope for the geographical location is limited to two optimal locations found for the 6 kW electrolyzer system in a previous study for ZEF, namely Portugal and Oman. The three farm size options that will be considered throughout the design are farms of 50 MW, 150 MW and 1,5 GW [12], [13]. With 6 kW electrolyzers, these farm sizes translate to roughly 8400, 25.000, and 250.000 electrolyzers, respectively. The quantities produced per farm size, considering the average ESH per location, are given in the following table.

Table 2: Farm size, number of electrolyzers and average daily production of hydrogen calculated based on the 6 kW electrolyzer, molecular weight of hydrogen, and average running hours per day [12], [13]

Farm size	Electrolyzers	Daily operating hours (ESH)	Q daily (kg of 50 Bar hydrogen)	Q yearly (kg of 50 Bar hydrogen)
50 MW	8.400	5,65	5.900	2.160.000
150 MW	25.000	5,65	17.750	6.480.000
1,5 GW	250.000	5,65	177.500	64.790.000
50 MW	8.400	7	7.300	2.680.000
150 MW	25.000	7	22.000	8.030.000
1,5 GW	250.000	7	220.000	80.300.000

Note that for the purpose of the scope of this research, the average ESH will be used as determined in previous studies for ZEF, aimed to optimize the location of prospective farms for GHI [12], [13]. In reality, upon having selected a location and building a plant, the number of electrolyzers will be optimized considering exact GHI levels, temperature differences, height differences of the landscape, etc. The variation of GHI between the winter and summer times will be taken into consideration for both water supply system as well as hydrogen outflow system and will be tailored to support maximal (potential) production - meaning that the infrastructure will be built according to the needs of the peak production periods while retaining the capacity to support the requirements of the electrolyzers during the least productive months as well.

4.1 Design Goal

The initial step in any analysis is problem definition. For this research, a process tree method will be used to systematically formulate all system requirements for the system processes. This is to be done separately for both water intake and hydrogen outflow. The process tree method allows for identification of the system functions and subsequent requirements, to be used at the following design steps.

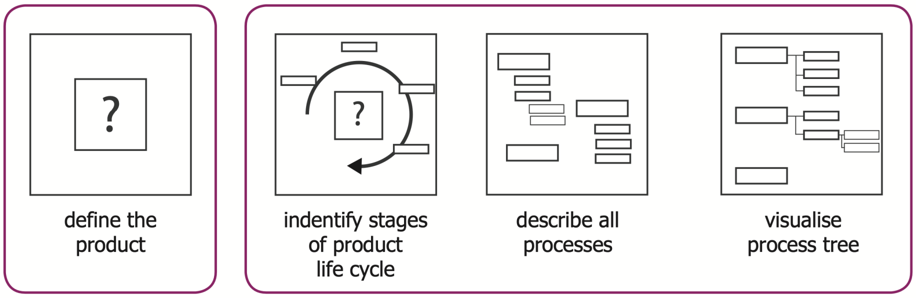


Figure 6: Process tree methodology [63]

The process tree method is tailored to product design. To direct it towards system design, it will be used in combination with the design specification method. According to the design specification method the criteria for the design should be distinguished based on their importance and organized in a hierarchy. This entails that all requirements for the system will be posed as functional constraint, non-functional constraint, functional objective and non-functional objective. Each type of requirement is used at a different phase in further design steps.

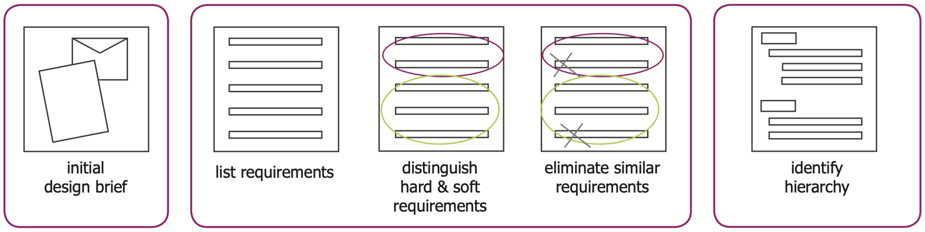


Figure 7: Design specification method [63]

4.2 Design Conceptualization

Conceptual designs will be made by finding means for the defined functions of the system (from the design goal step). Plausible designs will be investigated using function analysis. This entails that all conceptual design options are verified to cover all functions of the system. Means can differ between farm sizes and farm locations.

4.3 Design Selection and Evaluation

Design selection will be done according to the weighted objectives method. The hierarchy of the requirements from the process tree and design specification will form the basis of the weights. Conceptual designs will first be tested against the non-functional constraints. Then, the conceptual designs are graded based on the functional objectives and non-functional objectives. Additional grading is possible based on the importance of the requirements in case relevant. Design selection thus includes a preliminary design evaluation step.

The chosen systems will be tested based on cost, preliminary to the full LCOH calculation that will follow in the final step. To substantiate this intermediary cost determination, data validation will be done based on theoretical values and expert input. The calculations will be verified by examination of the validated input parameters for accuracy and coherence, scrutiny of intermediate computational steps, validation of underlying assumptions, juxtaposition of outcomes against established benchmarks or theoretical predictions, attention to unit consistency, and, expert input.

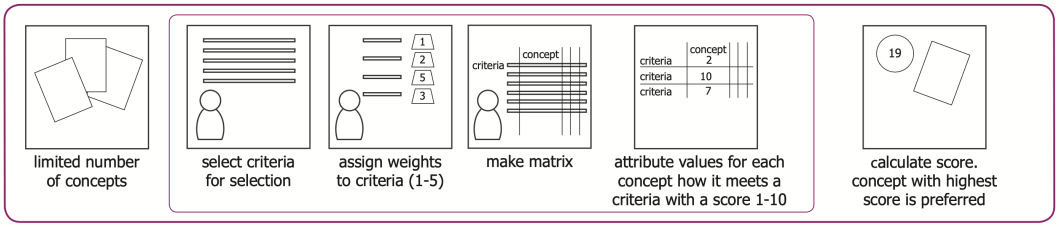


Figure 8: Weighted objective method [63]

4.4 Design Evaluation based on LCOH

Usually, design evaluation for initial system designs is predominantly done by concept evaluation (reviewing by expert groups) or simulation. This method is done when evaluating the functionality of a design. As the scope of this thesis entails a market competitive system LCOH – the evaluation will be done mathematically.

The design specifications will be used to calculate the LCOH for each possible configuration of water supply system and hydrogen outflow system; per farm size; for both locations. The interdependence of the water requirement, hydrogen production and total energy usage for each farm size, configuration, and location will be assessed and incorporated in a sensitivity analysis. The resulting values will indicate which water supply systems and which hydrogen outflow system could be adopted for certain farm sizes and production values to result in a market-competitive LCOH. The general formula for LCOH will be used with components as discussed in subsection 3.4[35]:

$$LCOH = \frac{I + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1+i)^t}} \tag{4.1}$$

Where:

- I - Initial investment for the system in €
- A_t - Annual costs (operation and replacement) in year t in €
- H_t - Hydrogen produced in year t in kg
- i - Discount rate in % (taken as 5 % for both locations)
- n - System lifetime in years (30 years for all the scenarios)
- t - Time in years

The initial investment for the system (I) consists of the CAPEX of the system:

- PV CAPEX (including BoP, transport, land costs and installation)
- Electrolyzer CAPEX (including BoP, transport and installation)
- Water supply system CAPEX - pipelines, pumping, water treatment equipment, etc.
- Hydrogen outflow system CAPEX - pipelines, compression and storage

The annual costs (At) consist of the following components:

- PV OPEX
- Electrolyzer OPEX
- Water supply system OPEX - water costs, maintenance for subsystems and waste streams, and interest over CAPEX. Water costs (location and source dependent)
- Hydrogen outflow system OPEX - maintenance for subsystems and interest over CAPEX.

A full list of assumptions is provided in Appendix III.

5 Water Supply System Design

In this section, designs for the water supply system for the off-grid PV 6 kW hydrogen farm are determined based on the design steps specified in section 4. The design steps followed are design goal, design conceptualization, design selection and design evaluation. In the design goal step, the water supply system functions and requirements are specified. In the design conceptualization step, the means for the functions are given. Design selection is done by reusing the requirements to test (combinations) of the water supply system means that have been selected. Design evaluation is done by using objectives to rate the design – the objectives being predefined requirements of the design step. Design evaluation will also take place once both water supply system and hydrogen outflow system have been designed, in section 7. This section will entail expanded literature than presented in section 3.

5.1 Design Goal

The design goal for water intake is to determine a strategy to supply a small-capacity electrolyzer based farm with water, and to provide each electrolyzer with water. It is a twofold question. The first is determining the type of water source and second is the distribution of water to the electrolyzers on the farm. Both water source and distribution must ensure that the water specific requirements for the alkaline electrolyzer are met.

The process tree method and design specification method are carried out in this section. This entails the listing of the functions and processes of the water intake system and corresponding requirements. System requirements are formulated separately for functions/domains of the water supply system. The following functions/domains are covered: water source, water quality and quantity requirements, infrastructural requirements, energy and transport.

The design goal is expanded upon by formulating functional and nonfunctional constraints as well as functional - and nonfunctional objectives for all functions and domains of the water intake system. Functional objectives and constraints indicate what the system must (at least) do. Nonfunctional objectives and constraints indicate what the system should (at least) have or be. Based on the functionality or non-functionality and the constraint or objective, the requirements of the system can be listed hierarchical: constraints have higher priorities than objectives. As mentioned in section 4 all requirements will be used in further design steps.

5.1.1 Water source requirements

The water supply system begins with a water source, for which requirements can be formulated. They can be used for quantitative and qualitative assessment in further design steps. The fulfillment of these requirements will be largely dependent on the location of the farm. The two considered locations for the standalone PV electrolyzer hydrogen production farm of ZEF resulted from previous optimization studies and are Al Buraimi, Oman and ínsua, Portugal [13].

The requirements are based on the identified qualitative criteria for water usage solutions for electrolysis in hydrogen production by Simoes et al [16]. These were the criteria used by Catarino et al. as well for determining the optimal water source for hydrogen production as explained in subsection 3.2 [17]. The criteria will be measured in the design selection and evaluation section, based on the indicated performance levels of Table 25 and Table 26. The nine resulting criteria are given below, with requirements for the water source coupled to each.

1. Short-term reliability of availability with respect to effects of weather factors on the water source such as droughts:

NFO1: There should be minimum effect of weather factors on the water source.

2. Long-term reliability of availability which can affect authorization on water use by environmental authorities:

NFO2: The perceived future impact of climate change on the water source should be minimal.

3. Reliability of supply based on non-weather-related intermittencies, such as maintenance pauses or redundancy of equipment required to ensure continuity of water supply. Limiting the redundancy of equipment required is tackled in the infrastructure section.

NFO3: Preferably, the water source requires minimal processing and maintenance steps before being available to obtain/transport to the farm.

4. Competition with other uses at water abstraction/collection level:

FC1: The water supply source cannot be saturated prior to the hydrogen farms' usage. NFO4: The water supply source should preferably be used by the hydrogen farm only or shared with a minimal number of other users.

5 Complexity of abstraction or collection should be minimal. It is important not to undermine local or existing beneficiaries of a water source. This is from both a social responsibility and acceptance as well as obtaining permits, etc.

6 The distance between the water source and production site should be minimal.

NFO5: The number of involved entities and existence of previous experience with this type of water for a similar use, should be minimized.

NFO6: Transport distance from water source to hydrogen production plant site should be minimal.

7. The degree of water treatment needed up to electrolyzer input requirements should be minimized. This is covered thoroughly through the requirements regarding the water purity and the requirement regarding the water supply system having minimal amount of system and process components.

NFO7: The water source should require the minimal processing steps before being usable for the alkaline electrolyzer.

8. Social acceptance is imperative for the longevity of the production plant:

NFO8: Usage of the water source should be socially accepted.

9. Complexity of the permitting process required should be limited.

NFO9: Complexity regarding permits for the water source should be minimal.

5.1.2 Water quality and quantity requirements

This section entails the water requirements for the hydrogen production system. The requirements are listed regarding the water quality aspects first, after which water quantity requirements will follow. To investigate the quality requirements, the chemical process is expanded upon.

Alkaline water electrolysis is known as the principal process for the water splitting reaction. The process consists of reactions happening two electrodes: the cathode (-) and anode (+), in an alkaline medium. The anode converts hydroxide to oxygen, hydron and electrons. The cathode converts the electrons and water to hydrogen. The stoichiometry of the chemical reactions is as follows:

- Anode: $2\,OH^- \longrightarrow \frac{1}{2}\,O_2$
- Cathode: $2\,H_2O + 2\,e^- \longrightarrow 2\,OH^- + H_2$
- Overall: $H_2O \longrightarrow H_2 + \frac{1}{2}\,O_2$

The process requires water, energy, and a hydroxide facilitator – an alkaline medium. Usually, this alkaline medium is a potassium hydroxide (KOH) solution [64]. This is the case for the 6 kW electrolyzer by ZEF as well [12]. Depending on the material of the electrodes, the addition of other minerals to the electrolyzer cell can be either beneficial or disadvantageous [65], [66]. Minerals studied for interference included Calcium, Magnesium, Iron, Copper, Zinc, Sulfates, Sodium and Chlorides and trace elements (Iodine, Bromine, etc.) due to their appearance in water sources as tap water, ground water and seawater. Though benefits are measurable on laboratory scale, they have not been found for electrolyzers used in the industry. On the contrary, issues as electrode corrosion, catalyst activity and electrode contamination emerge when minerals other than the alkaline medium are present.

Electrode corrosion entails that the electrodes degrade faster due to the presence of a metal or other mineral. Corroded electrodes decrease the stability and efficiency of the electrolysis process [67]. Catalyst activity denotes the interference of materials with the original chemical reaction. Catalysts influence the efficiency of a chemical reaction by either enhancing or decreasing the reaction speed [68]. Furthermore, the presence of minerals can cause other reactions to take place, resulting in (undesired) byproducts. Electrode contamination happens when metals or minerals react with the electrode, affecting the conductivity of the electrode or interfering with the reactions happening at the electrode(s) [66].

Large alkaline electrolyzer producers such as NEL, [69] Siemens Energy [70], Green Hydrogen Systems [71], McPhy Energy [72] and Enapter [73] all require demineralized or purified water to prevent the above-mentioned interferences and to ensure optimal hydrogen production. Demineralized or pure water as referred to by producers and papers, is also known as type II water [16], [69], [73]. Type II water is a result of both reverse osmosis and ion exchange. The American Society for Testing and Materials (ASTM) has defined type II water as pure water with resistivity of > 1 MΩ-cm, a conductivity of < µ S/cm and < 50 ppb of Total Organic Carbon (TOC). Type I water is known as ultrapure water. Aside of being demineralized, there are no traces of biochemical material in the water. Type I water has a resistivity of >18 MΩ-cm, a conductivity of <0.056 µS/cm and < 50 ppb of TOC [74].

Thus, the water quality should be set at type II (demineralized). The functional constraint and functional objectives for the water supply regarding purity are as follows:

FC2: The water supply system must provide type II (demineralized) water to the small-capacity electrolyzer based farm.
FO1: The water supply should ideally provide type I (pure) water to the small-capacity electrolyzer based farm.

Another aspect that falls under the water quality is the pressure characteristic. As mentioned in section 2, the electrolyzer is equipped with a compressor to pressurize influx water to 50 bar. Testing of the electrolyzer was done with demineralized water with average pipeline pressure: 1 – 5 Bar [12], [75]. A constraint and flexible objective for water pressure can be set as follows:

FC3: The water supply system must provide water to the electrolyzers of at least 1 Bar.
FC4: The water supply system must provide water to the electrolyzers of at most 5 Bar.
FO2: The water supply system ideally provides water with minimal fluctuation in water pressure.

Following water quality is water quantity. The stoichiometry of the electrolysis reaction contains information regarding the amount of water required. The mole ratio of water to hydrogen is 1:1, meaning that 1 mol of water is require for every mol of hydrogen produced. The electrolyzer of 6 kW produces 60 mol of hydrogen per hour [13]. The amount of water required is thus 60 mols per hour, using the molar weight (18.02 g/mol), that translates to 1,082 liter or kilo water per hour. On average, 7 full work hours are made, whereas the productivity can be spread over more hours. Testing at ZEF verified that throughout the running hours of the electrolyzer, 1 kilo of water on average was used per hour [12]. This quantity forms the basis for the following functional constraint and functional objective:

FC5: The water supply system must provide each electrolyzer with at least one kilo of water per (running) hour.

It is common practice to apply a safety margin when planning the demand and/or usage of commodities. In the Netherlands, the prediction is not restrictive as most industrial farms can obtain exceeding amounts of water relatively easy from the government. The excess is then taken into consideration for the coming year [76] The safety margins used for water demand estimation and prediction vary per company, region, country and industry. Agriculture is one of the most published sectors on water demand prediction for a relatively standalone process, compiled data shows that a safety margin 10 and 20 percent is standard, to compensate for leakages, etc [77], [78]

As mentioned, for the scope of this research, the water supply will be designed according to maximal production and thus maximal amount of water required. One kilo per running hour per electrolyzer assumes 100% production (i.e., operating at 6 kW capacity), whereas in reality, on the peak sun hours of each day at most 83% (Insua) and 87% (Oman) will be achieved on summer peak days [79]. In reality, even maximal capacity can be achieved in case oversizing of PV is incorporated in the design of the farm. However, as this is not included in the scope of this thesis, roughly one kilo of water per electrolyzer per running hour inherently provides a safety percentage of 19% to 13% on peak days - and an even larger percentage on off-peak days. The average running hours for both locations have been determined so that they would cover seasonal outliers in combination with these true capacity percentages(days with more sun hours and so more working hours) [13].

In addition to the inherent safety margin, the standard 20 percent excess usage safety margin is taken. The previous functional objective can thus be fine-tuned to:

FC6: The water supply system must hold 20% more water than required per electrolyzer daily to compensate for leakages in the water distribution.

Having set the functional objectives and constraint for the total amount of water, one important aspect of the process remains. The 6 kW electrolyzer, runs dynamically, meaning that the electrolyzer runs when the solar panels deliver energy, which is subsequently linked to the ESH. These vary from day to day and additionally vary among the seasons. As mentioned, the water supply system will be built according to maximal production. Nevertheless, the system must be able to withstand fluctuations in water demand. This fluctuation must be supported by the water supply system. Note that this aspect is influenced by both the water quantity as well as the infrastructure of the water supply system. Two functional constraints are posed.

FC7: The water supply system must support the daily dynamic demand pattern for water for each micro plant on the farm.
FC8: The water supply system must support the seasonally dynamic demand pattern for water for each micro plant on the farm.

5.1.3 Infrastructural requirements

This section covers more standard requirements that are widely applicable in system design. The infrastructure of the system denotes all process components in terms of machinery and piping. This includes the process components of the sourcing, quality, and quantity steps. It is important to note that in the previous functions, the requirements are limited to number of steps. In this section stricter requirements are posed for all infrastructural aspects of the water supply system. The requirements are in alignment with many process optimization strategies such as Lean Six Sigma, Kanban, theory of constraints, etc. the underlying logic is based on simplicity, quality control and cost-effectiveness. Items such as lifetime, setup, maintenance, and cost will be specified in this section.

First, the required lifetime of the water supply system. This should correspond to the lifetime of the electrolyzer: 30 years as specified in section 2. As this is something the system must have, the nonfunctional constraint and objective are formulated as follows:

NFC1: The water supply system must have a minimum lifetime of 30 years.
NFO10: The water supply system ideally has a longer lifetime than 30 years.

The hydrogen production system as envisioned by ZEF, aims to function with minimal human interference and/or physical maintenance required on-site. Partial or fully automated maintenance on the farm are favoured [12]. To adhere to these aims, any system of the hydrogen farm should require minimal physical human interference regarding both operations and maintenance:

NFC2: The water supply system should not require physical human assistance or interference for operation.
NFO11: The water supply system should require minimal physical human assistance or interference for maintenance.
NFO12: The water supply system should ideally be able to undergo automated or robotic maintenance procedures.
NFO13: The water supply system preferably includes a self-regulatory component.
NFO14: The water supply system preferably has a predictable maintenance requirement.

Furthermore, the required maintenance of a system can be minimized by limiting the number of system components, as the Kanban theory suggests. By having less system components, the coordination required between sub-systems decreases, resulting in a reduction of risks (safety, operation, etc.) related to subsystem coordination.

NFC3: The water supply system should not contain system components that are not crucial for delivering the water quantity and quality to the electrolyzer.
NFO15: The water supply system should consist of as little sub-systems or system components as possible.

The usage of mature and well-established technology for the water supply system is another form of mitigating risk. Moreover, it aligns with the aim to focus predominantly on hydrogen production systems and rely on supportive technology and systems available on the market for completion.

FC9: Technology and subsystems of the water supply system should be well established and available on the market.
NFO16: Technology and subsystems of the water supply system should require as little adaptations and innovations as possible.

Lastly, efforts of installment, maintenance and operation are included in terms of finances and time for system design. Efficient installment, removal, maintenance and operation is expected as technologies mature. Even so, efficient installment as well as cost-effectiveness are stated through the following requirements:

NFO17: Ideally, the water supply system must have a straightforward, and mechanically uncomplicated installation procedure. This implies that ideally, no digging, altering, etc. is required for installment.
FO3: The water supply system ideally does not produce any side-products or waste that can form an additional

task before removal.
NFC4: The maintenance of the water supply system must be time efficient. This implies that interruptions of the system due to maintenance should not halt production. In other words the maintenance should be able to be done within the time frame for which the system provides a backup water supply.
NFO18: Ideally, the water supply system must have a straightforward, and mechanically uncomplicated maintenance procedure.
FC10: The water supply system must operate with minimal time delays.
NFC5: The costs of the water supply system for installment, maintenance, operation and removal should be market competitive.
FO4: The energy usage of the water supply system is ideally as low as possible.

5.1.4 Energy and transportation requirements

In the previous domains, energy efficiency and minimal distances have been mentioned. This section specifies the requirements for supplying the required energy for the water supply system as well as the requirements for the inevitable transportation that will be required.

The hydrogen farm is not connected to an energy grid. The energy required for the water supply system must be conform this aim. The energy supply must be cost-effective and ideally sustainable, which is conform the off-grid flexibility of the hydrogen farm:

FC11: The water supply system must not be dependent on the grid for energy.
NFC6: The cost of energy supply for the water supply system must be market-competitive regarding the production scale. Considering the largest percentage that the energy proportionally contributes to the LCOH found in recent reports (by TNO) is nearly 47%, that the energy supply system should contribute to at most 47% of the LCOH.
NFO20: The energy supply of the water supply system is ideally a sustainable energy source.
Note that the requirements of the infrastructure regarding installation, maintenance hold for the energy source and supply. In accordance with what was mentioned about fluctuations of water quantity, the energy supply must support this as well:

NFC7: The energy supply must be able to cope with the daily and seasonal fluctuation of the demand pattern for water.
The water supply system will require transportation. As indicated in the water source, ideally the distance between source and farm is minimized. The following requirements are posed for the method of transportation. They align with the ideals of cost-effectiveness, flexibility, and sustainability.

NFC8: The method of transportation for the water supply system must be cost-effective.
NFC9: The method of transportation for the water supply system must be flexible and able to respond to the fluctuations of water source and demand.
NFO21: The method for transportation ideally requires minimal infrastructural installments.
NFO22: The method for transportation is ideally sustainable or has positive sustainability aspects.

5.1.5 Requirement overview

The many functional and non-functional constraints, functional and non-functional objectives will be schematically recapitulated in a sequence of lists. Tables are given for the functions of the system and their respective functional constraints (Table 3). This is done as well for the non-functional constraints (Table 4), functional objectives (Table 5), and non-functional objectives (Table 6).

Table 3: System functions and functional constraints for the water supply system

	System function	**Functional constraint (FC)**
FC1	Water source	The water supply source cannot be saturated prior to the hydrogen farms' usage.
FC2	Water purity	The water supply system must provide type II (demineralized) water to the small-capacity electrolyzer based farm.
FC3	Water pressure	The water supply system must provide water to the electrolyzers of at least 1 Bar.
FC4	Water pressure	The water supply system must provide water to the electrolyzers of at most 5 Bar.
FC5	Water quantity	The water supply system must provide each electrolyzer with at least one kilo of water per (running) hour.
FC6	Water quantity	The water supply system must hold 20% more water than required per electrolyzer daily to compensate for leakages in the water distribution.
FC7	Water quantity	The water supply system must support the daily dynamic demand pattern for water for each electrolyzer on the farm.
FC8	Water quantity	The water supply system must support the seasonally dynamic demand pattern for water for each electrolyzer plant on the farm.
FC9	Infrastructure	Technology and subsystems of the water supply system should be well established and available on the market.
FC10	Infrastructure	The water supply system must operate with minimal time delays.
FC11	Energy	The water supply system must not be dependent on the grid for energy.

Table 4: System functions and non functional constraints for the water supply system

	System function	**Non-functional constraint (NFC)**
NFC1	Infrastructure	The water supply system must have a minimum lifetime of 10 years.
NFC2	Infrastructure	The water supply system should not require physical human assistance or interference for operation.
NFC3	Infrastructure	The water supply system should not contain system components that are not crucial for delivering the water quantity and quality to the electrolyzer.
NFC4	Infrastructure	The maintenance of the water supply system must be time efficient.
NFC5	Infrastructure	The costs of the water supply system for installment, maintenance, operation and removal should be market competitive.
NFC6	Energy	The cost of energy supply for the water supply system must be market-competitive regarding the production scale (at most 50% LCOH).
NFC7	Energy	The energy supply must be able to cope with daily and seasonal fluctuation of the demand pattern for water.
NFC8	Transportation	The method of transportation for the water supply system must be cost-effective.
NFC9	Transportation	The method of transportation for the water supply system must be flexible and able to respond to the fluctuations of water source and demand.

Table 5: System functions and functional objectives for the water supply system

	System function	**Functional objective (FO)**
FO1	Water purity	The water supply should ideally provide type I (pure) water to the small-capacity electrolyzer based farm.
FO2	Water pressure	The water supply system ideally provides water with minimal fluctuation in water pressure.
FO3	Infrastructure	The water supply system ideally does not produce any side-products or waste that can form an additional task before removal.
FO4	Infrastructure	The energy usage of the water supply system is ideally as low as possible.

Table 6: System functions and non functional objectives for the water supply system

	System function	**Non-functional objective (NFO)**
NFO1	Water source	There should be minimum effect of weather factors on the water source.
NFO2	Water source	The perceived future impact of climate change on the water source should be minimal.
NFO3	Water source	The water source should require as little preprocessing and maintenance steps before being available to obtain.
NFO4	Water source	The water supply source should preferably be used by the hydrogen farm only or shared with a minimal number of other users.
NFO5	Water source	The number of involved entities and existence of previous experience with this type of water for a similar use, should be minimized.
NFO6	Water source	Transport distance from water source to hydrogen production plant site should be minimal.
NFO7	Water source	The water source should require the minimal processing steps before being usable for the alkaline electrolyzer.
NFO8	Water source	Usage of the water source should be socially accepted.
NFO9	Water source	Bureaucracy regarding permits for the water source should be minimal.
NFO10	Infrastructure	The water supply system ideally has a longer lifetime than 15 years.
NFO11	Infrastructure	The water supply system should require minimal physical human assistance or interference for maintenance.
NFO12	Infrastructure	The water supply system should ideally be able to undergo automated or robotic maintenance procedures.
NFO13	Infrastructure	The water supply system preferably includes a self-regulatory component.
NFO14	Infrastructure	The water supply system preferably has a predictable maintenance requirement.
NFO15	Infrastructure	The water supply system should consist of as little sub-systems or system components as possible.
NFO16	Infrastructure	Technology and subsystems of the water supply system should require as little adaptations and innovations as possible.
NFO17	Infrastructure	Ideally, the water supply system must have a straightforward, and mechanically uncomplicated installation procedure.
NFO18	Infrastructure	Ideally, the water supply system must have a straightforward, and mechanically uncomplicated maintenance procedure.
NFO19	Infrastructure	The costs of the water supply system for installment, maintenance, operation and removal should be as low as possible.
NFO20	Energy	The energy supply of the water supply system is ideally a sustainable energy source.
NFO21	Transportation	The method for transportation ideally requires minimal infrastructural installments.
NFO22	Transportation	The method for transportation is ideally sustainable or has positive sustainability aspects.

5.2 Design Conceptualization

As mentioned in section 4, design conceptualization entails providing means for the defined system functions. The means must comply with the functional constraint(s) of the system function. As three farm sizes are considered, minimum farm sizes required per mean - the minimal farm size at which a certain mean is cost-effective - will be given as well as the typical advantages and disadvantages in terms of energy usage and process-related efficiency. Because total costs are dependent on the means of all domains in combination with infrastructure, expected costs (investment, maintenance, and operation) will be calculated be expanded upon in further sections - design selection and evaluation. The system functions for which means are given adhere to those in the design goal: water source, water quality and quantity, infrastructure, energy, and transportation.

5.2.1 Water source

For both water source and purity, the work of Simoes et al. is used. As mentioned in the section 3, the paper presents the required treatments per possible water source to result in filtered water [16]. The included water sources of this study are surface water (rivers, streams, lakes); ground water; industrial wastewater; urban wastewater; seawater; estuary; water supply network; cooling towers; and rainwater. These are all possible water sources for (industrial) electrolyzer based hydrogen production plants according to both Simoes et al. and Catarino et al [16], [17].

Ínsua, Portugal

The paper lists the water sources that are available for two types of areas withing Portugal: a semi-urban location on the Atlantic coast and a rural area far from the coast. The ZEF location of Ínsua is identified as a relatively rural area far from the coast. The water sources available for such areas given by Simoes et al. have been verified and are as follows:

- Surface water – rivers (Rio Dão), streams (Ribeira de Coja), and lakes (Albufeira da Barragem de Fagilde)
- Groundwater [80] [81][82]
- Industrial wastewater (technology offered by Interagua)[82]
- Treated urban wastewater [82]
- Water grid [80] [81]
- Rainwater

Seawater is unavailable as it is too far to obtain in Ínsua. Treated seawater is not an option as all current desalination plants are saturated and the dedicated desalination plant in Albufeira is yet to be built [83].

The means for the water sources must comply with FC1: The water supply source cannot be saturated prior to the hydrogen farms' usage. This holds for all plausible water sources for Ínsua, Portugal. Most competition for water abstraction is found for wastewater, water grid and rainwater [16], [17].

Al Buraimi, Oman

Al Buaraimi, Oman has been investigated. Available water sources are as follows:

- Surface water and groundwater are readily available in the A' Dhahirah area [84]–[86]
- Treated industrial wastewater and urban wastewater [87], [88]
- Water grid [86]

The unavailable water sources have been investigated as well:

- Seawater is not available. However, the largest seawater treatment plant is currently being built on the coast of Oman. Treated seawater is thus available at a large distance [89], [90]
- Estuaries are rarely present in Oman, and not available in the Al Buraimi governate or immediate surroundings
- Cooling towers have not been found in Al Buraimi
- Though Al Buraimi shows shows little seasonal variation, the annual rainfall is less than 100mm. There is currently not enough rainwater available for the projected usages. Rainwater availability thus does not comply with FC1 and will not be considered as water source for Al Buraimi [86]

Al Buraimi is one of the few governates with a water surplus, mainly due to groundwater, surface water and waste water treatment. Grid water is not saturated in the area [86], [91]. Treated seawater is readily being offered to the market, and therefore not considered saturated [89], [90]. Therefore, all listed available water sources comply with FC1. The following table shows the means for this domain for both considered farm locations.

Table 7: Plausible water sources for both farm locations

Water source	***Ínsua, Portugal***	***Al Buraimi, Oman***
Surface water	available	available
Groundwater	available	available
Industrial wastewater (treated)	available (secondary treatment)	available (tertiary treatment)
Urban wastewater (treated)	available (secondary treatment)	available (tertiary treatment)
Water grid	available	available
Rainwater	available	-
Treated seawater	-	at large distance

5.2.2 Water purity

The functional constraint for water purity is as follows: The water supply system must provide type II (demineralized) water to the small-capacity electrolyzer based farm (FC2). The number of treatment steps or treatment required to result in demineralized water, depends on the water source. The research by Simoes et al. presents the required treatments per possible water source to result in filtered water [16]. The paper assumes that a deionization step – the step that transforms filtered water to demineralized water - is included in the electrolyzer, which for ZEF, is not the case. Therefore, aside of treatments to achieve filtered water, various methods for demineralization will thus be listed as means for the system function of water purity.

Water filtration

Filtering water entails the removal of pollutants. General water pollutants can be grouped as follows: total suspended solids (TSS), dissolved solids, biochemical organic pollutants, chemical organic pollutants and, salinity [16]. The largest pollutants by size are the TSS. The first method for removing solids from water (in e.g., wastewater treatment) is fine screening. It is a method where the feedwater passes through a screen which holds back solids: filtering. Screens with different sizes of opening are used throughout water treatment; large solids are removed from water with course screens which have openings of 6 mm. For TSS, fine screens can be used. Fine screens have screen opening sizes of 1.5 to 6 mm or even 0.2 to 1.5 mm. These can reduce TSS to levels near those achieved by primary clarification – which removes all solids from water. Fine screening requires 0.5-1.5 Wh/m3 in energy usage, has negligible water losses and produces wet sludge as waste stream [16], [92].

Two methods are well known and used for removing biochemical and chemical organic pollutants. The first is coagulation-flocculation and filtration. This method removes particulates - particles with a variable composition and a diameter of <100 μm - and decreases turbidity (relative clarity of a liquid). Coagulation entails that a coagulant - most commonly iron or aluminium salts with polymeric materials – is added to the water and mixed. The coagulant adsorbs to the particles, forming flocs. The flocs settle into a settling sludge and can be filtered out through sedimentation. Depending on the feedwater, multiple flocculation steps might be necessary. Coagulation-flocculation requires less than 0.05 kWh/m3, has negligible water losses and produced wet sludge as waste [16], [93]. The process is graphically depicted below in Figure 9.

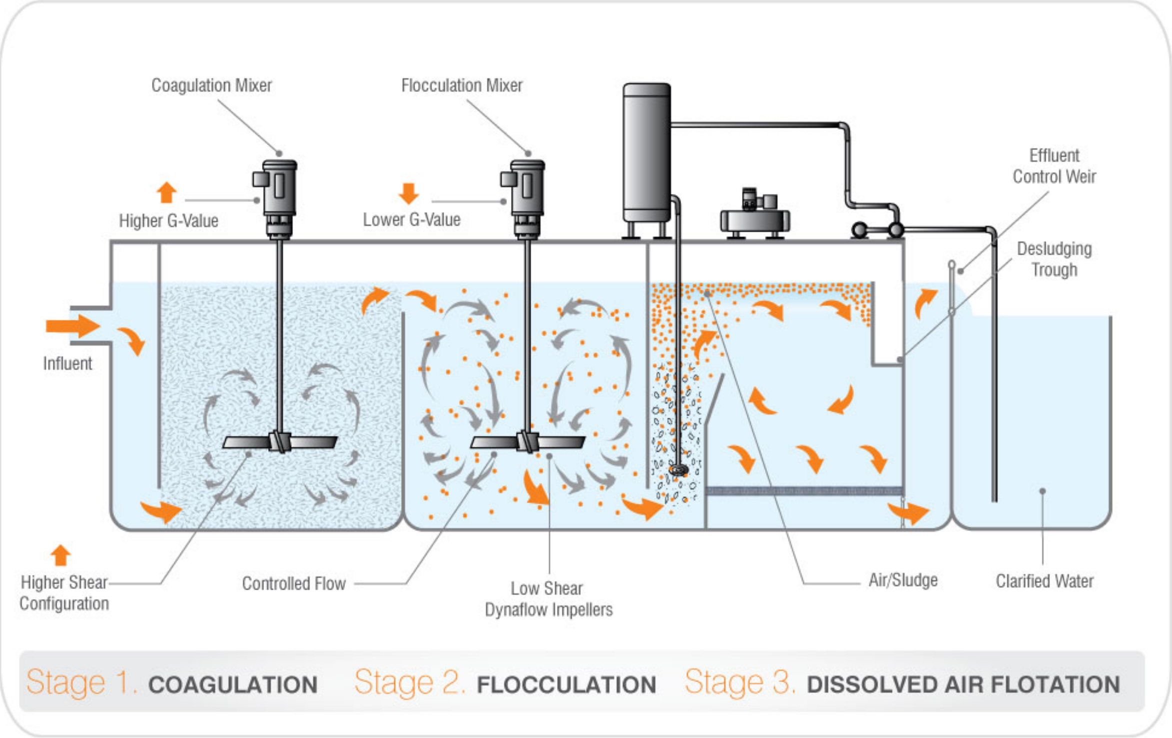


Figure 9: Coagulation-flocculation process graphically depicted [93]

The second method for removing particulates and decreases turbidity is ultrafiltration. This method uses a membrane as filter to hold back all particulates. It is more cost effective, more compact in design, lower maintenance requirements, lower in waste production and cheaper in operating costs than coagulation-flocculation. Ultrafiltration is generally the preferred method to remove particulates from water over coagulation-flocculation [93]. For the removal of salinity one general method is used worldwide: reverse osmosis (RO). In RO a partially permeable membrane is used to remove ions, unwanted molecules, and residual particles from the feedwater water. Salt water is driven through the membrane by chemical potential differences of the solvent behind the membrane. In this way, the salt water overcomes the osmotic pressure and flows through the membrane. It is often necessary for the feedwater to pass the membrane twice to reach sufficiently low concentrations of pollutants.

For specific elements such as chlorine, water hardness and dissolved gasses, additions to the standard RO. Chlorine must be removed using active carbon, to avoid oxidation of the selective layer of the membrane. Water hardness (due to ions as Ca and Mg) can cause membrane scaling – formation of a dense layer due to the precipitation soluble salt ions. To avoid membrane scaling a softener can be used that will exchange multivalent ions with Na. The reaction with Na will block precipitation. Alternatively, an antiscalant solution can be added. Dissolved gasses are not held back through the permeable membranes of RO. They must be removed with a separate process. Either a degasser can be installed after the RO membrane, or lye can be added to the feedwater water. CO2 and lye will react to bicarbonate ions which can then be removed with the RO system [94]. RO's efficiency and waste streams depends on the water source used. On average the reverse osmosis process uses 1.9-6 kWh/m3 [95]. The following table entails a summary of the presented water filtering methods. It should be noted that all values are given for centralized treatment of water.

Table 8: Water filtering methods and the pollutants each removes, average energy usage based on a centralized filtering system, water losses and waste production [16], [93]–[95]

Water filtering method	Pollutants removed	Energy usage	Water losses	Waste stream production
Fine screening	TSS	0.5-1.5 Wh/m3	negligible	Wet sludge
Coagulation-flocculation	biochemical and organic pollutants (particulates)	<0.05 kWh/m3	negligible	Wet sludge
Ultrafiltration	biochemical and organic pollutants (particulates)	0.025-0.1 kWh/m3	10%	7% of water input sludge type saline concentrate
Reverse osmosis - groundwater	salinity, residual particles and molecules	2–4 kWh/m3	15-25%	14% Brine concentrate - high-saline solution (dissolved solids)
Reverse osmosis - wastewater	salinity, residual particles and molecules	1.9-4.4 kWh/m3	20-30%	21% Brine concentrate - high-saline solution (dissolved solids)

Water demineralization

Demineralization is most done by ion exchange. Ion exchange is a process wherein a material is used that can absorb or bind to a particular ion and in exchange, release an ion. For electrolysis-based processes, a mixed bed filter or electrodeionization (EDI) unit is used for ion exchange. Both methods result in type II water, also known as demineralized or deionized water.

The mixed bed filter is a unit made up of a cation resin and anion resin. Positively charged ions in the feedwater such as Na will bind to the cation resin, which in turn will release a hydrogen ion. Negatively charged ions originating from the filtered water will replace a hydroxide ion of the anion resin. The hydrogen ion and hydroxide ion form water once combined. The infrastructure required for ion exchange by mixed filter consists of a tank and of the mixed resins. The mixed bed resin must be regenerated or exchanged once saturated [14], [94], [96]. The ion exchange concept of the mixed bed system is graphically given in the following figure.

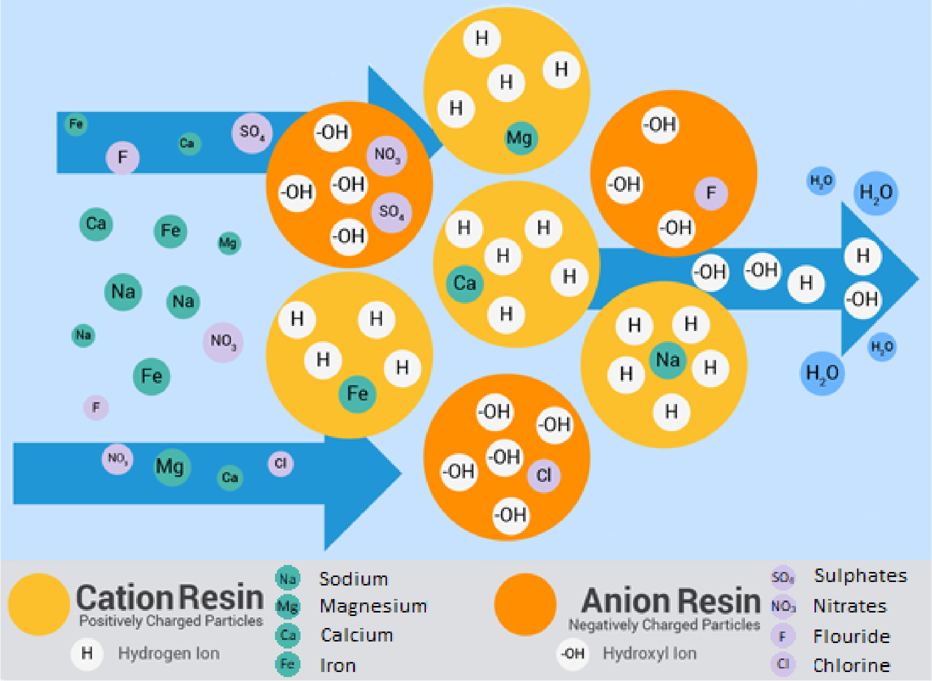


Figure 10: Mixed bed system, graphicallu [97]

EDI uses cation and anion resins. In addition to this, EDI has cation-exchange membranes and anion-exchange membranes throughout the resin as well as a cathode and anode. Cations from the feedwater will be attracted to the cathode while passing through the selective cation-exchange membranes. The same holds for the anions, anion-exchange membranes, and anode. Deionized water is discharged from the system, as well as the concentrate waste stream. Unlike the mixed bed, EDI can operate continuously due to a self-regenerating design. The main consumable is electricity, which on average is between 0.053 and 0.79 kWh per m3 of product water [94], [97]. The process is schematically depicted in Figure 11, where only one membrane is shown for simplicity. EDI is extremely efficient.

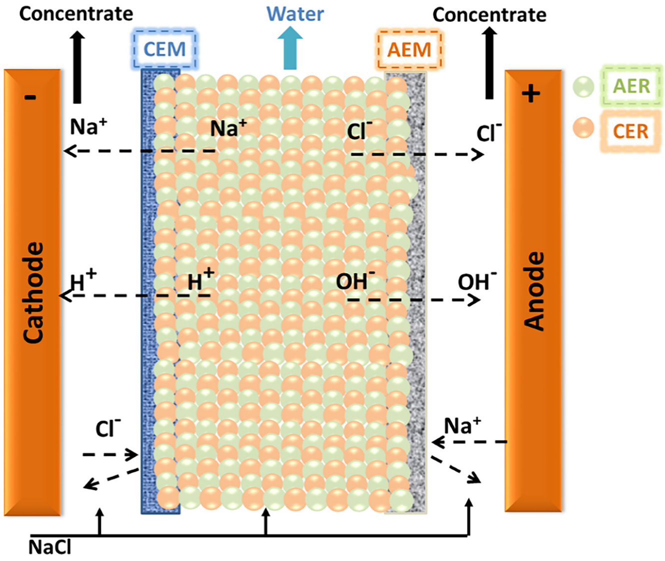


Figure 11: EDI schematically [97]

Depending on the type of resin, ions can be removed with an efficiency 97.5 – 99.9%. To achieve type II water, often EDI is done first after which a mixed bed filter is used for a final ‘polishing’ of the water [94], [97]. The following table summarizes characteristics of the mixed bed filter, EDI and combination methods.

Water demineralization method	Energy usage	Water losses	Waste stream production	Efficiency
Mixed bed filter	*negligible, <0.0005 kWh/m3*	*negligible*	*no stream* - saturated mixed bed*	*88.9 – 98.5%*
Electrodeionization (EDI)	0.053-0.79 kWh/m3	5-10%	Concentrated ions	97.5 – 99.9%
Combination EDI + mixed bed filter	0.053-0.79 kWh/m3	5-10%	Concentrated ions*	99.9%

Table 9: Water demineralization method and average energy usage based on a centralizedfiltering system, water losses and waste production and efficiency [14], [94], [97]

5.2.3 Water pressure

The water supply system must comply with two functional constraints for the water pressure. The system must provide water of at least 1 Bar (FC3) and at most 5 Bar (FC4). The range of 1-5 Bar for water pressure is coherent to that found in industrial processes for water treatment and residential areas [75], [76], [98]. The required pressure for a mixed bed filter system is 40-80 psi, equal to 2.8 – 5.5 Bar [96].

Water must be distributed across the solar farm to each individual electrolyzer. Therefore, the water pressure at the initial point should be higher, so that the decrease in pressure over the distance of the pipes results in a pressure no lower than 1 bar. The ZEF electrolyzer can handle a range of pressures [12]. In this instance, a pressure gauge for measurement and a booster pump to ensure sufficient pressure at the initial point could be used. Moreover, booster pumps could be placed throughout large farm sizes to maintain adequate pressure levels at the electrolyzers.

In case all electrolyzers must receive water with the same pressure, a pressure reducing valve can be added prior to the electrolyzer or a set of electrolyzers which will minimize the difference in water pressure throughout the farm [99]. The plausible means for regulating and controlling the water pressure on the hydrogen production farm are thus pressure gauges, pressure booster pumps and pressure reducing valves. The energy consumption is dependent on the number of gauges, pumps, and valves in combination with the amount of water to be distributed. This is defined in the following section.

Ultimately, water pressure is determined by the rate of flow and the resistance of the system that the water is moving through. The pipes used for water distribution on the farm will influence the booster pump(s) and pressure reducing valves required. This will be expanded upon in the following infrastructure section as well.

5.2.4 Water quantity

Four functional constraints hold for water quantity. Two cover account for the quantity of water the system must supply and two account for the variation of the demand pattern for the electrolyzer:

The water supply system must provide each electrolyzer plant with at least one kilo of water per (running) hour. (FC5) The water supply system must hold 20% more water than required per electrolyzer daily to compensate for leakages in the water distribution. (FC6) The water supply system must support the daily dynamic demand pattern for water for each electrolyer on the farm. (FC7) The water supply system must support the seasonally dynamic demand pattern for water for each electrolyer on the farm. (FC8)

As mentioned, per running hour one electrolyzer consumes 1,082 L of demineralized water for hydrogen production. This demand is covered in FC5. FC6 account for leakages in the water distribution system, but not for water losses of previous filtration and demineralization steps. These additional losses should be accounted for using the found water loss percentages of the processes in Table 9 and Table 8. Table 10 presents the hourly water demand for the different farm sizes. Note that the hourly demand is equal for both farm locations.

Table 10: Hourly water demand for different farm sizes depending on treatment process.

Farm sizes	***50 MW***	***150 MW***	***1,5 GW***
Number of electrolyzers (unit)	8400	25000	250000
Water usage of electrolyzers (m3/hour)	9	27	271
Electrolyzers' water usage - leakage, UF, RO ground and surface water, demineralization (m3/hour)	14 - 16	43 - 49	431 - 491
Electrolyzers' water usage - leakage, UF, RO wastewater, demineralization (m3/hour)	15 - 17	459 - 51	450 - 511

FC7 and FC8 cover both daily and seasonal variation of sun hours, thus running hours and thus demand of water for the electrolyzers. Previous TIL reports found that when using an average of 5,65 ESH per day are taken for Ínsua, and 7 ESH per day for Al Buraimi, that both seasonal and daily variations are accounted for [13]. Using these values in combination with the hourly water usage per electrolyzer and water loss percentages, the daily amount of required water per farm size per location has been calculated. The findings are presented below in Table 11.

Table 11: Daily water demand for different farm sizes and locations depending on treatment process.

Farm sizes	***50 MW***	***150 MW***	***1,5 GW***
Number of electrolyzer (unit)	8400	25000	250000
Water usage of electrolyzers Insua (m3/day)	51	153	1528
Water usage of electrolyzers Insua - leakeage (m3/day)	61	183	1834
Water usage of farm Insua - leakage, UF, RO ground and surface water, demineralization (m3/day)	81 - 92	244 - 277	2436- 2774
Water usage of farm Insua - leakage, UF, RO wastewater, demineralization (m3/day)	85- 96	254 - 289	2542 - 2889
Maximal water usage of farm Insua - rounded up (m3/day)	97	289	2885
Water usage of electrolyzers Al Buraimi (m3/day)	63	189	1894
Water usage of electrolyzers Al Buraimi - leakage (m3/day)	76	227	2272
Water usage of farm Al Buraimi - leakage, UF, RO ground and surface water, demineralization (m3/day)	101 - 115	302 - 344	3018 - 3437
Water usage of farm Al Buraimi - leakage, UF, RO wastewater, demineralization (m3/day)	105 - 119	315 - 357	3149 - 3574
Maximal water usage of farm Al Buraimi - rounded up (m3/day)	120	358	3575

5.2.5 Infrastructure

This section presents the means in terms of infrastructure for the water supply system. All domains presented thus far influence the type of equipment and infrastructure necessary. Equipment and infrastructure means will be given per water source and corresponding filtering process. The same will be done for the demineralization process. Per farm size, infrastructural elements as water tanks and piping are considered next.

Three functional constraints must be met for all means of the infrastructure. The technology should be well established on the market (FC9); the system must operate with minimal time delays (FC10); and operate based on an off-grid energy source (FC11).

A schematic overview of all processes of the water supply system is given below. The figure depicts all processes required to deliver water to the electrolyzers dispersed across the farm (solar to hydrogen production area). Plausible infrastructural means will be given for each process of this system. This will be done in the order of the schematic flowchart: transportation, storage, water treatment process and water distribution.

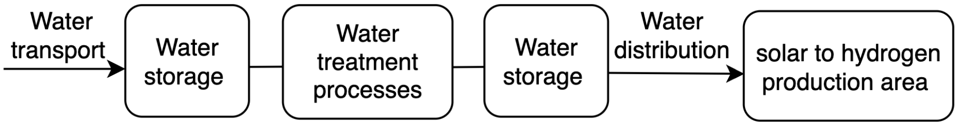


Figure 12: Schematic flowchart for the water supply system

Transportation

No functional constraints are posed for the transportation aspect of the water supply system. The means for acquiring water from potential water sources to the water treatment area are limited to either trucks or through pipelines. The farm using the least amount of water on a daily basis is the 50 MW farm located in Ínsua (97 m3/day - Table 11). Larger water lorries can transport up to 40 m3 [16], [100]. For the smallest farm more than two large water lorries are required daily. Transporting such amounts of daily water volumes may not be logistically feasible. This is certainly the case for the larger farms, which will require even more trips by large lorries daily.

Piping is a capital-intensive investment though the only means to acquire large volumes of water to the water treatment areas of the farm. Distance of water sources to the farms will be used in the following sections to evaluate the costs per source per location of the farm. The benefit of transport of water through pipes is that the water storage tanks prior to water treatment can be do not have to encompass a full day's worth of water. Utilizing pipelines for water transport to the farm is not in alignment with a complete off-grid solar-to-hydrogen farm. It requires installation of long term equipment in the form of underground pipelines connected to the water grid or to a WWTP. As it is the only form of transportation that allows the required volumes of water to reach the farm, it will be considered for all farm designs for this research. It will be evaluated if connection to the water grid, and/or creation of a pipeline network to an external source for water transport in combination with an off-electricity grid design for hydrogen production can provide benefits and result in a market competitive LCOH.

Water storage tanks

The water treatment area will entail initial water storage, water treatment and final water storage - as depicted in Figure 12. The initial water storage tank holds water from the source after being transported from the source to the farm. In case trucks are used for transport, the tank should thus be able to hold the maximum amount of water as presented in Table 11.

Assuming that the water demand is replenished daily and that the water tank costs are

- 300 €/m3 times a factor of 1.9 to account for installation costs for smaller tanks (up to 1000 m3) - this factor corresponds to the Lang-factor mentioned in section 3, which is significantly lower for water tanks than i.e., hydrogen tanks due to technical maturity and safety [16], [69]
- 200 €/m3 times a factor of 1.9 to account for installation costs for bigger tanks (1000 m3 and up) [16]

The initial water storage tank details have been calculated and are as presented below in Table 12. They are based on the water quantities defined for the farm of Table 11.

Table 12: Initial water storage tank sizes and costs as presented in Table 11 [16]

Farm sizes	***50 MW***	***150 MW***	***1,5 GW***
Maximal water usage of farm Insua - rounded up (m3/day)	97	289	2885
Tank size (m3)	100	300	3000
Tank cost (euro)	57.000	171.000	1.140.000
Maximal water usage of farm Al Buraimi - rounded up (m3/day)	120	358	3575
Tank size (m3)	150	400	4000
Tank cost (euro)	85.500	228.000	1.520.000

If pipelines are utilized to transport water from the water source to the farm, smaller storage tanks can be used prior to water treatment. The initial water storage tank no longer must hold the total amount of water (required per day) at once, as the supply flow can be semi-continuous. In this case, an initial storage tank for 50 MW and 150 MW farms of 100 m3 can be used, and for the 1,5 GW farm an initial storage tank of 1000 m3 will suffice [16], [17].

This implies that in case pipelines are used to supply water from the water source to the water treatment area, the following initial storage tanks (Table 13) are required instead of those mentioned in Table 12.

Table 13: Initial water storage tanks required in case piping is used to supply water

Farm sizes	***50 MW***	***150 MW***	***1,5 GW***
Maximal water usage of both farms - rounded up (m3/day)	150	400	4000
Tank size (m3)	100	100	1000
Tank cost (€)	57000	57000	380000

The second and final water storage tank holds the demineralized water. This water storage tank is located closest to the solar to hydrogen production area depicted in Figure 13. The second water tank is filled as the water treatment plant operates. It is thus not required to hold the total amount of water that the electrolyzer requires - though this is suggested by Simoes et al., in case of disruptions or maintenance (to give the system redundancy for at least one day of operation) [16]. Furthermore, compared to the initial storage tank, the total amount of water is reduced due to leakage and brine produced by the water treatment process. The tank sizes and corresponding costs for the demineralized water are given below in Table 14. These tank sizes are based on the required water per farm size as determined in Table 11.

Table 14: Tank sizes and costs for the final storage tanks [16]

Farm sizes	***50 MW***	***150 MW***	***1,5 GW***
Water usage of electrolyzers Insua accounting for leakeage (m3/day)	61,14	183,40	1833,99
Tank size (m3)	100	200	2000
Tank cost (euro)	57.000	114.000	760.000
Water usage of electrolyzers Al Buraimi accounting for leakage (m3/day)	75,75	227,22	2272,2
Tank size (m3)	100	250	3000
Tank cost (euro)	57.000	142.500	1.140.000

Water treatment process - centralized water treatment

As mentioned, there are different methods for filtration and different combinations used to achieve sufficiently filtered water. Water filtering can be done using either coagulation-flocculation or fine screening, after which ultrafiltration and reverse osmosis. The combinations required depend on the water source. The possible combinations are as follows:

- Reverse osmosis
- Fine screening with ultrafiltration and reverse osmosis
- Coagulation-flocculation with ultrafiltration and reverse osmosis
- Ultrafiltration and reverse osmosis

All methods are commonly used in water treatment plants with a larger daily capacity than required for the hydrogen production farm. For consideration, a small to medium sized (waste) water treatment plant (WWTP) processes around 1200 m3 per day - though assets for filtration can be produced and operated on a smaller scale, it is less cost-effective [101]. All presented filtering methods have been analyzed as a centralized treatment process. In general, WWTPs have centralized processes as due to the large capital investment required for filtering to be compensated for using economies of scale.

As Table 11 shows, roughly a third of a small to medium size WWTP is required for even the biggest farm size, depending on the location of the farm. Inherently this means that there is no large benefit in terms of the economy of scale principal – as the total amount of required water is relatively low. This could be omitted in case more water is treated than required for the hydrogen farm. The large expenses could be spread over a larger amount of filtered water, of which the surplus could be sold and in exchange generate income.

Limiting the scope of this research to producing water for hydrogen production on the hydrogen farm only would mean that in case centralized filtering methods are used for the hydrogen farm, the cost-efficiency and effectiveness of the water treatment will be lower than those of general WWTPs. Considering the large investment costs required for coagulation-flocculation, fine screening, ultrafiltration, and reverse osmosis, this implies that water treatment should be done centralized for the hydrogen production farm [16], [93]–[95], [97]. A schematic layout for such a farm setup is given below.

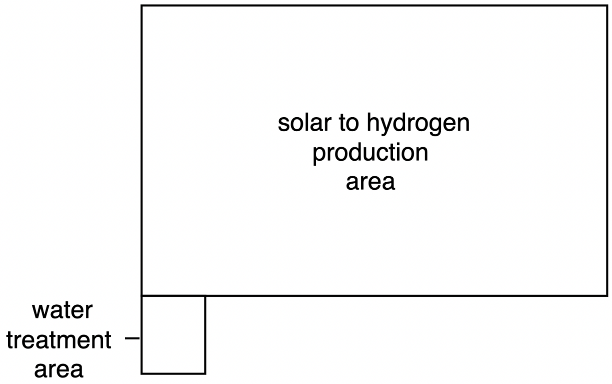


Figure 13: Schematic farm layout. Separation of water treatment area and solar-to-hydrogen area

Water treatment process - equipment and initial costs

The costs for all water treatment processes are based on those found by Simoes et al. and - where found - supported by quotes from suppliers.

A coagulation-flocculation process for a WWTP with a flow below 400 m3/day or between 400-600 m3/day – which holds for the 50 MW and 150 MW farm size – a tank with coagulation and filtration chemicals and a 4 m x 5 m filtration membrane suffice. Installation and terrain preparation, equipment and testing are assumed to cost an initial investment of €80.000. For a WWTP of flows between 2000-4000 m3/day – corresponding to the 1,5 GW farm size at both locations - two or three 4 m x 5 m filters are to be used [16], [17]. Including the tank and chemicals the assumed initial investment cost is €590.000 [16].

For fine screening, a tank with a 5 m x 5 m membrane can be used for 50 MW and 150 Mw farm sizes, for which the tank, membrane, and installation aspects (including pressure, pump, piston for water flow) are posed at €150.000. For a 1,5 GW farm size (flows between 2000-4000 m3/day), two to three membranes are require paired with larger tanks for which a cost of €1.200.000 is estimated [16].

Ultrafiltration for the two smaller farm sizes requires piping and housing with compact membranes, 6 m x 10 m in two parallel streams. Tank, membranes, and installation aspects (including pressure, pump, piston for water flow) are posed at €200.000. For the largest farm size, three 6m x 10 m membranes in parallel are estimated at €960.000 [16].

For reverse osmosis coupled with EDI, pipes and housing with compact membranes, 6 m x 10 m in two parallel streams is required as well for the 50 MW farm. Initial investment of €500.000 is assumed. For the 150 MW farm this is estimated at €1.200.000. For the largest farm size, four compact membranes and equipment are required with an estimated initial investment cost of €6.000.000 [16].

The mixed bed filter process requires tanks and resins. For the 50 MW farm that would entail a cost of €100.000 for the tank, resin, and pump. The 150 MW farm will require a larger tank and more resin amounting to €250.000. The 1,5 GW farm will require the largest tank and amount of resin, estimated at €700.000 [16], [96].

Farm sizes	***50 MW***	***150 MW***	***1,5 GW***
Coagulation flocculation CAPEX (€)	80.000	80.000	590.000
Fine screening CAPEX (€)	150.000	150.000	1.200.000
Ultrafiltration CAPEX (€)	200.000	200.000	960.000
Reverse Osmosis + EDI CAPEX (€)	500.000	1.200.000	6.000.000
Mixed bed filter CAPEX (€)	100.000	250.000	700.000

Table 15: Estimated CAPEX in EUR for water filtering and demineralization methods, based on values by Simoes et al. and Puretec B.V [16], [96]

Water distribution

Demineralized water must be distributed to all electrolyzers across the farm. Required infrastructure as piping, pumps and valves are determined based on the farm layout. In shape and size, the largest objects on the farm will be the solar panels and their infrastructural support system. The solar panels and the infrastructural tracker system thereof is supplied by Chint [33]. The tracker system allows for always shifting the orientation of the solar panel towards the sun. An impression including measurements is shown in Figure 14.

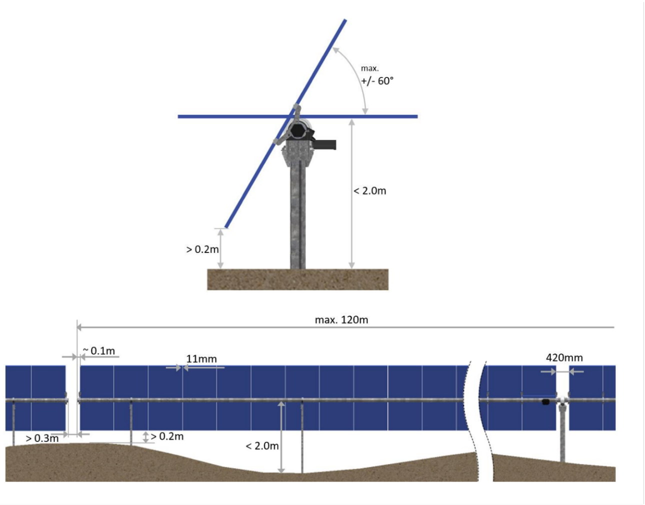


Figure 14: Example setup of trakcer-system by CHINT [33]

For the Chint tracker systems, the following details hold [33]:

- The smallest unit of tracker support is a tracker-string
- The tracker system supports 25 solar panels (635 W each) per tracker-string of 29 meters
- In between tracker-strings a distance of 420mm is required for the tracker motor
- Due to the distance between tracker-strings being minimal, solar panels of two tracker-strings can be connected to one electrolyzer
- No additional distance between the electrolyzer required in terms of safety conditions [12]
- Thus, a 116m long tracker table holds 100 solar panels which support 10 electrolyzers (this implies that the

distance between electrolyzers on a tracker table is 14,5 m)

- The distance between tables in the North-South direction must be at least 300mm
- The width of the tracker-string in a flat orientation is 2,28m
- Accounting for leeway, the distance between two adjacent electrolyzers in north-south direction is given as 3,0 m

For the purpose of this assessment, the following assumptions were made for both farm locations:

- The farm areas consist of very flat terrain
- Minimum temperature values do not go below 0°C when the sun is shining [33]
- Dimensions of the farm are square-like in order to support the solar panel tracker systems

The assumptions and measurement requirements have been used to calculate estimates for dimensions of the different farm sizes. These are given in Table 16.

Table 16: Dimensions for the three farm sizes, considering that one tracker table supports solar panels for 10 electrolyzers and has a length of 116 meters, and the distance between rows is 3 meters [33]

Farm sizes	***50 MW***	***150 MW***	***1,5 GW***
Number of electrolyzers (unit)	8.400	25.000	250.000
Number of tracker tables placed in a row (unit)	5	8	25
Length of the farm - of one tracker string row (m)	**580**	**928**	**2900**
Number of rows	168	312	1000
Width of the farm (m)	**504**	**936**	**3000**

These farm dimensions are used to estimate the pumping and piping equipment required for distribution of demineralized water at appropriate water pressure levels across the farm. Materials for the piping system for water distribution that are deemed suitable are both (carbon) steel and standard PVC, as found in literature and approved by experts at Aqualeap B.V. (by Artechno group B.V) [15], [16], [102]. Both materials have lifetimes longer than 30 years if maintained and installed properly. Standard PVC can achieve a lifetime of 30 years or more if placed slightly below ground. With proper installment, steel can achieve an even longer lifetime [15], [102]. Above ground, 30 years is achievable for both materials [15].

Steel piping can endure larger pressure ranges than standard PVC pipes (these can support up to 16 Bar of pressure) [15]. Conversely, steel pipes are a larger investment than PVC pipes in terms of CAPEX and OPEX.

The pressure loss of a pipeline depends on i.a. the material of the pipeline. For pressure losses the following equation stands: [103]

$$\Delta P = f * \frac{L}{D} * \frac{\rho v^2}{2}$$

- ΔP = Pressure loss
- f = Darcy friction factor, which depends on the Reynolds number and the relative roughness of the pipe (which depends on the material of the pipe)
- L = Length of the pipe

- D = Diameter of the pipe
- ρ = density of the fluid
- v = flow velocity

The pressure increases linearly with the friction factor and the friction factor increases with a larger surface roughness. The surface roughness of steel is larger than that of PVC (0,045 mm compared to 0,02 mm) [103], [104]. As PVC is lower in cost as well, it is suggested to use PVC pipe roughness for pressure loss estimation of the farm so that the minimal pressure loss is determined [15].

To assess the piping required at the farm, first the size pipes are determined after which the pressure losses and capacities are assessed. The equation for flow rate is used to determine the diameter of the pipes required to deliver the required amount of (demineralized) water at a certain speed: [103]

$$Q = v * A$$

- Q = flow in m^3/s
- v = average speed in m/s
- A = internal surface of the pipe in m^2

The diameter follows from the internal surface of the pipe according to the general formula:

$$d = \sqrt{4A/\pi}$$

- d = diameter in m^2
- A = internal surface of the pipe in m^2

The rule of thumb for the diameter of the suction pipeline (prior to the pump) is a speed of 1 m/s and for the pressure pipeline (after the pump) is 2 m/s [15]. This is because at a higher water speed, more control is required to manage the fluid hammer across the system. The flow rate capacities were determined for the standard PVC pipe sizes (external diameters of 25, 32, 40, 50, 63, 75, 90, 110, 125, 160, 200, 250 and 310 mm) [15].

Points throughout the farm do not have identical flow requirements. The largest flow requirements hold for points closest to the water supply tank, where all water must flow through. Rows further away from the (demineralized) water tank will require less flow as they only require water for the remaining electrolyzers. The exact diameters of pipes per row of electrolyzers thus varies. On an even smaller level of detail, PVC pipelines can vary in diameter across the rows.

As this is an initial estimation for pipelines across large farms, the estimation for the pipeline diameters should be done based on percentages of the farm. Dividing the rows of the farm in ten parts of 10 percent each was suggested by experts at Aqualeap B.V [15]. This means that per set of rows, the required flow to supply these rows and the following rows should be used to determine the internal surface and therefrom the diameter. This is schematically visualized in Figure 15.

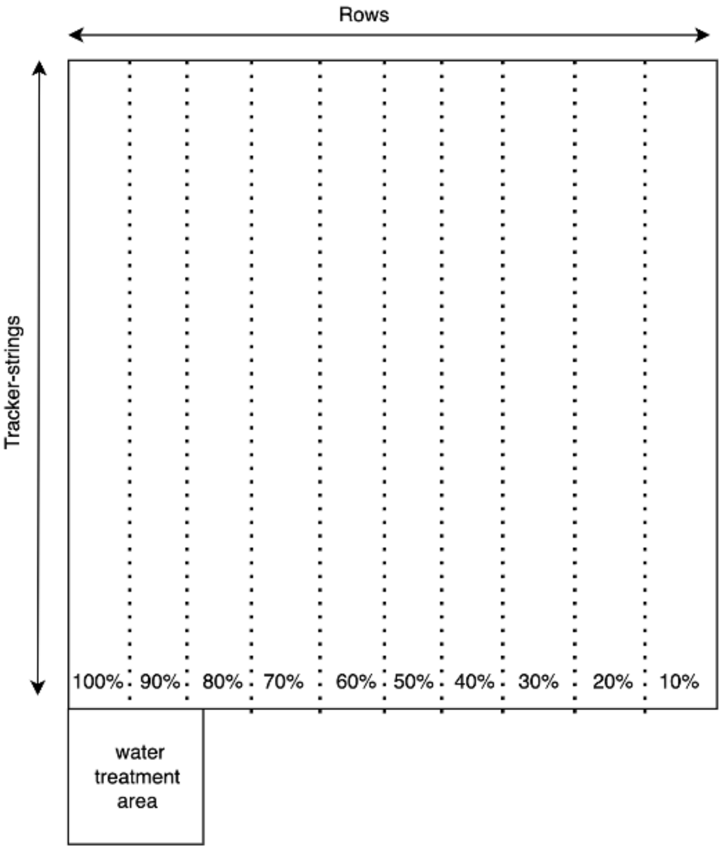


Figure 15: Schematically presented row sets for the water feed system on the hydrogen farm.

The required flow for all farm sizes in m3/hour, was calculated using Table 11 and Table 12. For reference, the total mount of water for Ínsua was taken, and divided by its available ESH. The resulting water usage per row of electrolyzers is equal to that of the Al Buraimi farms total water usage divided by the available average ESH of Al Buraimi. The values can be found in Table 17.

Table 17: Flow rates required per farm size, using the flow rate per unit per hour of 1,082 L and 20% leakage losses throughout the pumping and piping distribution system. Values of usage for Ínsua have been used to derive the average water usage per electrolyzer row - this is equal value for the Al Buraimi farm (see water usage and ESH Al Buraimi of Table 12)

Farm sizes	***50 MW***	***150 MW***	***1,5 GW***
Number of electrolyzers (unit)	8400	25000	250000
Q - water usage of farm accounting for leakage (m3/hour)	10,8	32,5	324,6
Units per row	50	80	250
Q - water usage per row accounting for leakage (m3/hour)	0,07	0,10	0,33
Rows per farm	167	313	1000

Using the flow rate per row set and the length of the pipe, the pipeline diameters have been selected based on the flow rate fact sheet provided by Aqualeap B.V [15] Results are posed in Table 18, Table 19, and Table 20. The

PVC suction pipes required are given in Table 21.

Table 18: PVC pipes required per row set for the 50 MW farm, including the length of the PVC pipe covering the row set

50 MW				
Percentage flow rate required at row set - v = 2 m/s	Flow rate Q (m3/hour)	Internal diameter (mm)	External diameter (mm)	Length of PVC (km)
100%	10,84	45,2	50	0,58
90%	9,76	45,2	50	0,63
80%	8,67	45,2	50	0,68
70%	7,59	45,2	50	0,73
60%	6,50	36	40	0,78
50%	5,42	36	40	0,83
40%	4,34	28,4	32	0,88
30%	3,25	28,4	32	0,93
20%	2,17	22,5	25	0,98
10%	1,08	22,5	25	1,03

Table 19: PVC pipes required per row set for the 150 MW farm including the length of the PVC pipe covering the row set

150 MW				
Flow rate required at row set - v = 2 m/s	Flow rate Q (m3/hour)	Internal diameter (mm)	External diameter (mm)	Length of PVC (km)
100%	32,51	83	90	0,93
90%	29,26	83	90	1,024
80%	26,01	69,2	75	1,118
70%	22,76	69,2	75	1,212
60%	19,51	69,2	75	1,306
50%	16,26	58,2	63	1,4
40%	13,00	58,2	63	1,494
30%	9,75	45,2	50	1,588
20%	6,50	36	40	1,682
10%	3,25	28,4	32	1,776

Table 20: PVC pipes required per row set for the 1,5 GW farm including the length of the PVC pipe covering the row set

1,5 GW				
flow rate required at row set - v = 2 m/s	flow rate Q (m3/hour)	Internal diameter (mm)	External diameter (mm)	Length of PVC (km)
100%	324,6	296,6	315	2,9
90%	292,14	230,8	250	3,2
80%	259,68	230,8	250	3,5
70%	227,22	230,8	250	3,8
60%	194,76	230,8	250	4,1
50%	162,3	174,6	200	4,4
40%	129,84	174,6	200	4,7
30%	97,38	147,6	160	5,0
20%	64,92	115,4	125	5,3
10%	32,46	83	90	5,6

Table 21: PVC pipes required for the suction pipes of all farm sizes - note that the speed of 1,3 is used for the 1,5 GW farm as the largest standard PVC pipe available has a diameter of 315mm.

Farm size	Flow rate Q (m3/hour)	Internal diameter (mm)	External diameter (mm)
50 MW - $v = 1$ m/s	10,84	69,2	75
150 MW - $v = 1$ m/s	32,51	115,4	125
1,5 GW - $v = 1, 3$ m/s	324,6	296,6	315

The length of the pipes and the diameter can now be used to determine the loss in pressure over the entire pipe – which in turn can be used to determine the pressure at the starting point of the pipe. Upon planning, the loss per pipe to each electrolyzer can be assessed. For the current scope of the water system, the greatest and smallest loss of pressure over the pipes supplying the sets of rows of the farm is estimated. This is done using the resistance calculator of the TU Delft Werktuigbouwkunde [104]. The pressure losses from the point of exit to the last point of every pipe supplying water to the row set is given in the following table.

Table 22: Pressure loss estimation for all row sets for all farm sizes

	50 MW	***150 MW***	***1,5 GW***
Row set	Pressure loss from supply to final point (bar)	Pressure loss from supply to final point(bar)	Pressure loss from supply to final point (bar)
100%	2,5	*1,7*	0,9
90%	2	1,6	2,4
80%	2,3	3,4	2,1
70%	1,7	2,8	1,8
60%	3,4	2,4	1,4
50%	2,7	4,2	3,3
40%	5,2	3	2,4
30%	3,5	5,8	4,4
20%	5,4	7,2	7,2
10%	2,6	7,4	10,8

The minimal loss of pressure for the 50 MW farm is 1,7 whereas the maximum is 5,4. For the 150 MW farm this is 1,6 and 7,4; for the 1,5 GW farm 0,9 and 10,8, respectively.

It should be noted that instead of the total lengths, the pressure loss of the previous pipe is considered and the additional pressure loss over the branching supply pipe was added. This calculation does not include the pipe elbows needed for branching. A minimum of four elbows are considered. Assuming that the PVC pipes are installed slightly underground as suggested by experts, an elbow is required for every point of entering and exiting the ground [15]. For the further row (supplying the last 10% of water) the water pipe thus enters the ground upon exiting the water treatment area, turns towards the row, enters the row and must come above ground again. This is schematically depicted with red dots as elbows in Figure 16. Each elbow is estimated to cause an additional loss of at most 0,5 Bar.

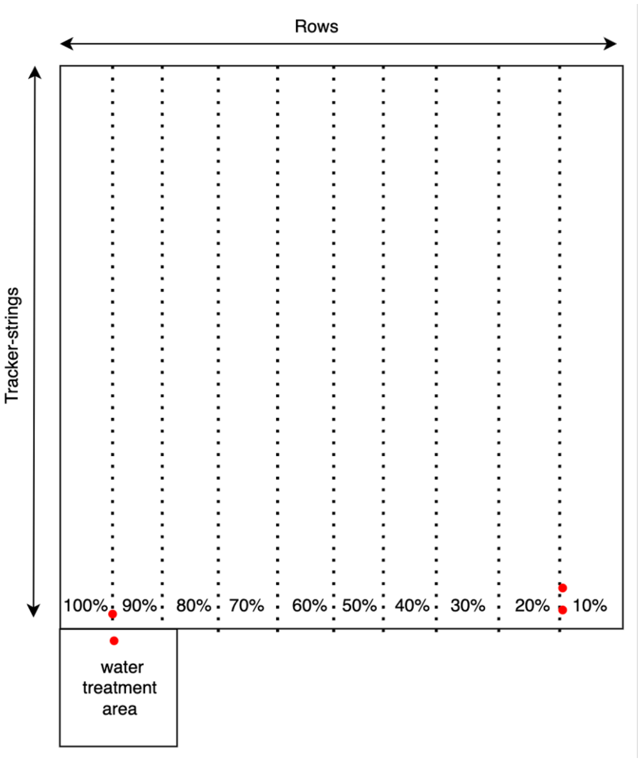


Figure 16: Depiction of elbows in main pipeline over the hydrogen farm

Accounting for the elbows on the farm, the minimal loss of pressure for the 50 MW farm is 3,7 whereas the maximum is 7,4. For the 150 MW farm this is 3,6 and 9,4 and for the 1,5 GW farm 2,9 and 12,8, respectively.

This estimate indicates that even in the most extreme cases, PVC pipes can supply water under the required pressure as they have capacity to hold up to 16 Bar [15]. The estimate also shows that due to the difference between minimal and maximal pressure losses not exceeding 16 Bar on either farm sizes, one pump per farm should suffice the water pressure constraints - no additional booster pumps are required based on these results. To increase the redundancy of the system, a ring pipeline system can be made by connecting all rows through another pipeline on the opposite side of farm as well - along the farm width. Regulator valves can be used for the branches to decrease pressure if needed.

If the pressure differences were larger over the farm, steel pipes could be used. Steel pipes can endure more pressure, have larger lifetime expectation, and come with a larger capital investment cost [15].

It should be noted that both PVC and steel pipes as well as all other equipment mentioned are readily available on the market and well-established. Both materials comply with all functional constraints.

5.2.6 Energy

The water supply system has one functional constraint regarding the energy source. The water supply system must not be dependent on the grid for energy (FC11). It outside of scope to add an area for the processing of non-renewable energy sources as coal, oil, gas or nuclear. Adding renewable sources is favored – as will emerge in design selection according to NFO21. The addition of an area for converting biomass or geothermal energy is out of scope for the hydrogen farm. Well established renewable sources that are potential for the farm are solar energy, as it is already included in the hydrogen farm, or wind energy, a well-established renewable energy source and often used in combination with solar energy on industrial sites [4]. The hydrogen farm already includes solar PV, adhering to one technology for energy generation is favourable.

Even so, as the water supply system must hold a safety margin over the production hours of the electrolyzers, a battery will be required to support semi-continuous water treatment.

The energy usage of the water supply system is dependent on the water source and subsequent filtering (coagulation-flocculation, fine screening, reverse, ultrafiltration, and/or reverse osmosis) and demineralization method. As specified in Table 8 and Table 9, these methods have varying energy demands. The cost estimation for energy usage will therefore be one after these prior system functions are been defined in the design selection step.

5.2.7 Morphological chart

The following table gives an overview of the means for all water supply system functions that have been presented and elaborated upon. The means will be evaluated and selected in the following design step.

Table 23: Overview of the water supply system functions and means.
* only available for Ínsua
** only available for Al Buraimi

Means ***System Function***							
Water source	Surface water	Ground water	Industrial wastewater	Urban wastewater	Water grid	Rainwater*	Treated seawater **
Water purity	Fine screening	Coagulation-flocculation	Ultrafiltration	Reverse osmosis - groundwater	Reverse osmosis - wastewater	EDI	Mixed bed filter
Water pressure	Main pump	Pressure valves	Pressure gauges				
Water quantity	Large storage tanks - no pipeline supply	Smaller storage tanks - pipeline supply					
Infrastructure	PVC pipes	Steel pipes					
Energy	Solar	Wind	Batteries				
Transport	Trucks	Pipelines					

5.3 Design Selection and Evaluation

In this section means will be selected through evaluation for all defined system functions - water source, water quality and quantity, infrastructure, energy, and transportation. Evaluation is done by testing all means against the non-functional constraints for the system function. Testing against non-functional constraint is a pass-or-fail test. The means that comply with non-functional constraints are then graded using the functional and non-functional objectives, resulting in the best scoring means per system function. After the set of means have been chosen, a final CAPEX and OPEX overview is given.

5.3.1 Water source

Plausible water sources per location were given in Table 7. Aside of availability no other functional constraints are posed for the water source. The means for this system function is thus to be decided through grading based on the nine non-functional objectives. They are stated below as posed in Table 24. As mentioned, these are qualitative objectives and will be graded according to the criteria posed by Simoes et al., shown in Table 25 and Table 26. All criteria receive the same weight for evaluation [16].

Table 24: Non-functional objectives for water source selection and evaluation

	System function	***Non-functional objective (NFO)***
NFO1	Water source	There should be minimum effect of weather factors on the water source.
NFO2	Water source	The perceived future impact of climate change on the water source should be minimal.
NFO3	Water source	The water source should require as little preprocessing and maintenance steps before being available to obtain.
NFO4	Water source	The water supply source should preferably be used by the hydrogen farm only or shared with a minimal number of other users.
NFO5	Water source	The number of involved entities and existence of previous experience with this type of water for a similar use, should be minimized.
NFO6	Water source	Transport distance from water source to hydrogen production plant site should be minimal.
NFO7	Water source	The water source should require the minimal processing steps before being usable for the alkaline electrolyzer.
NFO8	Water source	Usage of the water source should be socially accepted.
NFO9	Water source	Bureaucracy regarding permits for the water source should be minimal.

Table 25: Non-functional objectives and their corresponding criteria for the qualitative assessment of water sources by Simoes et al. [16]

	Criteria	**Performance level**	
		1	*2*
NFO1	*Reliability of availability (weather)*	Highly dependent on weather factors (water source not available throughout the whole year)	Medium dependent on weather factors (can be lower than needed by electrolyser)
NFO2	*Reliability of availability (climatic effect)*	High climate change impact expected	Medium climate change impact expected
NFO3	*Reliability of availability (continuity of supply)*	Strong possibility of interruptions in supply	Medium possibility of interruptions in supply
NFO4	*Competition with other uses*	Competition with human water supply and/or agricultural uses	Competition with agricultural uses
NFO5	*Complexity of abstraction/collection*	Very difficult and with potential unexpected complications	Requires permit and payment of charges
NFO6	*Transport distance*	Long distance	Medium distance (up to 50 km)
NFO7	*Treatment needed*	Very high- fine screening + coagulation/filtration (or ultrafiltration) and RO	High - microfiltration (or ultrafiltration)
NFO8	*Social acceptance*	Difficult acceptance due to the possibility of exhaustion of the resource	Weak acceptance due to the possibility of rejection of brines in the ecosystem
NFO9	*Complexity of permitting process*	High complexity	Medium complexity

Table 26: Non-functional objectives and their corresponding criteria for the qualitative assessment of water sources by Simoes et al. continued [16]

	Criteria	**Performance level**	
		3	*4*
NFO1	*Reliability of availability (weather)*	Low dependence on weather factors (will not be lower than needed by electrolyser)	Not dependent on weather
NFO2	*Reliability of availability (climatic effect)*	Low climate change impact expected	No climate change impact expected
NFO3	*Reliability of availability (continuity of supply)*	Light possibility of interruptions in supply	No interruptions in supply
NFO4	*Competition with other uses*	Competition with other uses	Without expected competitio
NFO5	*Complexity of abstraction/collection*	Requires negotiations and eventually payment of charge/tariff	Freely accessible
NFO6	*Transport distance*	Short distance	At location
NFO7	*Treatment needed*	Medium - fine filtration (or fine screening) and ultrafiltration	Light - fine filtration (or fine screening) and ultrafiltration
NFO8	*Social acceptance*	Possibly difficult acceptance due to impact on water availability	No anticipated problems with acceptance
NFO9	*Complexity of permitting process*	Low complexity	Permit not necessary

Ínsua, Portugal

For the Ínsua location, plausible water sources defined were:

- Surface water – rivers (Rio Dão), streams (Ribeira de Coja), and lakes (Albufeira da Barragem de Fagilde)
- Groundwater [80] [81][82]
- Industrial wastewater (technology offered by Interagua)[82]
- Treated urban wastewater [82]
- Water grid [80] [81]
- Rainwater

Their grading is based on the findings of Simoes et al., as it the paper presents a full evaluation of water availability and water usage solutions for electrolysis in hydrogen production for rural areas further than 100 km from the coast in Portugal [16]. The results of the qualitative assessment are given in Table 27. The results are based on those given by Simoes et al. for a rural area and have been checked using technical reports, governmental papers and information provided by local WWTPs [80]–[82]. The treatment methods required for the resulting water sources, are provided in the following filtering and demineralization section for water purity.

Table 27: Qualitative assessment of water sources for rural areas in Portugal by Simoes et al. - validated for Ínsua, Portugal [16]

NFO	***Criteria***	Surface water	Groundwater	Industrial wastewater	Treated urban wastewater	Water grid	Rainwater
NFO1	**Reliability of availability (short time - weather)**	3	2	2	4	4	1
NFO2	**Reliability of availability (climatic effect)**	2	2	3	4	4	1
NFO3	**Reliability of availability (continuity of supply)**	3	2	1	2	4	1
NFO4	**Competition with other users**	1	1	4	4	4	4
NFO5	**Complexity of abstraction/collection**	2	2	3	3	4	1
NFO6	**Transport distance**	3	3	2	2	4	4
NFO7	**Treatment needed**	3	2	1	3	4	3
NFO8	**Social acceptance**	4	1	4	4	4	4
NFO9	**Complexity of permitting process**	2	1	3	3	4	3
	Total points	23	16	23	29	36	22
	Total classification	**64**	**44**	**64**	**81**	**100**	**61**

As the assessment shows, using the water grid as best qualitative water source. This score could be influenced by water scarcity in the future. This would influence the reliability of availability (NFO2 and NFO3), competition with other users (NFO4), and social acceptance (NFO8). The second-best scoring water source is urban wastewater. This is due to the social acceptance (for re-using wastewater), low competition with other water uses and users, and its availability being less vulnerable to weather and climate effects – unlike most other sources. For Ínsua there are two industrial WWTPs within a 40 km distance range - ETAR de Viseu Sul or ETAR Gouveia [16], [17], [82]. For Ínsua, water grid and treated urban wastewater are selected as water source for the hydrogen production farm.

Al Buraimi, Oman

For Al Buraimi the possible water sources are:

- Surface water and groundwater are readily available in the A' Dhahirah area [84]–[86], [91]

- Treated industrial wastewater and urban wastewater [87], [88]
- Water grid [86]

They have been graded based on various sources. Surface - and groundwater show much promise as the A' Dhahirah region (where Al Buraimi is located) in Oman is one of the few regions where such water sources are readily available. Furthermore, this region is one on which the government lays focus on for water supply plans on a national level [84], [91]. Water levels are exceptionally stable in comparison to the water scarce governates of Oman. There is currently no known competition for the surface and ground water [84]–[86]. On the contrary, the A' Dhahirah governate is aiming to increase the accessibility to surface and ground water to attract industrial activity [84], [91]. This sustains the high score related to permits as well [91].

The ground water contains a higher percentage of hard metals than anticipated, causing a lower score for treatment required than for surface water [84], [85]. Sources found related to wastewater mention both urban and industrial wastewater and mention no clear difference. As mentioned, treated industrial wastewater and urban wastewater is available in Al Buraimi. Industrial wastewater treatment is done by HAYS STP Buraimi and urban wastewater by Buraimi STP [87]. For both sources, the resulting water is tertiary treated effluent. The wastewater is currently being marketed to the industrial market. Social acceptance is dependent on little to no competing users for wastewater usage, and an increase in customers of the Al Buraimi area [88].

Water from the water grid is available yet shared with multiple governates, including those without natural water sources as surface – or groundwater. This influences the social acceptance, competition for usage, and need for permit scores. Still, it is the most reliable water source, available on site and required least treatment and is therefore graded as such [86].

Treated seawater is available at a large distance for any location in Al Buraimi. The cutoff distance for the Simoes et al.'s study was 30 km distance to the sea or ocean. Al Buraimi is about 100 km removed from the Arabian sea. The only possibility is acquiring treated seawater at 120 km distance from the Sohar 4 IP desalination plant. The treated seawater will require as much treatment as water from the water grid and has even less competition as the anticipated supply should cover international demands aside of the national basis [89], [90]. The results are given in Table 28.

Table 28: Qualitative assessment of water sources for Al Buraimi, Oman.

NFO	***Criteria***	Surface water	Groundwater	Treated industrial wastewater	Treated urban wastewater	Water grid	Treated seawater
NFO1	**Reliability of availability (short time - weather)**	3	3	4	4	4	4
NFO2	**Reliability of availability (climatic effect)**	2	3	4	4	4	4
NFO3	**Reliability of availability (continuity of supply)**	3	3	3	3	4	4
NFO4	**Competition with other uses**	3	3	4	4	3	4
NFO5	**Complexity of abstraction/collection**	3	3	3	3	4	3
NFO6	**Transport distance**	2	2	3	3	4	1
NFO7	**Treatment needed**	3	2	3	3	4	4
NFO8	**Social acceptance**	2	3	4	4	3	4
NFO9	**Complexity of permitting process**	3	3	3	3	3	3
	Total points	**24**	**25**	**31**	**31**	**33**	**31**
	Total classification	67	69	86	86	92	86

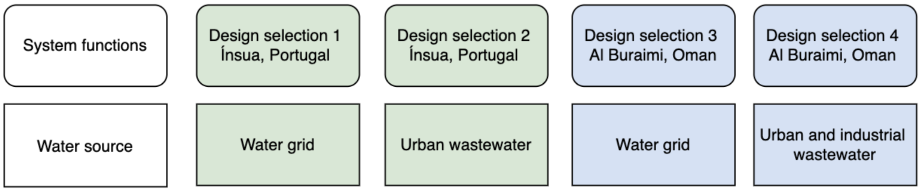
Qualitatively, the water grid emerges as the best water source. Treated industrial and urban wastewater following alongside treated seawater. All criteria have the same weight. The main practical consideration is the treatment needed for wastewater in comparison to the large transport distance for treated seawater. Since for large farms, the only form of transport for water will be pipelines, transportation for seawater should arguably receive a lower score than 1: manufacturing a pipeline across the country through governates for 120 km can be considered out of scope. Therefore, water grid and treated wastewater are considered as water sources for the Al Buraimi hydrogen farm.

For Ínsua, for industrial purposes water from the water grid is priced at €0,91/m3 [81]. Industrial wastewater is priced at 0,03 €/m3 [82]. For Al Buraimi, water from the water grid costs 0,96€/m3 for industrial usage, and (treated) urban and industrial wastewater is available for 0,05 €/m3 [87], [88]. An overview of the water costs are posed in Table 29.

Table 29: Water costs depending on the type of water source and location [81], [82], [88]

	Ínsua	***Al Buraimi***
Water grid (€/m3)	0,91 [81]	0,96 [88]
Waste water (€/m3)	0,03 [82]	0,05 [88]

The resulting water sources for both farm locations are presented in Figure 17.



System functions	Design selection 1 Ínsua, Portugal	Design selection 2 Ínsua, Portugal	Design selection 3 Al Buraimi, Oman	Design selection 4 Al Buraimi, Oman
Water source	Water grid	Urban wastewater	Water grid	Urban and industrial wastewater

Figure 17: Selected water sources for farms in Ínsua and Al Buraimi

5.3.2 Water purity

Water purity has been limited mostly through the functional constraints. The means have one functional objective to be graded on, in combination with the infrastructural limitations for the equipment of the filtering and demineralization processes.

The functional objective for water purity is as follows: the water supply should ideally provide type I (pure) water to the micro plant farm (FO1, Table 5). This objective reflects on the final demineralization process of the purity aspect, and not the initial filtering processes.

Filtering

The initial filtering methods for obtaining water of the right quality do not have additional requirements and will thus only be tested on the infrastructural requirements. The filtering methods are assessed for each water source.

- **Water grid** – Ínsua and Al Buraimi

  The water grid offers water free of TSS, dissolved solids, biochemical organic pollutants, and chemical organic pollutants for both Ínsua and Al Buraimi [16], [86]. The only filtering method required is reverse osmosis, to remove the salinity. The investment costs for RO including installation, terrain preparation and safeguarding for the two smaller farms is €500.000 and for the 1,5 GW €2.000.000, as mentioned previously [16].

- **Treated urban wastewate**r – Ínsua

  The treated urban wastewater of Ínsua requires fine screening, ultrafiltration, and RO as filtering methods due to its contamination with TSS, dissolved solids, biochemical organic pollutants, chemical organic pollutants, and salinity [16]. For the two smaller farms, an investment of € 100.000 is required for fine screening, and € 200.000 for ultrafiltration. For the 1,5 GW farm, € 400.000 and € 800.000 will be required respectively. These investment costs cover installation, equipment, terrain preparation and safeguarding permits and testing [16], [97]. Compared to water grid, using urban wastewater results in additional waste streams (NFO15). Moreover, the system consists of additional components (FO3). Aside of these requirements, the treatment for urban wastewater complies with all indirect infrastructure requirements.

- **Treated urban and industrial wastewater** – Al Buraimi

  Different from urban wastewater in Ínsua, the treated wastewater in Al Buraimi will only require ultrafiltration and RO as filtering methods. Wastewater is tertiary treated in Al Buraimi, which includes the removal of TSS [88].

Demineralization

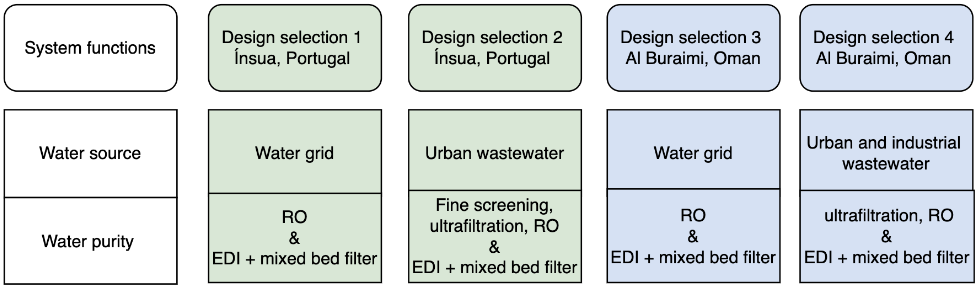
For type 1 water, both EDI and a mixed bed filter should be used for demineralization instead of a singular process. Considering the requirements for infrastructure, both EDI and mixed bed filter are well-established and available on the market with lifetimes over 30 years (NFC2). Both processes can be considered crucial for delivering the ideal water quality to the electrolyzers (NFC3). Due to the techniques being well-established, they operate in a time- and cost-efficient manner (NFC4 and NFC5). The main consideration for using both EDI and mixed bed filter in comparison to EDI only – mixed bed filter alone does not guarantee type 2 water, are as follows: [94].

The non-functional objectives for infrastructure entail a favor for less system components (NFO15), less system maintenance and costs (NFO20). The additional system components for a mixed bed filter system are the tanks and resin the water must run through. The additional cost ranges between €57.000 for the 50 MW farm, €200.000 for the 150 MW farm and €400,000 for the 1,5 GW farm [14], [16], [96]. Compared to EDI for each farm size, this is only a fraction of the cost as EDI requires an equipment investment of €500.000 for the 50 and 150 MW farms, and €1.000.000 for the 1,5 GW farm, for both locations [16].

The benefit op type 1 water over type 2 is less interactions with the metals and materials in the electrolyzer, which increases its lifetime and leads to less maintenance [13].

The second consideration is an additional waste stream. Resins of the mixed bed filter could be considered a waste stream as they must be replaced once saturated. However, resin suppliers offer cleaning of the resin so that they can be re-used indefinitely [14], [94], [96]. This additional waste stream can thus be considered a maintenance step as it is only required 1-2 times per year on average – can be less in case an overload of resin is used in the tank.

On the proportion of an entire farm, the cost of a mixed bed filter are negligible as will emerge in further sections. Maintenance for the mixed bed filter in terms of resin cleaning and replacement is not required at a higher frequency than that of other system processes (ultrafiltration, reverse osmosis and EDI requiring maintenance 3-5 times a year minimal [16]). Furthermore, obtaining type 1 water instead of type 2 water will lead to less maintenance for the electrolyzers at no additional energy costs as the EDI pump is sufficient to support the water flow through the mixed bed filter, directly into the final water storage tank [14], [94], [96]. The combination of EDI and a mixed bed filter system will therefore be used for further analysis. The filtering and demineralization methods for the different water sources and locations have thus been selected as follows:



System functions	Design selection 1 Ínsua, Portugal	Design selection 2 Ínsua, Portugal	Design selection 3 Al Buraimi, Oman	Design selection 4 Al Buraimi, Oman
Water source	Water grid	Urban wastewater	Water grid	Urban and industrial wastewater
Water purity	RO & EDI + mixed bed filter	Fine screening, ultrafiltration, RO & EDI + mixed bed filter	RO & EDI + mixed bed filter	ultrafiltration, RO & EDI + mixed bed filter

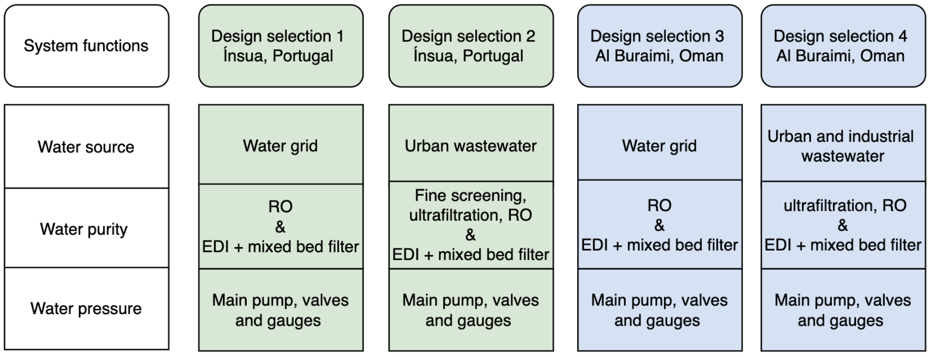
Figure 18: Filtering and demineralization methods to ensure water purity for the different water sources at both farm locations

5.3.3 Water pressure

Per the investigation of farm layouts and pressure losses in subsubsection 5.2.5, one pump should suffice per farm for delivery of water between 1 and 5 Bar to each electrolyzer. Based on the hourly water consumption per farm size (10,8 m3/hour, 32,5 m3/hour and 324,6 m3/hour respectively), the prices of pumps for the smaller farms including installation and shipment are estimated at € 80.000. For the 1,5 GW farm, € 120.000 was suggested by Van der Ende Group [105].

The costs for pressure valves and gauges are negligible for the purpose of this research' scope. Pressure valves and gauge are crucial to assure minimal fluctuation in water (FO2). Their inclusion is thus assumed for every farm size.

The means to ensure water pressure have thus been defined as follows:



System functions	Design selection 1 Ínsua, Portugal	Design selection 2 Ínsua, Portugal	Design selection 3 Al Buraimi, Oman	Design selection 4 Al Buraimi, Oman
Water source	Water grid	Urban wastewater	Water grid	Urban and industrial wastewater
Water purity	RO & EDI + mixed bed filter	Fine screening, ultrafiltration, RO & EDI + mixed bed filter	RO & EDI + mixed bed filter	ultrafiltration, RO & EDI + mixed bed filter
Water pressure	Main pump, valves and gauges	Main pump, valves and gauges	Main pump, valves and gauges	Main pump, valves and gauges

Figure 19: Means for ensuring water pressure and all previously defined system functions for the water supply system

5.3.4 Water quantity

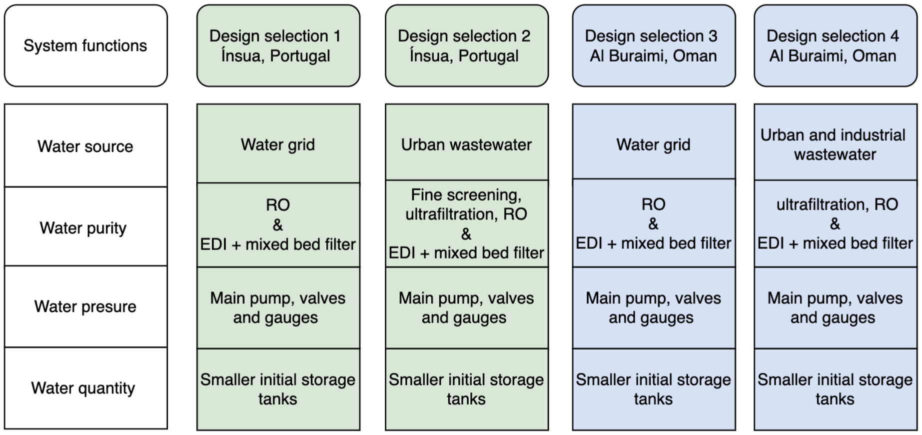
In subsubsection 5.2.5 it has been briefly mentioned that water transport with trucks is not practically feasible for the larger farm sizes. It is disputable even for the 50 MW farm, as more than 50 trucks will be required on a daily basis - during operating hours would imply 50 large trucks of water being delivered within 6 or 7 hours (depending on the farm location). This is based on previous projects by Aqualeap B.V. and the farm evaluated by Simoes et al. who quoted more than 10 trucks per hour for a 30 MW plant [15], [16].

Pipeline transport is thus selected for acquiring water from the water source for all farm sizes. This results in the smaller tank sizes for initial storage, and the quoted tank sizes and costs for the final storage tank. An overview of the costs for all tank sizes for both locations is given in Table 30.

Table 30: Overview of the initial and final storage tank sizes and costs for all farm sizes and both locations.

	Insua			Al Buraimi		
Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
Initial tank size (m3)	100	100	1000	100	100	1000
Initial tank cost (€)	57000	57000	380000	57000	57000	380000
Final tank size (m3)	100	200	2000	100	250	3000
Final tank cost (€)	57000	114000	760000	57000	142500	1140000

The supplemented overview for the selected means of all system functions so far is thus:



System functions	Design selection 1 Ínsua, Portugal	Design selection 2 Ínsua, Portugal	Design selection 3 Al Buraimi, Oman	Design selection 4 Al Buraimi, Oman
Water source	Water grid	Urban wastewater	Water grid	Urban and industrial wastewater
Water purity	RO & EDI + mixed bed filter	Fine screening, ultrafiltration, RO & EDI + mixed bed filter	RO & EDI + mixed bed filter	ultrafiltration, RO & EDI + mixed bed filter
Water presure	Main pump, valves and gauges	Main pump, valves and gauges	Main pump, valves and gauges	Main pump, valves and gauges
Water quantity	Smaller initial storage tanks	Smaller initial storage tanks	Smaller initial storage tanks	Smaller initial storage tanks

Figure 20: Selected means for water quantity and all other system functions.

5.3.5 Infrastructure

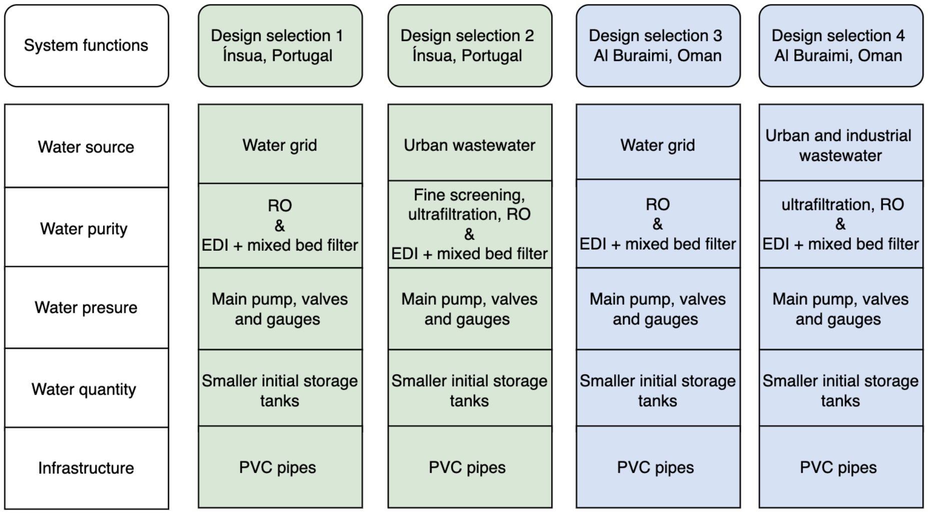
The two means for infrastructure are limited to the piping for water distribution across the farm. Both PVC and steel pipes comply with all non-functional constraints and objectives. The largest differences are the lifetimes of the products and thresholds. Steel pipes have a longer lifetime than PVC. However, with a desired lifetime of 30 years for the farm both materials suffice. Both materials are cost-competitive on the market. For the hydrogen farm, PVC is a more cost-effective option. As steel pipes over qualify in terms of safety for the delivery of water across the farm, this option can be considered non-crucial for the farm (NFC3) [15] It is therefore that PVC pipes will be used for the water supply system design.

From Table 21, an estimation of the total length of PVC material can be made. Together with the prices per km of PVC by Aqualeap B.V., the PVC costs have been determined as posed in Table 31. Operation and maintenance cost for PVC pipes was suggested to be excluded from cost overviews as it is minimal and usually is guaranteed by the supplier [15] Therefore, the PVC costs include CAPEX only, as posed in Table 31. As mentioned in the design conceptualization, due to relatively low pressure losses throughout the PVC distribution system, one pump per farm can suffice for operations. Van der Ende Group provided the following quotes for water pumps for the 50 MW, 150 MW and 1,5 GW, respecitvely: €80.000, €150.000 and €800.000 [105] The updated overview for selected means is given in Figure 21.

Farm size	***50 MW***	***150 MW***	***1,5 GW***
Total PVC cost (€)	72.000	385.000	6.700.000

Table 31: PVC piping and installation costs for all farm sizes, based on quotes provided by Aqualeap B.V. (by Artechno group B.V) [15]

The updated overview for selected means is given in Figure 21.



System functions	Design selection 1 Ínsua, Portugal	Design selection 2 Ínsua, Portugal	Design selection 3 Al Buraimi, Oman	Design selection 4 Al Buraimi, Oman
Water source	Water grid	Urban wastewater	Water grid	Urban and industrial wastewater
Water purity	RO & EDI + mixed bed filter	Fine screening, ultrafiltration, RO & EDI + mixed bed filter	RO & EDI + mixed bed filter	ultrafiltration, RO & EDI + mixed bed filter
Water presure	Main pump, valves and gauges	Main pump, valves and gauges	Main pump, valves and gauges	Main pump, valves and gauges
Water quantity	Smaller initial storage tanks	Smaller initial storage tanks	Smaller initial storage tanks	Smaller initial storage tanks
Infrastructure	PVC pipes	PVC pipes	PVC pipes	PVC pipes

Figure 21: Selected means for infrastructure and all other system functions for the water supply system.

5.3.6 Energy

The energy sources plausible for the hydrogen farm are solar and wind. NFC6 entails the cost contribution of energy to the LCOH. Renewable energy sources currently used for electrolysis processes on industrial level, and with most technical maturity are wind and solar energy [36]–[40]. NFC7 demand that the energy source be able to cope with daily ans seasonal fluctuating demand, which is solved using power control and energy storage using batteries. Both solar and wind are sustainable energy sources and thus comply with NFO21 as well. From a practical perspective, solar energy is already used for the to be designed hydrogen farm. Moreover, the farm locations emerged as optimal based on solar radiation and activity [13]. Wind has not been considered for this optimization. Therefore, it is more likely for solar to perform better than wind in terms of energy yield for the possible ZEF farm locations. The addition of solar energy and batteries to provide energy for the water supply system is assumed.

Energy is required for water abstraction and collection at the source. This is only required for urban and industrial wastewater, as no pipes, sand removal, pump and accessories, or large infrastructure (adaptations) are required for collecting water from the grid. Energy is also required for pumping water from the source to the farm, for all water treatment processes, for waste disposal and for distribution across the farm.

The total amount of energy required for all plausible farm designs has been determined using the energy usage per defined means - found in literature, project reports or given by suppliers/manufacturers with a safety factor of 1,5 as suggested by Yang et al., to ensure the energy required for all previous steps and an overhead margin [39] - and the final daily demand of water as determined in Table 11. The energy requirements for both farms with grid water as source is given in Table 32 and with wastewater as source is given in Table 33.

Table 32: Energy requirements for Ínsua and Al Buraimi when grid water is taken as source. Energy usage per system function derived from literature, technical reports and manufacturers.

		Insua - wastewater			***Al Buraimi - wastewater***		
		m3/day					
System function	**kWh/m3 water**	97	289	2885	120	358	3575
Abstraction/collection - grid water	-	-	-	-	-	-	-
Transport to farm - pumping grid water	8 (Van der Ende Group) [105]	728,5	2170,4	22000	901,2	2688,6	27000
Fine screening	-	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-
RO	2 (Simoes et al., and Kim et al.,) [16], [95]	7	21	206	9	26	255
EDI + mixed bed	1 (Simoes et al., and Puretec) [14], [16]	219	652	6511	271	808	8069
Additional treatment - overhead	1 (Aqualeap B.V. and Yang et al.)[15], [39]	10	30	294	12	37	364
Waste disposal - sludge pumping	0,1 (Simoes et al., and Kim et al.,) [16], [95]	12	35	346	14	43	429
Distribution across farm - pumping	16 (Van der Ende Group) [105]	158	471	4703	196	584	5827
TOTAL - rounded		1250	3700	37000	1500	4500	45000

Table 33: Energy requirements for Ínsua and Al Buraimi when wastewater is taken as source. Energy usage per system function derived from literature, technical reports and manufacturers.

		Insua - wastewater			***Al Buraimi - wastewater***		
		m3/day					
System function	**kWh/m3 water**	97	289	2885	120	358	3575
Abstraction/collection wastewater	0,3 (Simoes et al.,)[16]	25	75	750	31	93	930
Transport to farm - pumping wastewater	15 (Peters and Timmerhaus, Van der Ende Group) [102], [105]	1490	4440	44314	1843	5500	54912
Fine screening	0,1 (Simoes et al.) [16]	3	9	86	-	-	-
Ultrafiltration	0,1 (Simoes et al.) [16]	153	457	4560	1990	566	5650
RO	2,4 (Simoes et al., and Kim et al.,) [16], [95]	7	21	206	9	26	255
EDI + mixed bed filter	1,4 (Simoes et al., Puretec) [14], [16]	220	650	6510	270	810	8070
Additional treatment - overhead	1,4 (Aqualeap B.V. and Yang et al.,) [15], [39]	10	30	295	12	37	365
Waste disposal - sludge pumping	0,3 (Simoes et al., and Kim et al.,) [16], [95]	56	170	1680	70	210	2075
Distribution across farm - pumping	16 (Van der Ende Group) [105]	160	470	4700	200	585	5850
TOTAL - rounded		2100	6300	63000	2600	7800	78000

The energy required is to be supplied with solar panels. The minimal number of solar panels required per design selection has been calculated with the wattage of the solar panels (0,6 kW solar panel) and the average ESH per location. In reality a solar panel will never deliver 100% of its wattage in energy (for which once again, a solution lies in oversizing PV). Throughout this research this is accounted for as the official wattage of the solar panels is 620 Watt. The cost - both CAPEX and OPEX for the solar panels is given as well. These values are based on the previous ZEF study done to acquire CAPEX and OPEX estimates per solar panel for each farm location. The total CAPEX per solar panel (throughout its lifetime) is €163,86 for Ínsua and €130,36 for Al Buraimi. These costs include procurement, transportation, installment, land costs, and solar tracker costs. The annual OPEX per solar panel is €2,57 for Ínsua and €1,14 for Al Buraimi [12], [13]. The results for grid water (design selections 1 and 3) can be found in Table 34, and for wastewater (designs 2 and 4) are posed in Table 35.

Table 34: Solar panels and corresponding CAPEX and OPEX required to provide energy to farms utilizing grid water as water source for Ínsua and Al Buraimi. Calculation based on 600 Watt effective energy production per solar panel, average ESH per location, and provided CAPEX and OPEX per solar panel per farm location by ZEF.

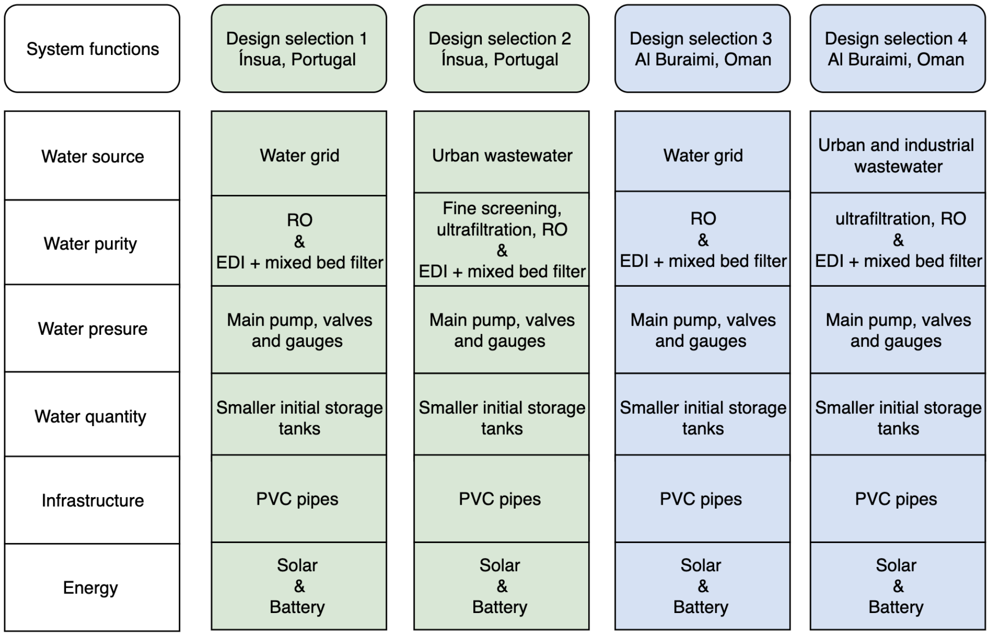
	Insua - 5,65 ESH			***Al Buraimi - 7,0 ESH***		
Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
Daily required kWh (kWh/day)	1231	3667	36611	1523	4543	45367
Maximal kwH per 0,6 kW solar panel	3,4	3,4	3,4	4,2	4,2	4,2
Minimal amount of solar panels required	363	1.080	10.800	363	1.080	10.800
CAPEX - solar panels	59.500	177.300	1.770.000	47.300	141.000	1.410.000
OPEX - solar panels for 30 years	9400	27.800	278.000	4200	12.350	123.200

Table 35: Solar panels and corresponding CAPEX and OPEX required to provide energy to farms utilizing wastewater as water source for Ínsua and Al Buraimi. Calculation based on 600 Watt effective energy production per solar panel, average ESH per location, and provided CAPEX and OPEX per solar panel per farm location by ZEF.

	Insua - 5,65 ESH			***Al Buraimi - 7,0 ESH***		
Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
Daily required kWh (kWh/day)	2.100	6.300	63.100	2.600	7.800	78.000
Maximal kwH per 0,6 kW solar panel	3,4	3,4	3,4	4,2	4,2	4,2
Minimal amount of solar panels required	626	1865	18650	624	1860	18600
CAPEX - solar panels	102.540	305.500	3.049.800	81.350	242.700	2.423.500
OPEX - solar panels for 30 years	16.100	47.900	479.000	7.100	21.200	212.000

As mentioned, for the scope of this research, the minimal required solar panels to support the water supply system based on the average ESH is taken for evaluation. Depending on the season there will thus be a shortage or surplus of energy - in case the panels are not utilized for another form of energy storage of supply. A battery is required to ensure energy availability and redundancy hereof for hydrogen production. It is required to ensure a daily reserve of water for the farm; to ensure that the water tanks are equipped with demineralized water after a day of less solar radiation and can supply the farm immediately the following day when the electrolyzers are powered. A battery for energy storage is not included in the energy supply cost estimate. This is due to the difficulty of finding reliable quotations for solar batteries, especially considering the fact that the solar panel-electrolyzer system of this research is directly connected and thus does not include power control. In addition, determining the appropriate size battery considering fluctuations in demand for all farm sizes is out of scope.

An overview of the selected means for all system functions is given in Figure 22.



System functions	Design selection 1 Ínsua, Portugal	Design selection 2 Ínsua, Portugal	Design selection 3 Al Buraimi, Oman	Design selection 4 Al Buraimi, Oman
Water source	Water grid	Urban wastewater	Water grid	Urban and industrial wastewater
Water purity	RO & EDI + mixed bed filter	Fine screening, ultrafiltration, RO & EDI + mixed bed filter	RO & EDI + mixed bed filter	ultrafiltration, RO & EDI + mixed bed filter
Water presure	Main pump, valves and gauges	Main pump, valves and gauges	Main pump, valves and gauges	Main pump, valves and gauges
Water quantity	Smaller initial storage tanks	Smaller initial storage tanks	Smaller initial storage tanks	Smaller initial storage tanks
Infrastructure	PVC pipes	PVC pipes	PVC pipes	PVC pipes
Energy	Solar & Battery	Solar & Battery	Solar & Battery	Solar & Battery

Figure 22: Selected means for energy and all prior system functions of the water supply system.

5.3.7 Transportation

The means of a truck has been eliminated when the storage tanks were selected, leaving only pipeline as transportation method for water to the farm. Pipeline transport suffices all remaining constraints and objectives pose for transport. For both locations, WWTPs are situated in the area, and average distance of 10 km is assumed for calculating transportation costs.

Pre-filtered water is to be transported through stainless steel piping. The cost for piping – including purchase, welding, and overhead construction - amount to €2.200.000 for 10 km distance transport for stainless steel with an external diameter of 50 cm [102]. This corresponds to the largest diameter required for the 50 MW farm before distribution and is therefore the minimum size diameter required to support the smallest farm in case a singular pump is used for transport [15]. It is also the base value used by Simoes et al. for a 50 MW hydrogen farm under continuous production [16]. Though smaller pipeline sizes could be used for the design selections of the 50 MW farm, no quotes could be provided or found. Especially for the 50 MW farm, this cost should be seen as the maximal cost for pipeline transport [15], [16].

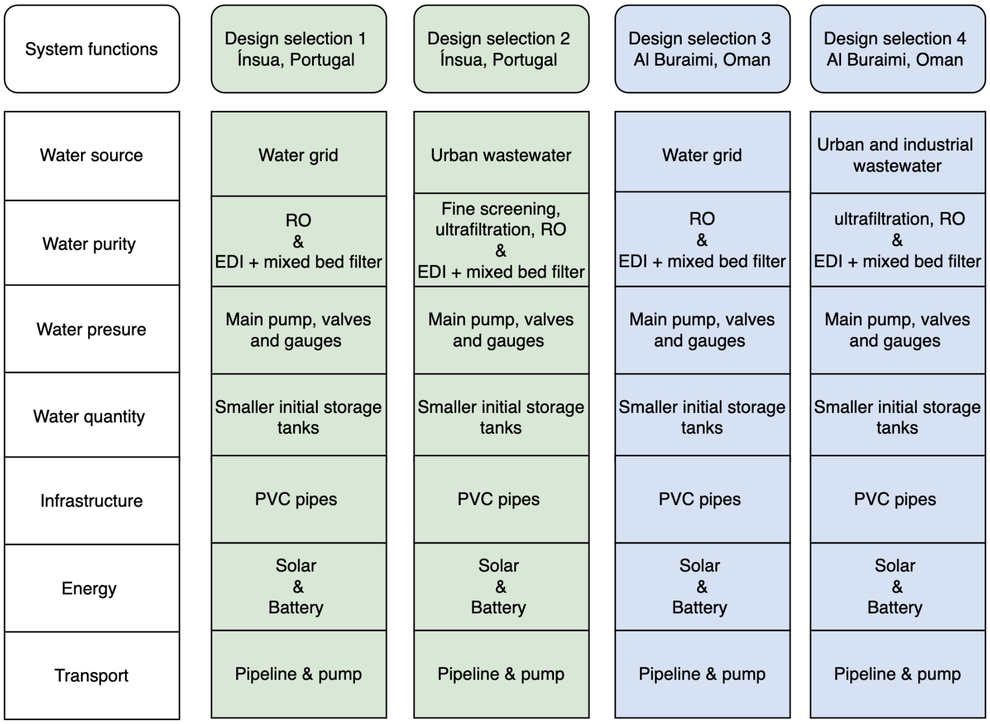
Larger farms can be supplied using the same diameter pipeline paired with a larger pump or multiple pumps [15]. The investment costs for one pump, for the 50 MW and plausibly the 150 MW farm is estimated at €350.000 by Van der Ende Group in case grid water is used [105]. As there is no existing pipeline or pumping network in case wastewater is used, the pumping costs for the 50 and 150 MW farm should be taken as €550.000 [105].

For the 1,5 GW farm, €1.700.000 was advised as estimate for the total CAPEX for pumps for grid water and €2.300.000 for waste water [105]. The warranty of pumps of the Van der Ende Group includes maintenance, therefore no OPEX should be considered for pumping water from the water source to the farm. As the energy usage of the pumping and costs hereof have been included in the energy section, the table below contains only the total CAPEX for the various farm sizes for transport of source water to the farm.

Table 36: Estimated CAPEX for water transport of source water to the farm, based on estimates found in literature, suggestions by experts at Aqualeap B.V., and quotations and estimates provided by pump supplier Van der Ende Group.

	Ínsua						**Al Buraimi**					
	Water grid			Waste water			Water grid			Waste water		
	50 MW	150 MW	1,5 GW	50 MW	150 MW	1,5 GW	50 MW	150 MW	1,5 GW	50 MW	150 MW	1,5 GW
CAPEX for steel piping (€)	2.200.000	2.200.000	2.200.000	2.200.000	2.200.000	2.200.000	2.200.000	2.200.000	2.200.000	2.200.000	2.200.000	2.200.000
CAPEX for pumping (€)	350.000	350.000	1.700.000	550.000	550.000	2.300.000	350.000	350.000	1.700.000	550.000	550.000	2.300.000
TOTAL	€ 2.550.000,00	€ 2.550.000	€ 3.900.000	€ 2.750.000,00	€ 2.750.000	€ 4.500.000	€ 2.550.000	€ 2.550.000	€ 3.900.000	€ 2.750.000	€ 2.750.000	€ 4.500.000

The final overview of all means selected for the system functions of the design selections is thus as follows:



System functions	Design selection 1 Ínsua, Portugal	Design selection 2 Ínsua, Portugal	Design selection 3 Al Buraimi, Oman	Design selection 4 Al Buraimi, Oman
Water source	Water grid	Urban wastewater	Water grid	Urban and industrial wastewater
Water purity	RO & EDI + mixed bed filter	Fine screening, ultrafiltration, RO & EDI + mixed bed filter	RO & EDI + mixed bed filter	ultrafiltration, RO & EDI + mixed bed filter
Water presure	Main pump, valves and gauges	Main pump, valves and gauges	Main pump, valves and gauges	Main pump, valves and gauges
Water quantity	Smaller initial storage tanks	Smaller initial storage tanks	Smaller initial storage tanks	Smaller initial storage tanks
Infrastructure	PVC pipes	PVC pipes	PVC pipes	PVC pipes
Energy	Solar & Battery	Solar & Battery	Solar & Battery	Solar & Battery
Transport	Pipeline & pump	Pipeline & pump	Pipeline & pump	Pipeline & pump

Figure 23: Final overview of all selected designs and the means for their system functions.

5.3.8 Discussion - critical design components, system redundancy and flexibility

The water supply system consist of various system functions which contribute to the stability of operations on the hydrogen production farm. For all potential breakdowns and malfunctions within the system holds that the discontinuous operational hours of the farm provide windows of opportunity for maintenance and interference.

The water source is limited to two sources for each location; different water sources could have resulted from the analysis in case different weights are used for the qualitative criteria (e.g., increase the importance of social acceptance.). For the scope of this research, equal weights are used and have resulted in water grid and urban or urban and industrial wastewater as optimal water sources for both farm locations.

Regarding redundancy and guaranty of water availability, for both countries, the water grid is considered a reliable source of water [80], [81], [91]. Disturbances for obtaining water from the water grid are either external or caused by the pipeline transport system to the farm - pumping or pipeline leakage. Maintenance for pumping and safety upon installation of the pipeline should minimize these disruptions.

Due to the abundance of urban - or industrial and urban wastewater, this water source is promoted for industrial usage at both locations. WWTPs guarantee availability and semi-filtered quality of water for both locations. For this source again, the disturbance is either due to external (from the WWTPs) or due to the pipeline transport system. To increase the redundancy of the system, the pipeline system can be linked to the water grid in addition to the WWTP outlet. In case the availability or quality of waste water is not conform workable standards for (water treatment system at) the farm, the installed pipeline for transport can be coupled to the water grid instead. The costs of this additional coupling are not have not been considered in this research, though the overestimation of the pipeline costs for the smaller farm sizes could potentially cover such an adaptation.

The water filtration and demineralization system is crucial for all system designs. The maturity of the technologies and experience revolving malfunctions should result in less intervention time required in case of a malfunction. Filtration and mixed bed filter system have least mechanical components and rely mostly on static measures (filtering rack or resin beads) and a continuous flow supported by pumps and thus energy. The capacity of all water treatment system components can produce filtered and demineralized water at a higher flow rate than the farm requires. The second storage tanks - those entailing filtered and demineralizaed water - hold nearly one days worth of water for the farm usage considering the average ESH. The storage tank, during operational hours, is continuously filled as water is being used by the electrolyzers as long as the treatment system is functioning. In case of interruptions, the tanks supply is thus covers water for approximately one day of operation. These tanks could be enlarged to increase the reserve water in case of interruptions or malfunctions of the treatment system.

The infrastructure for water delivery to the electrolyzers provides redundancy in the form of a ring pipeline system. Furthermore, the ring pipeline system has a larger capacity than is required by the electrolyzers: the PVC pipeline system functions as intermediate storage for filtered and demineralized water as well.

Operations on the farm are dependent on energy, therefore as mentioned a battery should be included in the system design to provide sufficient backup for the water supply system. In this way, i.a., the water reserves can be filled up to ensure a full tank prior to the electrolyzers operations for the day. Though theoretically it would be sufficient to use solely solar panels, in practice, the inclusion of a battery is required to ensure the water filtering and demineralization to run prior to the electrolyzers, to guarantee sufficient water [15].

Due to experience and high maturity of solar panels malfunctions and maintenance can be anticipated. As the solar panels of the water supply system are identical to those of the electrolyzers, scheduled maintenance can take place in roughly the same time frames, in this case the decrease of water availability corresponds to the decrease of electrolyzer capacity.

The risk mitigation for the overall water supply system relies on surveillance and timely maintenance for mature technologies - filtering methods, demineralization methods, solar panels and batteries. In the designs, redundancy is increased by usage of intermediate water storage tanks and a ring pipeline system for water distribution, as well an energy backup in the form of a battery (or batteries). Redundancy and/or robustness can be increased by a dual coupling of the pipeline infrastructure to both water grid and WWTPs, which is not included in the designs.

Water transportation to the farm, for each farm design, is by pipeline transport. As mentioned, this is not in alignment with a complete off-grid PV-hydrogen farm, but is necessary due to the volumes of eater required. For a complete off-grid farm, different water sources should be available locally (e.g., ground water, rainwater or river water) so that no extensive grid-like infrastructure is required for equipping the farm with water. Another solution would be an off-grid method for acquiring water such as AWG, as mentioned before. The current technical maturity of this process does not comply with the requirements of being available on the (industrial) market nor being market-competitive in cost (per m3 of water) [30]. However, with more technical maturity, this or alike processes could pose as a solution for off-grid (electrolysis-based) hydrogen farms.

5.3.9 Data validation and calculation verification

Throughout the previous sections, various calculations and estimations have been done. Sources and data used for the calculations – found in literature or project reports or given by experts – have been mentioned in the sections as well. This section provides an overview for data validation of these calculations. The calculations done have been verified by confirming the input parameters and computational coherence as well as revision of the underlying assumptions. Furthermore, expert verification has been used specifically for the calculations of the farm dimensions (Chint), pressure losses and pipeline costs (Aqualeap B.V.) and distribution costs (Van der Ende Group). Below follows a list of main calculations with inputs specified and validation elaborated upon, as well as their output.

- Water demand per farm size.
  - Input: Number of electrolyzers, hourly water usage of electrolyzers, average ESH per location, water losses in treatment processes
  - Data validation: Numbers of electrolyzers, water usage, and ESH as determined by ZEF and previous study [12], [13]. Water lossess per process as found in literature reviews, and by Puretec (supplier for demineralization equipment) [14], [94], [97]
  - Output: Corrected water requirements per farm size per location; Table 10 for hourly water requirements and Table 11 for daily requirements
- Tank sizes and costs
  - Input: Daily amount of required water as determined in Table 11, average tank sizes, minimal amount of water to be held depending on water transportation.
  - Data validation: Tank costs in € per m3 by Simoes et al., factor 1.9 for installation in accordance with NEL and Aqualeap B.V [15], [16], [69]
  - Output: Water storage tanks required and their costs: Table 12, Table 14, Table 13, recapitulated in Table 30
- Farm dimensions (lengths and widths)
  - Input: Solar panel tracker system dimensions, minimal spacing required between tracker strings, square shape for total surface requirement
  - Data validation: Tracker system requirements as provided by Chint [33]
  - Output: Farm dimensions for each farm size Table 16
- Electrolyzer hourly flow rate
  - Input: Number of electrolyzers, hourly water usage of electrolyzers, water losses for distribution system as quoted by Aqualeap B.V. (20% maximal in water losses)
  - Data validation: Electrolyzer requirements as given by ZEF, water loss percentage by Aqualeap B.V. [12], [13], [15]
  - Output: Flow rates required per farm size, shown in Table 17
- Energy requirements for the water supply system
  - Input: Energy requirements for different processes of Table 32 and of Table 33, 600 Watt effective energy and CAPEX and OPEX per solar panel, average ESH.
  - Data validation: Energy requirements from literary sources and suppliers (Table 32 and Table 33), Solar and ESH information by ZEF [12], [13]
  - Output: Solar panel requirements - numbers, CAPEX and OPEX in Table 34 and Table 35

- CAPEX for water transportation from source to farm
  - Input: Steel pipeline and pumping costs.
  - Data validation: Steel pipeline costs as found and used in literature. Smaller pipeline sizes could be used (suggested by Aqualeap B.V.) for the 50 MW farm though no reliable quotes have been found. The large lump sum required for he steel pipeline for water transport should be seen as maximal cost for the 50 MW farm, and could even be too large for the 150 MW farm as well. Pumping costs quoted by Van der Ende Group [15], [16], [102], [105]
  - Output: CAPEX for water transport of source water to the farm for all farm sizes and locations, Table 36

5.3.10 Cost estimation - CAPEX and OPEX

The following section entails the overall CAPEX and OPEX estimations for all four design selections – Ínsua farms utilizing the water grid as water source and urban wastewater as water source as well as Al Buraimi farms utilizing the water grid as water source and urban wastewater as water source. For each design selection, CAPEX is determined for the following system functions:

- Water transport as determined in Table 36. This cost includes a steel pipeline of 10 km to cover the distance from the water source to the farm as well as the required pumps.
- Initial water storage tanks as determined in Table 13 – the initial storage tanks that do not require to hold a full days worth of water as pipeline transportation offers sufficient redundancy for semi-continuous acquirement of water.
- Water treatment – filtering method and demineralization as given in Table 15. Costs for the filtering method equipment are based on those used by Simoes et al. No other studies or project reports have been found with in dept and transparent estimations for equipment costs that cover the entire filtration process whilst including farm sizes and water throughput. For the filtering methods, no reliable quotes have been given by suppliers. However, the overarching estimates per farm size have been deemed viable by Puretec, supplier of water demineralization equipment. Furthermore, it should be noted that the values derived from the paper date from 2019, however they are thoroughly substantiated in the additional data sheets provided alongside the paper [14], [16]
- The disposal of waste streams – taken as lump sum of €100.000 for the 50 MW and 150 MW farm when water grid is used, and €150.000 for both farm sizes when wastewater is used. For the 1,5 GW farm €550.000 is taken for water grid, and €750.000 for wastewater [16]
- Final water storage tanks as determined in Table 14 – holding nearly all water required to feed electrolyzers of each farm, accounting for leakage throughout the distribution system.
- Distribution across the farm – piping (PVC) and pumping. PVC costs taken as quoted in Table 31. Costs for the pumps are given as quoted by Van der Ende Group: €120.000, €275.000 and € 1.800.000 [105]
- Energy in CAPEX – cost of solar panels as determined in Table 34 for all farms utilizing grid water and in Table 35 for the farms utilizing waste water.

OPEX (for the full 30-year lifetime of the farm) is considered for the following system functions:

- Water abstraction/collection. The total cost is determined based on the water requirements per farm of Table 11, the respective water costs as posed in Table 29, and the 30-year lifetime (considering year-round operation of 365 days).

- Water treatment. OPEX entails 10% of the CAPEX as suggested by Puretec B.V. and found throughout literature [16]
- Disposal of waste streams. OPEX entails 10% of the CAPEX [16]
- Energy – solar panels. The OPEX for the solar panels required to provide energy to the water supply system as given in Table 34 for all farms utilizing grid water and in Table 35 for the farms utilizing waste water. The values are based on a previous study for ZEF [13]
- Interest over CAPEX. As taken from the previous ZEF study, at least 85% of the CAPEX will be financed through bank loans, for which an interest rate of 3% is considered for both farm locations [12], [13]

An overview of the CAPEX and OPEX for all design selections can be found in Table 37. Note that the costs have been corrected based on the 30-year lifetime and account for a 5 % discount rate.

The total cost per m3 of water shows that, as expected due to large capital investments, the water supply system is more costly as the farm size decreases. The costs for per m3 of water are approximately halved when increasing the farm size from 50 MW to 150 MW (three times larger). The cost is approximately halved again when increasing the farm size further to 1,5 GW.

The high costs for the 50 MW farm can be traced back mainly to the costs for water transport and water treatment. These costs scale less than linear as the farm size increases. As mentioned, the cost for water transport is in all likelihood overestimated in this calculation due to the aforementioned reasons. It is therefore presumable that the cost for the 50 MW farm will be slightly lower per m3 - however, no percentage or range of how much lower could be found.

The costs for the 150 MW farm fall within the ranges found mostly throughout literature, which are roughly between 4 - 8 €/m3 depending on the water source. These sources assess hydrogen farms between 80 - 200 MW [4]–[10]

The costs for water on the 1,5 GW farm are difficult to compare as no literature or project information is available for hydrogen farms of this size. It can be expected that the price for water is lower than that of the 50 MW and 150 MW farm. The cost estimations include factors for installation and water supply systems are well-established and mature on the markets other than hydrogen as well. However, as a 1,5 GW is an unprecedented scale for solar to hydrogen production, the costs for the supporting systems are likely to be higher by a factor between 1-6 according to the Lang-factor theory as given by the Institute of Energy Economics [57]

The water source chosen affects the total costs through the filtering methods required for water processing (and its corresponding energy demand) as well as through the its price for acquiring - which is larger for grid water than waste water. Results show that only the 50 MW farm benefits from the higher cost for acquiring grid water than for the additional filtering required for waste water treatment, as indicated in Figure 24. For the two larger farms, the scale of the farm and its production outweighs the additional filtering equipment required for processing waste water, and benefits from the significantly lower cost for acquiring wastewater, which can be seen in Figure 25 and in Figure 26. The figures show that, as the farm size increases, the proportional increase of water transport costs and water filtering decreases between the water sources whereas the cost for water abstraction (the price of the water) proportionally increases with the increase of farm size. This holds for the Al Buraimi farms as well - these cost breakdowns can be found in Appendix I (in subsection 10.1).

Therefore, for both locations, for the 50 MW farm, grid water will be taken as water source for further investigation. The 150 MW and 1,5 GW farm size will utilize waste water for further design scenario's and evaluation.

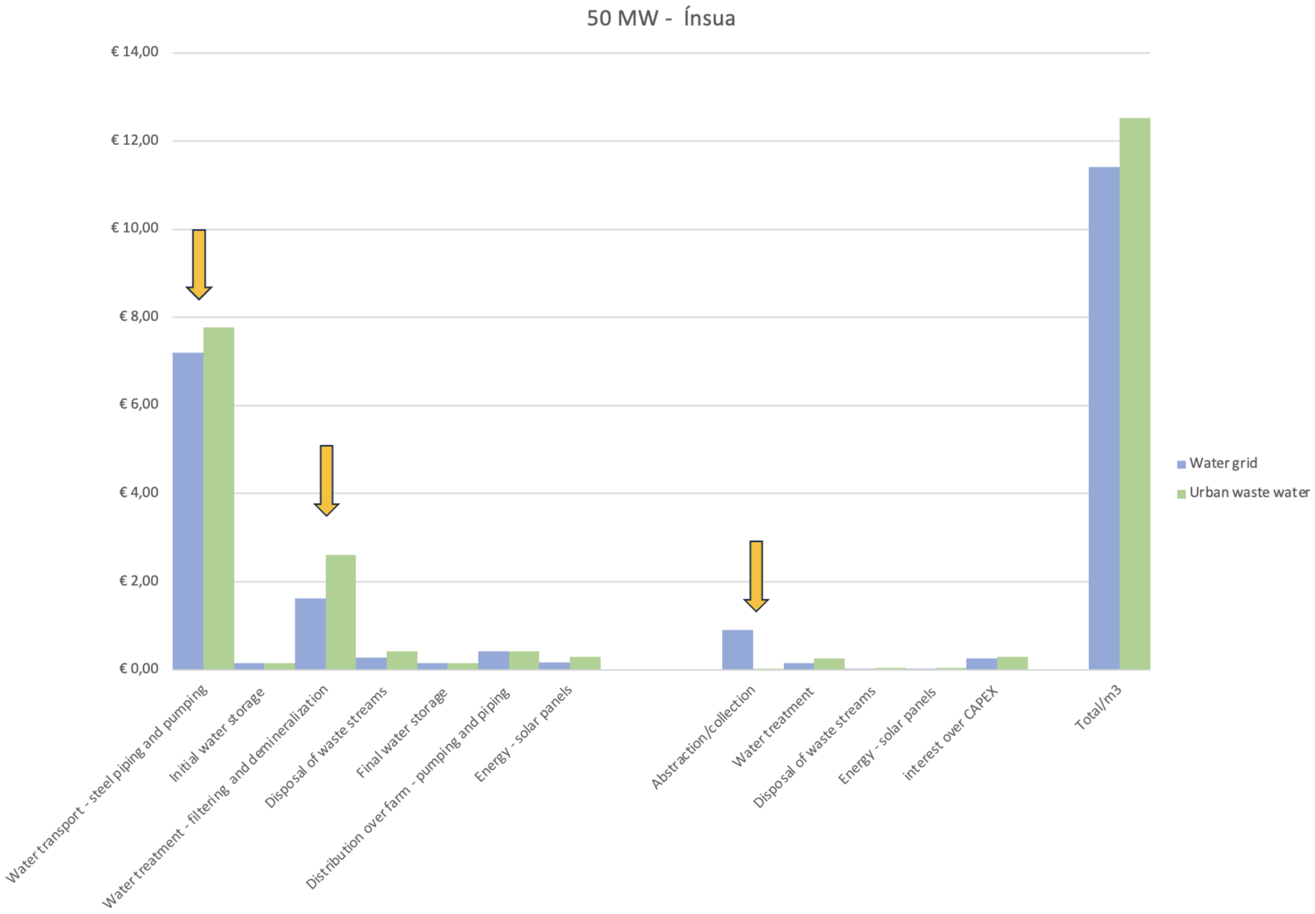


Figure 24: Cost breakdown for the 50 MW farm in Ínsua for water grid and urban waste water

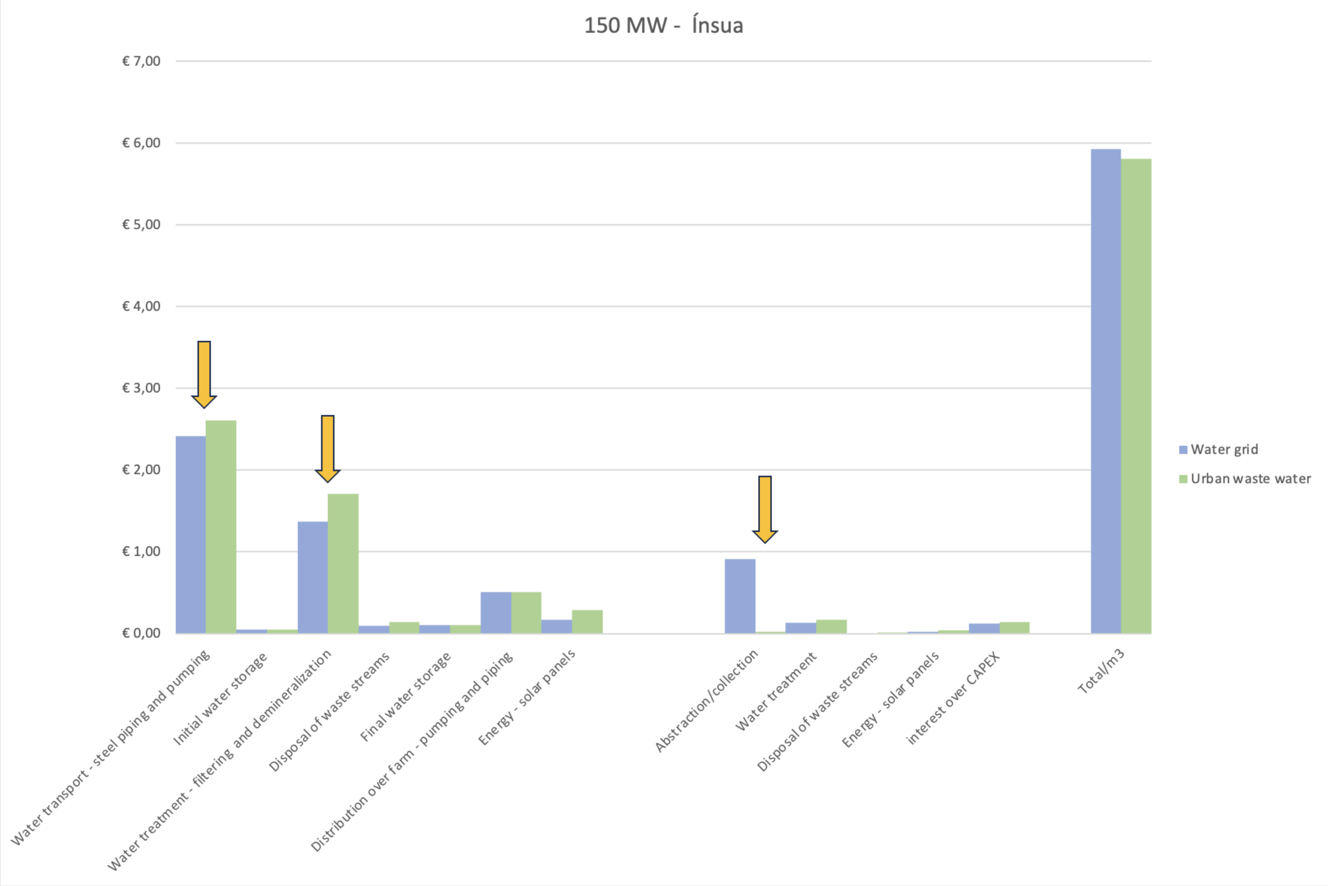


Figure 25: Cost breakdown for the 150 MW farm in Ínsua for water grid and urban waste water

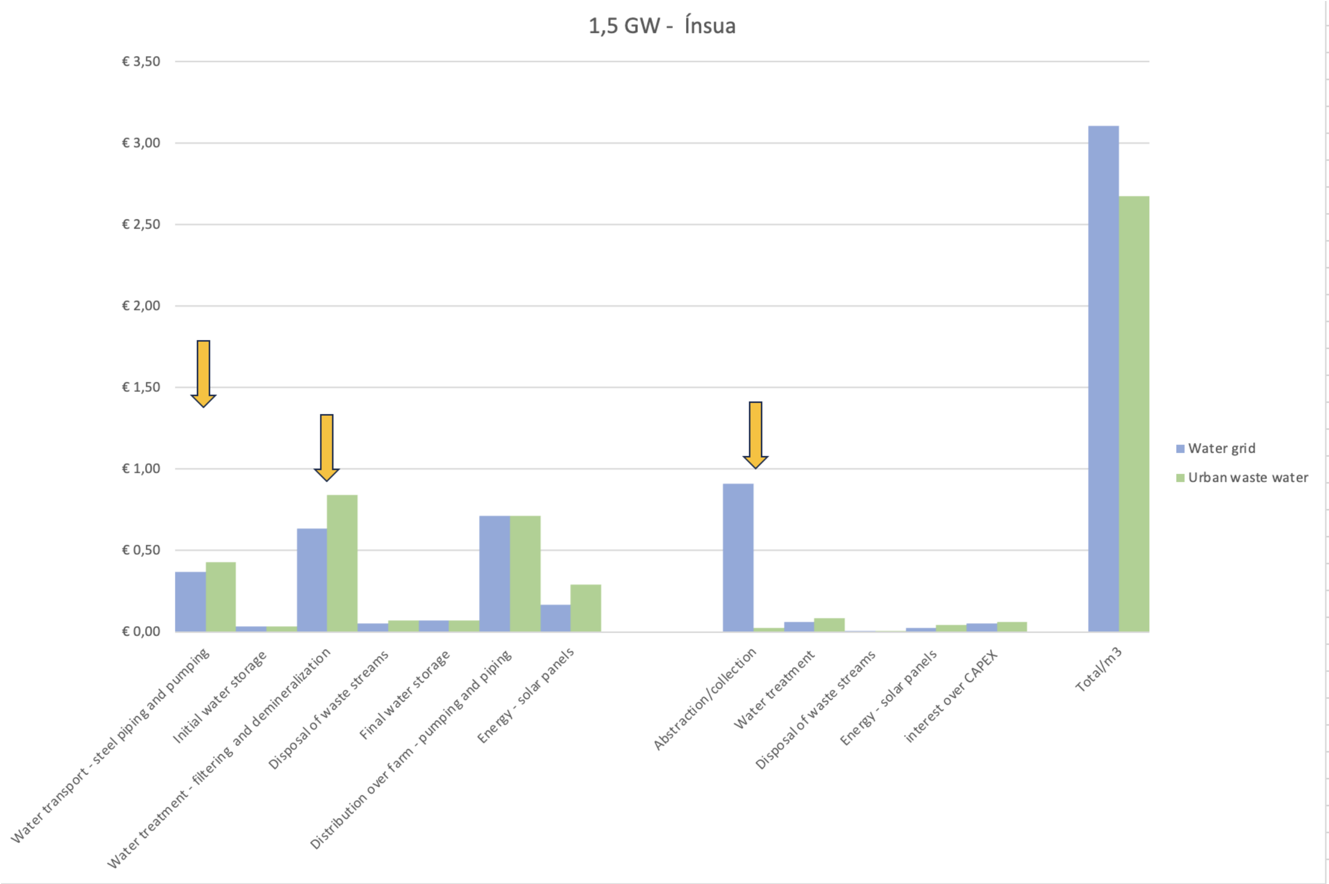


Figure 26: Cost breakdown for the 1,5 GW farm in Ínsua for water grid and urban waste water

Table 37: Total CAPEX and OPEX estimations for two water sources per farm location, for all farm sizes, in euro (€). The water quantity is not discounted for this calculation.

	Ínsua						Al Buraimi					
	Water grid			WWTP			Water grid			WWTP		
Farm size	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***	**50 MW**	**150 MW**	**1,5 GW**	**50 MW**	**150 MW**	**1,5 GW**
CAPEX												
Water transport - steel piping and pumping	€ 2.550.000,00	€ 2.550.000	€ 3.900.000	€ 2.750.000	€ 2.750.000	€ 4.500.000	€ 2.550.000	€ 2.550.000	€ 3.900.000	€ 2.750.000	€ 2.750.000	€ 4.500.000
Initial water storage	€ 57.000,00	€ 57.000	€ 380.000	€ 57.000	€ 57.000	€ 380.000	€ 57.000	€ 57.000	€ 380.000	€ 57.000	€ 57.000	€ 380.000
Water treatment - filtering and demineralization	€ 575.000,00	€ 1.450.000	€ 6.700.000	€ 925.000	€ 1.800.000	€ 8.860.000	€ 575.000	€ 1.450.000	€ 6.700.000	€ 925.000	€ 1.800.000	€ 8.860.000
Disposal of waste streams	€ 100.000	€ 100.000	€ 550.000	€ 150.000	€ 150.000	€ 750.000	€ 100.000	€ 100.000	€ 5.500.000	€ 150.000	€ 150.000	€ 750.000
Final water storage	€ 57.000,00	€ 114.000	€ 760.000	€ 57.000	€ 114.000	€ 760.000	€ 57.000	€ 1.142.500	€ 114.000	€ 57.000	€ 142.500	€ 1.114.000
Distribution over farm - pumping and piping	€ 152.000	€ 535.000	€ 7.500.000	€ 152.000	€ 535.000	€ 7.500.000	€ 152.000	€ 535.000	€ 7.500.000	€ 152.000	€ 535.000	€ 7.500.000
Energy - solar panels	€ 59.498	€ 177.272	€ 1.769.652	€ 102.541	€ 305.534	€ 3.049.826	€ 47.265	€ 141.010	€ 1.408.119	€ 81.351	€ 242.687	€ 2.423.454
OPEX												
Abstraction/collection	€ 322.186	€ 959.914	€ 9.582.528	€ 8.851	€ 26.371	€ 263.256	€ 420.480	€ 1.254.432	€12.526.800	€ 21.900	€ 65.335	€ 652.438
Water treatment	€ 57.500	€ 145.000	€ 670.000	€ 92.500	€ 180.000	€ 886.000	€ 57.500	€ 145.000	€ 670.000	€ 92.500	€ 180.000	€ 886.000
Disposal of waste streams	€ 10.000	€ 10.000	€ 55.000	€ 15.000	€ 15.000	€ 75.000	€ 10.000	€ 10.000	€ 550.000	€ 15.000	€ 15.000	€ 75.000
Energy - solar panels	€ 27.995	€ 83.412	€ 832.662	€ 48.288	€ 143.880	€ 1.436.214	€ 12.399	€ 36.993	€ 369.420	€ 21.342	€ 63.669	€ 635.793
interest over CAPEX	€ 90.538	€ 127.073	€ 549.771	€ 106.935	€ 145.644	€ 657.896	€ 90.226	€ 152.376	€ 650.304	€ 106.395	€ 144.768	€ 650.950
Total OPEX - discounted	€ 250.855	€ 650.659	€ 5.705.666	€ 122.663	€ 212.640	€ 1.209.756	€ 298.399	€ 806.612	€ 7.440.391	€ 124.470	€ 218.456	€ 1.268.903
TOTAL	€ 3.801.353	€ 5.633.931	€ 27.265.318	€ 4.316.204	€ 5.924.174	€ 27.009.582	€ 3.836.664	€ 6.782.122	€ 32.942.510	€ 4.296.821	€ 5.895.643	€ 26.796.357
Total cost/m3	€ 10,74	€ 5,34	€ 2,59	€ 12,19	€ 5,62	€ 2,56	€ 8,76	€ 5,19	€ 2,52	€ 9,81	€ 4,51	€ 2,05

5.4 Conclusion

Quantitative analysis has showed that the offsetting of higher abstraction costs and lower treatment costs provides benefits for the 50 MW farm size and vice versa for the 150 MW and 1,5 GW farm sizes for both locations. For further analysis, for both locations, the water grid will be taken as water source for the 50 MW farm sizes, and water from WWTPs for the 150 Mw and 1,5 GW farm sizes.

For acquiring water, the only appropriate means in practice is by utilizing pipeline transport, which is contradiction with a fully off-grid solar to hydrogen farm. Further analysis will indicate whether only connection to a water grid while remaining off-electricity grid, can result in a market competitive LCOH. Ideally, off-grid water acquiring methods such as AWG can be used on fully off-grid farms, in case technical maturity allows it.

An additional reason for this is that water transport (of acquiring water to the farm), is the largest cost component of the water supply system for all farm sizes and locations. This is anticipated even when considering that especially for the 50 MW farm, these costs are overestimated in the analysis.

Due to the water quality, the required filtering methods for water from WWTPs in Ínsua require fine screening in addition to ultrafiltration and reverse osmosis. water from WWTPs in Al Buraimi requires only ultrafiltration and reverse osmosis. For both locations, the water grid only requires reverse osmosis as filtering method.

Components of the water supply system, due to their centrality and sizing, provide benefits in terms of economies of scale. This favours larger farm sizes.

6 Hydrogen Outflow System Design

This section entails the design for the hydrogen outflow system of off-grid PV-electrolyzer hydrogen farm. Similar to the previous chapter, design goal, conceptualization, selection and evaluation will be done. The design goal and requirements will be specified first, after which means for the system functions will be found. Plausible system designs will be determined using the defined requirements for testing and evaluation.

6.1 Design Goal

The design goal of the hydrogen outflow system is to provide a system which collects the produced hydrogen from each electrolyzer, compresses the hydrogen to 700 bar and stores it at a centralized storage point on the farm.

The hydrogen outflow system will consist of three system functions. The first system function is on-site collection of hydrogen from the individual electrolyzers across the production farm. On-site hydrogen collection entails the infrastructure and its influences on the hydrogen pressure prior to compressing, which is the second system function. The third system function is hydrogen storage. For compressed hydrogen at 700 bar there are few options, as mentioned in section 3 by Zhang et al [49].

For the three system functions, posed requirements will be functional or non-functional (requirements or constraints). Functional requirements relate to items that the hydrogen outflow system must do. Non-functional requirements cover items that the hydrogen outflow system has or supports.

6.1.1 On-site hydrogen collection requirements

The hydrogen farm will have many electrolyzers dispersed across its surface area. The produced hydrogen will be collected using a pipeline system. The on-site hydrogen collection system will have general infrastructural requirements, and system specific requirements that are tailored to the discontinuous production of 50 bar hydrogen. General infrastructural requirements are – as done before for the water supply system – as follows:

NFC1: The on-site hydrogen collection system has a minimum lifetime of 30 years.

FC1: The on-site hydrogen collection system must operate based on an off-grid energy source.

FO1: The on-site hydrogen collection system ideally requires minimum energy.

FC2: The on-site hydrogen collection system must be available on the market.

NFC2: The on-site hydrogen collection system should not require physical human assistance or interference for operation.

NFC3: The on-site hydrogen collection system should require minimal physical human assistance or interference for maintenance.

NFO1: The on-site hydrogen collection system should ideally be able to undergo automated or robotic maintenance procedures.

NFO2: The on-site hydrogen collection system preferably has a predictable maintenance requirement.

NFO3: The infrastructure of the on-site hydrogen collection system should consist of as little sub-systems or system components as possible.

NFC4: The on-site hydrogen collection system must comply with the ISO 22734 safety standards.

NFC5: The on-site hydrogen collection system must comply with the ISO 19880 safety standard – in terms of equipment, instrumentation and control system.

The hydrogen farm in question has a discontinuous production property. The on-site hydrogen collection system must operate with discontinuous in-flow of hydrogen:

FC3: The on-site hydrogen collection system must support discontinuous in-flow of hydrogen from the electrolyzers.

For the water supply system pressure losses were determined throughout the farm. Due to the farm dimensions and the initial pressure of 50 bar of the produced hydrogen, the pressure losses during transport across the farm must be anticipated. The on-site hydrogen collection system must be withstand the differences in pressure. Furthermore it must deliver the hydrogen at the required pressure for the hydrogen processing step.

FC4: The on-site hydrogen collection system must withstand the resulting pressure differences of hydrogen throughout the production farm.

FC5: The on-site hydrogen collection system must deliver hydrogen at the required pressure of the hydrogen processing technology to the hydrogen processing facility.

6.1.2 Hydrogen compressing requirements

The requirements for hydrogen compression include the standard infrastructural requirements, additional safety requirements, and purity requirements.

For systems on one production farm the general prerequisite entails that all infrastructure components have (nearly) equal lifetimes. Ideally the infrastructure is uses minimal energy, low investment costs, low maintenance efforts and minimal system components. For this specific case study, it it important that the technology and infrastructure is available on the market as well:

FC6: The hydrogen compression technology must be able to compress hydrogen delivered by the collection system to 700 bar.

NFC6: The hydrogen compression technology system has a minimum lifetime of 30 years.

FC7: The hydrogen compression technology must be energy efficient.

FO2: The hydrogen compression technology ideally requires minimum energy.

FC8: The hydrogen compression technology must be cost-effective regarding periodic production quantities.

NFC7: The hydrogen compression technology should not require physical human assistance or interference for operation.

NFC8: The hydrogen compression technology should require minimal physical human assistance or interference for maintenance.

NFO4: The hydrogen compression technology should ideally be able to undergo automated or robotic maintenance procedures.

NFO5: The hydrogen compression technology preferably has a predictable maintenance requirement.

NFC9: The infrastructure of the hydrogen compression technology should consist of as little sub-systems or system components as possible.

FC9: Technology and subsystems for hydrogen compression should be well established and available on the market.

As mentioned, one of the main challenges in the hydrogen industry is safety [43]. The many risks for fire or explosion in the hydrogen industry are mitigated through safety regulations, codes and guidelines. These are available and implemented throughout equipment that is available on the market. FC8 thus covers that there is a method for safety and explosion mitigation in place for the produced hydrogen. Specific constraints regarding different aspects of risks are formulated as well.

NFC10: The hydrogen outflow system must encompass monitoring and detection instruments to oversee the reactivity, boil-off, flammability, and presence of the produced hydrogen.

NFC11: The hydrogen outflow system must encompass monitoring instruments to mitigate the burning velocity of the produced hydrogen.

For hydrogen processes specifically, requirements can be formulated regarding the safety, purity of the end or intermediate product, and supporting transportation methods. The International Energy Agency (IEA) composed basic standards for hydrogen facilities to comply with in terms of explosion protectives: ISO 22734 and ISO 19880. The two are based on the explosion protectives standards for general facilities (IEC 60079 and IEC 80079). ISO 22734 covers operating conditions, risk management, mechanical and electrical equipment, control systems, ion transport medium and protection of service personnel for hydrogen generators using water electrolysis [46]. Though dedicated to large centralized production facilities, the risk management and mechanical and electrical equipment guidelines are applicable for hydrogen technologies [47].

ISO 19880 refers to guidelines for gaseous hydrogen and refueling stations. The guideline covers risk management, supply safety operation, storage and equipment, instrumentation and control systems, etc. As gaseous hydrogen is the final product of the hydrogen farm, it should comply with these standards as well [48].

NFC12: The hydrogen compression technology must comply with the ISO 22734 safety standards.

NFC13: The hydrogen compression technology must comply with the ISO 19880 safety standard.

Next is hydrogen purity levels. Hydrogen from alkaline electrolyzer processes range between 99.5–99.9% [4]–[10]. The 6 kW electrolyzer hydrogen purity level is expected at 99.5 % [12]. Ideally the purity does not decrease during compression:

FC10: The hydrogen compression technology must operate with 99.5 % pure hydrogen as initial product.

FC11: The hydrogen compression technology produces minimal side products or waste streams.

NFO6: Ideally, the hydrogen compression technology produces no side products or waste streams.

NFO7: The hydrogen purity level ideally does not decrease during compression.

6.1.3 Hydrogen storage requirements

Only few storage methods support hydrogen of 700 bar. Similar to the compression requirements, equipment and infrastructure for the storage method should be available on the market. General requirements such as cost-effectiveness, flexibility and sustainability should be considered as well. Flexibility is especially of importance as throughout the lifetime of the hydrogen farm, fluctuations in hydrogen demand – increases especially – should be anticipated. It is common to anticipate up to a doubling of hydrogen end-product when investing in transportation methods [18].

FC12: The storage method for 700 bar hydrogen must be well established and available on the market.

FC13: The storage method for the final hydrogen product must comply with ISO transportation safety guidelines.

FC14: The storage method for 700 bar hydrogen must be able to respond to a fluctuating demand.

NFO8: Ideally, the storage method has the capacity to allow for double the amount of end product.

NFO9: The method for storage ideally requires minimal infrastructural installments.

6.1.4 Requirement overview

The functional and non-functional constraints, functional and non-functional objectives are schematically recapitulated in the following tables. The system functions and their respective functional constraints are given in Table 38. For the non-functional constraints, functional objectives and non-functional objectives these are Table 39, Table 40, and Table 41, respectively.

Table 38: System functions and functional constraints for the hydrogen outflow system

	System function	Functional constraint (FC)
FC1	Collection	The on-site hydrogen collection system must operate based on an off-grid energy source
FC2	Collection	The on-site hydrogen collection system must available on the market.
FC3	Collection	The on-site hydrogen collection system must support discontinuous in-flow of hydrogen from the electrolyzers.
FC4	Collection	The on-site hydrogen collection system must withstand the resulting pressure differences of hydrogen throughout the production farm.
FC5	Collection	The on-site hydrogen collection system must minimize the pressure loss of 50 bar hydrogen.
FC6	Compression	The hydrogen compression technology must be able to compress hydrogen delivered by the collection system to 700 bar.
FC7	Compression	The hydrogen compression technology must be energy efficient.
FC8	Compression	The hydrogen compression technology must be cost-effective regarding periodic production quantities.
FC9	Compression	Technology and subsystems for hydrogen compression should be well established and available on the market.
FC10	Compression	The hydrogen compression technology must operate with 99.5 % pure hydrogen as initial product.
FC11	Compression	The hydrogen compression technology produces minimal side-products or waste streams.
FC12	Storage	The storage method for 700 bar hydrogen must be well established and available on the market.
FC13	Storage	The storage method for the final hydrogen product must comply with ISO transportation safety guidelines.
FC14	Storage	The storage method for 700 bar hydrogen must be able to respond to a fluctuating demand.

Table 39: System functions and non-functional constraints for the hydrogen outflow system

	System function	Non-functional constraint (NFC)
NFC1	Collection	The on-site hydrogen collection system has a minimum lifetime of 30 years.
NFC2	Collection	The on-site hydrogen collection system should not require physical human assistance or interference for operation.
NFC3	Collection	The on-site hydrogen collection system should require minimal physical human assistance or interference for maintenance.
NFC4	Collection	The on-site hydrogen collection system must comply with the ISO 22734 safety standards.
NFC5	Collection	The on-site hydrogen collection system must comply with the ISO 19880 safety standard – in terms of equipment, instrumentation and control system.
NFC6	Compression	The hydrogen compression technology system has a minimum lifetime of 30 years.
NFC7	Compression	The hydrogen compression technology should not require physical human assistance or interference for operation.
NFC8	Compression	The hydrogen compression technology should require minimal physical human assistance or interference for maintenance.
NFC9	Compression	The infrastructure of the hydrogen compression technology should consist of as little sub-systems or system components as possible.
NFC10	Compression	The hydrogen outflow system must encompass monitoring and detection instruments to control and ensure safety.
NFC11	Compression	The hydrogen outflow system must encompass monitoring instruments to mitigate the burning velocity of the produced hydrogen.
NFC12	Compression	The hydrogen compression technology must comply with the ISO 22734 safety standards.
NFC13	Compression	The hydrogen compression technology must comply with the ISO 19880 safety standard.

Table 40: System functions and functional objectives for the hydrogen outflow system

	System function	**Functional objective (FO)**
FO1	Collection	The on-site hydrogen collection system ideally requires minimum energy.
FO2	Compression	The hydrogen compression technology ideally requires minimum energy.

Table 41: System functions and non-functional objectives for the hydrogen outflow system

	System function	**Non-functional objective (NFO)**
NFO1	Collection	The on-site hydrogen collection system should ideally be able to undergo automated or robotic maintenance procedures.
NFO2	Collection	The on-site hydrogen collection system preferably has a predictable maintenance requirement.
NFO3	Collection	The infrastructure of the on-site hydrogen collection system should consist of as little sub-systems or system components as possible.
NFO4	Compression	The hydrogen compression technology should ideally be able to undergo automated or robotic maintenance procedures.
NFO5	Compression	The hydrogen compression technology preferably has a predictable maintenance requirement.
NFO6	Compression	Ideally, the hydrogen compression technology produces no side products or waste streams
NFO7	Compression	The hydrogen purity level ideally does not decrease during compression.
NFO8	Storage	Ideally, the storage method has the capacity to allow for double the amount of end product.
NFO9	Storage	The method for storage ideally requires minimal infrastructural installments.

6.2 Design conceptualization

In this section, means will be provided for the system functions of the hydrogen outflow system. All means must comply with the system functions' functional constraint(s). The system functions for which means are given adhere to those in the design goal: on-site hydrogen collection, hydrogen compression and hydrogen storage.

6.2.1 On-site hydrogen collection

The on-site hydrogen collection system must aggregate the produced hydrogen from all electrolyzers dispersed across the surface areas of the farm. It must do so based on an off-grid energy source, and cost-effective manner (FC1 and FC2). It must support the discontinuous inflow of hydrogen by the electrolyzers (FC3), withstand the pressure fluctuations (FC4) and minimize pressure loss while doing so (FC5).

The current hydrogen production market consists of centralized electrolyzers, producing large amounts. Hydrogen is transported through a (large) pipeline, either into a pipeline network for distribution or to their further step as compressing, liquifaction, etc. The only material that coheres to industrial safety guidelines is steel [46], [48]. For smaller hydrogen distribution networks such as distribution within neighborhoods, copper is allowed as hydrogen is transported in small volumes under atmospheric pressure – which is not the case for the 6 kW electrolyzer farm [24]. Steel is known as the most cost-effective and well established material for industrial use (FC2) [18].

Cost effectivity and efficiency can be i.a. the choice between using a linear distribution system or a ring pipeline (FC1 and FC2). It is highly recommended to adopt a ring pipeline for hydrogen, especially due to the safety risks it poses. A ring pipeline offers redundancy of the network as it offers the flow of hydrogen to be rerouted in case there is a break or maintenance at one point in the pipeline. Ring pipelines offer a more balanced flow and pressure management throughout the network in comparison to a linear distribution. The flow of hydrogen can be distributed evenly throughout the network, resulting in less critical points and pressure drops. Furthermore, ring pipelines offer more flexibility and scalability than linear pipelines. The operational benefits of improved redundancy and reliability, pressure management, efficiency and flexibility make ring pipelines more cost-effective than linear pipelines, for steel material the benefits outweigh the initial investment costs when a minimal lifetime of 8-10 years is anticipated [18], [24]. Therefore, the adoption of a ring system instead of a linear distribution system is assumed for the further design choices of the hydrogen collection system.

The discontinuous inflow of hydrogen is supported by steel pipelines in case the connection point to the pipeline network is leak proof and sealed (FC3). [24], [46], [48]. The hydrogen outflow system will be built according to average hydrogen production, as specified in section 4. Discontinuous and below average inflow of hydrogen will not affect the functioning of the steel pipelines [12], [18]. The running hours of the compressors on the back end of the system can be coordinated to the hydrogen production levels. In summer periods, the compressors can thus operate for more hours than in the winter [12], [15], [24]. Usage of steel pipes ensures the capacity to withstand pressure differences of the produced hydrogen (FC4) [24], [46], [48].

There are three aspects that influence energy-efficiency, cost-effectiveness and minimal pressure loss (FC1, FC2 and FC5). These are the choice between a linear or ring system, the pipeline diameters and lengths, and the set pressure for the hydrogen collection pipeline network. The exact the layout of the pipelines can be optimized to improve energy-efficiency, cost-effectiveness and minimal pressure losses. However, this level of detail is out of scope for this research. This section will thus further entail determining the minimal pipeline diameters and lengths required for the farm and the maximal pressure losses for a ring pipeline system.

Hydrogen flow through pipelines

The flow of hydrogen through the pipelines is facilitated through its pressure. According to Boyle's Law, gasses flow from areas with high pressure to areas of lower pressure. Hydrogen is a simple gas and exhibits such behaviour [106]. For the pipeline infrastructure considering that 50 bar hydrogen from dispersed electrolyzers must be aggregated at a centralized storage point for further compression, two strategies are possible:

1. Minimize the pipeline diameters and for on-site hydrogen collection.

   Minimizing the pipeline diameters is in accordance with minimizing the costs of steel. However, it results in maximal pressure loss of hydrogen due to frictional losses that are induced in various ways. The first is that minimal diameters cause more friction between the internal surface of the pipe and hydrogen, resulting in frictional losses. Second, to maintain a desired flow rate of hydrogen, the velocity must increase when using smaller diameters, resulting in additional frictional losses. Moreover, a higher velocity can induce a turbulent flow, which causes additional frictional losses as well.

   As hydrogen moves from high pressure areas to low pressure areas, the 50 bar pressure is used to ensure hydrogen flow to lower pressure points – to the central storage point in the pipeline for compression. In case the pressure loss is too high to ensure flow – approximately 50 bar of pressure loss – due to the diameter size, compression point will be required throughout the collection system in combination with valves and flow control systems. The latter to ensure that the hydrogen flows the correct direction after compression. The largest pressure loss per farm size is thus to be determined, to determine the number of compressors and/or pumps that are required to ensure flow to the centralized point for compression. Furthermore, if the pressure lost to enable flow, will have to be compensated by an increased number of compressors required at the back-end of the system to get the produced hydrogen to 700 bar.

   Minimizing the pipeline diameter will thus translate to a lower cost of steel, a larger number of running hours (and equipment) for compressors, and subsequently, an increased energy requirement for the system.

2. Maximizing the pipeline diameter to minimize pressure losses.

   Larger diameter pipelines will allow the produced hydrogen to flow at a slower rate, decreasing the interaction with the pipe and friction, which decreases the pressure loss. Compared to the first strategy, this results in less fluctuations of pressure of the hydrogen throughout the hydrogen outflow system. It requires less temperature control, less pumps, and less compressors at the final point of the collection system as pressure has been maintained. Hydrogen density fluctuates less due to more stability of pressure. The disadvantage of this approach is the increase in cost of steel.

In practice, the minimal diameter is usually used as pressure loss for hydrogen gas is not as problematic as theoretically anticipated. It was found for projects as the hydrogen neighborhood (WaterstofWijk), that theoretical losses were much higher than the resulting practical pressure losses, as found by hydrogen pipeline experts of Bureau Veritas, Centre of Expertise – Energy, and SoluForce [18], [19], [24].

Ideally one uses the minimal diameter sizes for steel pipes. This is because experience has shown that the pressure loss is lower in practice than it is according to calculations, especially if there is a laminar flow [18], [24]. The pressure for the collection system set as high as possible – for this the maximal pressure loss between the furthest electrolyzer and the centralized point of collection and compression should be determined [18], [19], [24].

In the experience of hydrogen pipeline design for neighborhood, practice has shown that the calculations for the minimal diameter size pipeline are conservative and that up to two diameter sizes smaller allowed for the same amount of hydrogen to flow at an acceptable flow rate, which ideally is between 2 and 10 m/s [19], [24].

Required pipelines

As portrayed in the previous chapter for the water supply system, the hydrogen production farm is taken as a square shaped farm consisting of multiple rows of electrolyzer-tracker-strings (columns) , for reference see Figure 15. The hydrogen is to be collected from each individual electrolyzer through a column pipeline. The column pipeline will be placed on the tracker infrastructure, beneath the solar panels so that it is not in direct contact with solar rays. Each electrolyzer is coupled to its column pipeline. The column pipelines are all connected to two row pipelines, making it a ring pipeline system. A schematic overview is given below. The column pipelines are indicated in green and row pipelines are indicated in red.

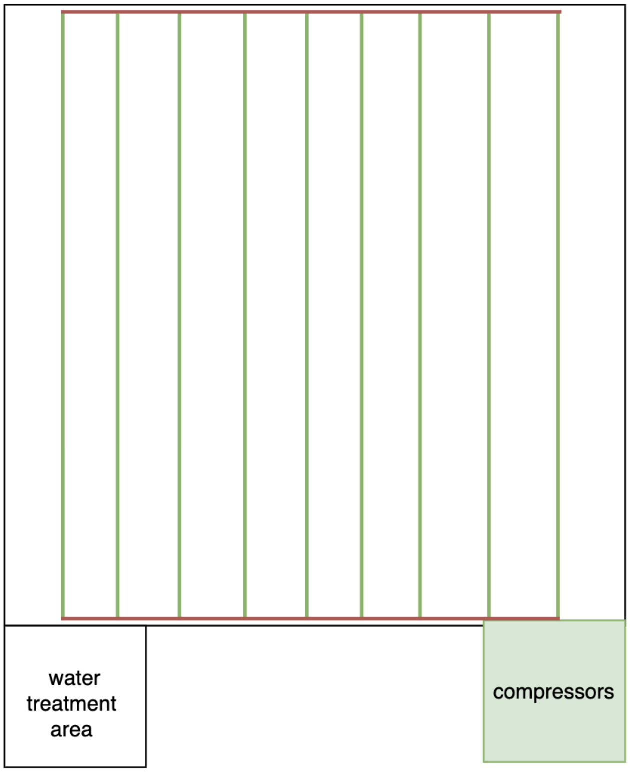


Figure 27: Schematic overview for the hydrogen collection pipeline system of an off-grid PV 6 kW hydrogen farm. Green lines indicate the column pipelines to which electrolyzers are connected, red lines are the row pipelines which are connected to all column pipelines and form a ring pipeline structure

The pressure losses over a pipeline with a certain diameter, given it's length, inlet pressure and system set pressure (also known as outlet pressure) can be calculated using the Weymouth, Panhandle A, and Panhandle B equations and is facilitated using the LMNO calculator for compressible gas [19], [107]. The Weymouth, Panhandle A, and Panhandle B equations are posed in Appendix II.

The pressure loss, the mass flow, and the velocity in the pipeline system are determined based on the pipeline diameter and length as input, as well as the initial pressure and the set final pressure of the system. The temperature was kept at 25 °Celsius as suggested by specialists at SoluForce [19].

The inputs for farm sizes cohere to the farm dimensions presented in the previous chapter in Table 16. For reference, the farm sizes as well as the hourly production rates – as derived in the methodology in Table 2 – are posed in Table 42. These production quantities set the mass flow rate restriction for the plausible pipelines.

Table 42: Farm dimensions and production quantities for all three farm sizes

Farm sizes	***50 MW***	***150 MW***	***1,5 GW***
Number of electrolyzer microplants (unit)	8334	25000	250000
Units per column	50	80	250
Rows per farm	167	313	1000
Q - production per column (kg/hour)	6,3	10,08	31,5
Q - total farm production (kg/hour)	1052	3155	31500
Farm length (km) - column pipeline	0,58	0,93	2,9
Farm width (km) – row pipeline	0,5	0,94	3

For both column and row pipelines, standard pipelines sizes were tested on the mass flow rate and velocity that results when setting the maximal pressure loss of the system to 2 or 3 bar. Hydrogen pipeline projects done by SoluForce, Veritas, and the Centre of Expertise has shown experts that the pressure drop in hydrogen tends to be minimal [18], [19], [24]. Soluforce has found that a 50 MW hydrogen farm (with a centralized alkaline electrolyzer), pipeline transport through a 100 mm (3.5 inch) diameter steel pipeline across a distance of 10 km leads to a 1.7 bar pressure loss [19]. Therefore, it was suggested to evaluate the mass flow rate and velocities with 2 to 3 bar loss in pressure.

For the pipeline diameter, the standard measurements were used as input: 15 mm, 20 mm, 25 mm, 40 mm, 50 mm, 65 mm, 80 mm, 90 mm, 200 mm, 250 mm and 300 mm.

For the column pipeline of the 50 MW farm, pipeline diameters of 15 mm, 20 mm, 25 mm, 40 mm were tested. The results are as shown in Table 43. The results show that the smallest diameter size facilitates a mass flow rate much larger than the production rate in addition to a velocity higher than the advised minimum of 2 m/s. Bureau Veritas and SoluForce adhere to the rule of thumb that for distances larger than 500 meters, a 20 mm pipeline should be the minimal size due to frailties of installment and risk of temperature increases [18], [19]. Thus the 20 mm diameter pipeline is chosen for the design of the column pipeline for the 50 MW farm.

It should be noted that the peak production is higher than the average production rate - which has been used for calculations. However, the difference between the production per column (Q) and the allowed mass flow rate of the pipe at the set pressure, is large enough to cover up to at least a fourfold of the average production rate. This holds for all farm sizes.

Table 43: Resulting mass flow rate and velocities for plausible column pipeline sizes along the length of the 50 MW farm.

Farm size	***50 MW***	***50 MW***	***50 MW***	**50 MW**
Q - production per column (kg/hour)	6,3	6,3	6,3	6,3
Column pipeline length (km)	0,58	0,58	0,58	0,58
Column pipeline diameter (mm)	40	25	20	15
Inlet pressure (bar)	50	50	50	50
Oulet pressure (bar)	48	48	48	48
Mass flow rate (kg/hour)	**722**	**245**	**113**	**38**
Pressure loss (bar)	2	2	2	2
Upstream Velocity (m/s)	**4,4**	**3,8**	**2,8**	**2,1**
Downstream Velocity (m/s)	**4,6**	**2,5**	**2,9**	**2,2**

For the row pipeline of the 50 MW farm, pipeline diameters of 40 mm, 50 mm, 65 mm, 80 mm were tested. Hydrogen will enter the row pipeline through the column pipelines, therefore the inlet pressure of the row pipeline is equal to the outlet pressure of the column pipeline. The results are as shown in Table 44. As can be seen in the table, the minimal diameter that provides sufficient mass flow rate and flow velocities is 50 mm.

Table 44: Resulting mass flow rate and velocities for plausible row pipeline sizes along the length of the 50 MW farm.

Farm size	***50 MW***	***50 MW***	***50 MW***	**50 MW**
Q - total farm production (kg/hour)	1052	1052	1052	1052
Row pipeline length (km)	0,5	0,5	0,5	0,5
Row pipeline diameter (mm)	40	50	65	80
Inlet pressure (bar)	48	48	48	48
Oulet pressure (bar)	46	46	46	46
Mass flow rate (kg/hour)	**760**	**1650**	**3000**	**4800**
Pressure loss (bar)	2	2	2	2
Upstream Velocity (m/s)	**4,9**	**5,9**	**6,8**	**7,7**
Downstream Velocity (m/s)	**5,1**	**6,1**	**7,1**	**8,04**

For the column pipeline of the 150 MW farm, diameters of 40 mm, 25 mm, 20 mm and 15 mm were tested as shown in Table 45. All diameter sizes provide sufficient mass flow rate to transport hydrogen according to the average production rate. The minimal diameter size for which the velocities are higher than 2 m/s, is 20 mm.

In Table 46 the row pipeline outcomes for the tested diameters of 50 mm, 65 mm, 80 mm and 90 mm can be seen. All pipelines provide hydrogen transport at velocities higher than 2 m/s. For the total production on an hourly basis the, an 80 mm pipeline suffices.

Table 45: Resulting mass flow rate and velocities for plausible column pipeline sizes along the length of the 150 MW farm.

Farm size	***150 MW***	***150 MW***	***150 MW***	**150 MW**	**150 MW**
Q - production per column (kg/hour)	10,08	10,08	10,08	10,08	10,08
Column pipeline length (km)	0,93	0,93	0,93	0,93	0,93
Column pipeline diameter (mm)	40	25	20	15	15
Inlet pressure (bar)	50	50	50	50	50
Oulet pressure (bar)	48	48	48	48	*46,5*
Mass flow rate (kg/hour)	**570**	**200**	**90**	**30**	**40**
Pressure loss (bar)	2	2	2	2	3,5
Upstream Velocity (m/s)	**3,5**	**2,7**	**2,2**	**1,7**	**2,2**
Downstream Velocity (m/s)	**3,6**	**2,8**	**2,3**	**1,8**	**2,4**

Table 46: Resulting mass flow rate and velocities for plausible row pipeline sizes along the length of the 150 MW farm.

Farm size	***150 MW***	***150 MW***	***150 MW***	**150 MW**	**150 MW**
Q - total farm production (kg/hour)	3160	3160	3160	3160	10,08
Row pipeline length (km)	0,94	0,94	0,94	0,94	0,93
Row pipeline diameter (mm)	50	65	80	90	15
Inlet pressure (bar)	48	48	48	48	50
Oulet pressure (bar)	46	46	46	46	*46,5*
Mass flow rate (kg/hour)	**1200**	**2200**	**3500**	**5300**	**40**
Pressure loss (bar)	2	2	2	2	3,5
Upstream Velocity (m/s)	**4,3**	**5**	**5,6**	**6,3**	**2,2**
Downstream Velocity (m/s)	**4,5**	**5,2**	**5,9**	**6,5**	**2,4**

Similarly, the following tables show the results for the column pipelines of the 1,5 GW farm (for diameters of 80 mm, 50 mm and 40 mm) in Table 47, and for the row pipelines (for diameters of 200 mm, 250 mm and 300 mm) in Table 48. The column pipeline diameter size appropriate for the 1,5 GW farm is 50 mm, with a pressure drop of 2 bar. For the row pipeline, this can be either 200 mm with a pressure drop of 3 bar – resulting in a final pressure of 45 bar before compressing – or 250 mm with a pressure drop of 2 bar. Experts advise the 1 bar pressure loss over the increased cost of a larger pipeline. The 200 mm pipeline with 3 bar pressure loss is therefore taken for the row pipeline of the 1,5 GW farm.

Table 47: Resulting mass flow rate and velocities for plausible column pipeline sizes along the length of the 1,5 GW farm.

Farm size	***1,5 GW***	***1,5 GW***	***1,5 GW***	**1,5 GW**	**1,5 GW**
Q - production per column (kg/hour)	31,5	31,5	31,5	31,5	31,5
Column pipeline length (km)	2,9	2,9	2,9	2,9	2,9
Column pipeline diameter (mm)	80	50	50	40	40
Inlet pressure (bar)	50	50	50	50	50
Oulet pressure (bar)	48	48	*47*	48	*47*
Mass flow rate (kg/hour)	**2000**	**700**	**850**	**320**	**390**
Pressure loss (bar)	2	2	3	2	3
Upstream Velocity (m/s)	**3,1**	**2,4**	**2,9**	**2**	**2,4**
Downstream Velocity (m/s)	**3,3**	**2,5**	**3,1**	**2**	**2,6**

Table 48: Resulting mass flow rate and velocities for plausible row pipeline sizes along the length of the 1,5 GW farm.

Farm size	***1,5 GW***	***1,5 GW***	***1,5 GW***	**1,5 GW**
Q - total farm production (kg/hour)	31500	31500	31500	31500
Row pipeline length (km)	3	3	3	3
Row pipeline diameter (mm)	200	200	250	300
Inlet pressure (bar)	48	48	48	48
Oulet pressure (bar)	46	*45*	*46*	46
Mass flow rate (kg/hour)	**27000**	**33000**	**49000**	**80000**
Pressure loss (bar)	2	2	2	2
Upstream Velocity (m/s)	**6,1**	**7,4**	**7**	**7,9**
Downstream Velocity (m/s)	**6,3**	**7,8**	**7,3**	**8,3**

The following table presents the appropriate pipeline diameters and lengths per farm size.

Table 49: Pipeline lengths and sizes for all farms and the final pressure of hydrogen prior to compression.

Farm size	***50 MW***	***150 MW***	***1,5 GW***
Column pipeline length (km)	0,58	0,93	2,9
Column pipeline diameter (mm)	20	20	50
Row pipeline length (km)	0,5	0,94	3
Row pipeline diameter (mm)	50	80	200
Final pressure (bar)	46	46	45

SoluForce B.V. provided cost estimations based on the average carbon steel cost as posed by Pipedata of €1000/ton, multiplied by a factor 2 for production and then by a factor 1,5 for installation – including welding [19], [20]. The cost for the required pipelines for all farms have been calculated and are posed below in Table 50. The total carbon steel pipeline costs including production and installation cost can be found in Table 51. Both calculations have been verified in terms of reconfirming input parameters and unit consistency. The order of magnitude of the total costs as posed in Table 51 were confirmed by SoluForce B.V. and Aqualeap B.V. [15], [19].

Table 50: Calculation of carbon steel pipeline costs based on the price of €1/kg and production - (2), and installation factor including welding (1,5) [19], [20]

Pipeline diameter (mm)	*Weight (kg/km)*	*Price (eur / km)*	*Cost including production and installation (eur/km)*
20	2466	2466	12331
50	15413	15413	77067
80	39458	39458	197292
200	246615	246615	1233075

Table 51: Total pipeline cost calculation for all farm sizes, based on the cost per km as determined in Table 50.

Farm size	*50 MW*	*150 MW*	*1,5 GW*
Column pipeline length (km)	0,58	0,93	2,9
Column pipeline diameter (mm)	20	20	50
Column pipeline cost including production and installation (eur)	7.152	11.468	223.495
Row pipeline length (km)	0,5	0,94	3
Row pipeline diameter (mm)	50	80	200
Row pipeline cost including production and installation (eur)	38.534	185.454	3.699.225
Total pipeline cost (eur)	45.686	196.922	3.922.720
Total pipeline cost - rounded (eur)	46.000	197.000	3.923.000
Final pressure (bar)	46	46	45

6.2.2 Hydrogen compression

The system boundary is centralized stored hydrogen at 700 bar. Hydrogen compression technologies must adhere to six posed functional constraints in order to be considered for the design of the hydrogen outflow system. The compression technologies must compress the hydrogen at the delivered pressure to 700 bar (FC6), doing so in an energy efficient and cost-effective manner (FC7 and FC8). The technology must be well-established on the market (FC9), must operate using hydrogen with a 99.5 % purity level (FC10) and do so while producing minimal side products or waste streams (FC11).

Hydrogen is produced by electrolyzers at 50 bar and loses pressure through the on-site collection pipeline network. The pressure of the collection network for the 50 MW and 150 MW farm is 46 bar, and 45 bar for the 1,5 GW farm, as determined in the previous section. The compression technology for the farms should be able to increase the hydrogen pressure by ± 650 bar.

There are five general compression technologies that are currently established and in use on the hydrogen market: piston compressors, diaphragm -, centrifugal -, ionic liquid piston -, and electrochemical compressors. Piston, diaphragm, and centrifugal compression are mechanical compression technologies.

Piston compression is based on positive displacement where a piston or rotor compresses gas by moving in the cylinder [49]. diaphragm compression utilizes a hydraulic fluid and a metal membrane (diaphragm) which isolates hydrogen from the hydraulic fluid. Pressure is increased through movement of a piston. The pressure increase is exerted from the piston, through the hydraulic acid and diaphragm onto the gas resulting in hydrogen compression.

As the piston is not in direct contact with hydrogen, the risk of contamination and leakage is reduced. However, diaphragm compression has a limited pressure range [22], [49]. Centrifugal compression relies on a rotary impeller to accelerate the gas. The kinetic energy is then converted to pressurize hydrogen [49].

Ionic liquid piston compression utilizes a piston as well, in combination with an ionic liquid. Hydrogen solubility in ionic liquids is negligibly low, which allows high volumetric efficiencies and high compression ratios to be achieved [22], [49]. Electrochemical compression compresses hydrogen with high efficiency as well (± 95% recovery ratios). The technology uses an electrochemical cell with a proton exchange membrane (PEM). Electrochemical power is used to separate hydrogen ions when passing through the membrane, and recombining them at a higher pressure on the cathode end of the cell. This is visualized in Figure 28 [22], [49].

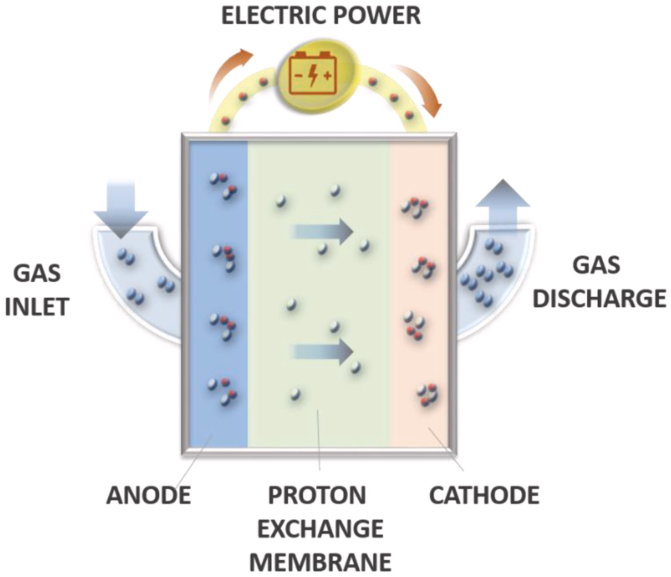


Figure 28: Schematic overview of the an electrochemical compressor by Danghi et al., [22]

All mentioned technologies are in use on the hydrogen market on an industrial scale. All compression technologies can operate discontinuously – according to a 0 – 100 down-turn ratio. This implies that all mentioned technologies are able to compress the discontinuously produced hydrogen at the designed farms. Characteristics such as average flow rate, compression range, energy efficient, CAPEX, and OPEX for all technologies are given in the following table.

Table 52: Characteristics of hydrogen compression technologies which are currently in use on the hydrogen market

Technology	***Flow rate (N m3/h)***	***Compression range***	***CAPEX in USD [21], [22]***	***Energy efficiency***	***Maintenance***
Piston compression	300 - 10.000 [22]	250 -1000 [22]	170000/year ∼2300/kg/day	± 45-95%	High - 5 % of CAPEX minimum, and operationally difficult
Diapragm compression	5 - 700 [22]	50 - 700 [22]	170000/year ∼2300/kg/day	65 - 85 %	Diaphragm failure and renewal is common - 5 % of CAPEX assumed
Centrifugal compression	10.000 [22]	250 - 1000 [22]	170000/year ∼2300/kg/day	± 45%	High - 5 % of CAPEX minimum, and operationally difficult
Ionic liquid piston compression	90 - 750 [22]	450 - 1000 [22]	150000/year ∼2000/kg/day	65 - 83%	Fluctuating, between 4 and 5% of the annual. CAPEX assumed
Electrochemical compression	1 - 500 [22]	10 - 1000 [22]	170 /kg/day	80 - 95 %	Moderate - 2 to 3% of CAPEX assumed; membrane replacement due to gas impurities

6.2.3 Hydrogen storage

The functional requirements for hydrogen storage entail that the method is well established on the market (F12), that is adheres to the ISO storage and transportation safety guidelines (FC13), and that can respond to a fluctuating demand (FC14).

There are two methods for storing (and transporting) 700 bar compressed hydrogen: pipeline transport or with storage cylinders/tanks (and transport through tube trailers) [108], [109]. The scope of this research limits the storage method to cylinder storage as pipeline storage is not considered centralized. There are four types of cylinder vessels classified for hydrogen storage. The types differ in material and availability of sub-chambers in the cylinders. The only vessel type suitable for hydrogen at a pressure higher than 450 bar is the type IV vessel.

Types I and II vessels are metal-based, and type III cylinders is made up of carbon fiber or carbon glass fiber composite with a metal liner as hydrogen permeation barrier. The type IV cylinder is made up of carbon fiber or carbon glass fiber composite as well. However, unlike types I, II, and III, type IV vessels contain a hydrogen permeation barrier consisting of a high-density polyethylene layer (plastic). This allows the cylinder to safely store hydrogen up to 1000 bar safely. Type IV vessels are the lightest cylinders for hydrogen transport as well [47], [110].

Type IV hydrogen cylinders are available on the market in different sizes, holding volumes ranging from 26 to 994 liters [18], [110], [111].

The daily production in liters of 700 bar hydrogen by different farm sizes and locations have been determined according to the ideal gas law and are posed in Table 53. Average daily ESH have been taken as 5,65 for Ínsua and as 7,0 for Al Buraimi. Controlled temperature at 25 °Celsius has been taken. Complete compression is assumed as this is achievable with all compression technologies. The quantities have been verified by SoluForce [19]. The number of required 994 L tanks required on a daily and hourly basis are given as well. The quantities have been verified by SoluForce as well [19].

From a practical perspective, loading, unloading and transporting the number of tanks for a 50 MW farm (108-133) per day is an exhaustive logistical process. SoluForce B.V. has found that for projects larger than 50 MW, storage and transportation with tank and tube trailers is not feasible [19]. It is thus unrealistic to load and transport the number of tanks required for the 150 MW and 1,5 GW farm. Though the system boundary of this research enables only storage tanks as storage option for hydrogen, a hydrogen system design without a centralized storage option will included in further evaluation as well.

Table 53: Daily production quantities for all farm sizes in both locations determined with the average ESH, assuming complete compression (100% conversion) and the ideal gas law at a constant temperature of 25 C, required number of 994 L storage tanks are given for a daily and hourly rate according to the average ESH.

	Insua - 5,65 ESH			Al Buraimi - 7,0 ESH		
Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
Electrolyzers (units)	8.400	25.000	250.000	8.400	25.000	250.000
Total daily production (kg/day) 50 bar	5.920	17.750	177.500	7.350	22.000	220.000
Total daily production (m3/day) 50 bar	1.499	4.495	44.948	1.861	5.571	55.710
Total daily production (L/day) 50 bar	1.499.114	4.494.809	44.948.088	1.861.231	5.571.031	55.710.306
Total daily production (L/day) 700 bar	107.000	321.000	3.211.000	132.000	398.000	4.000.000
Daily number of 994 L tanks required	108	323	3230	133	400	4024
Hourly number of 994 L tanks required	19	57	572	19	57	575

The number of storage tanks required on site is dependent upon the distance to the (consumer) destination of the hydrogen. If the following consumer is within proximity to the farm, the tanks can be returned to the farm for reuse. If hydrogen is sold along with the tank, this cost is excluded from the farms costs and LCOH as the expense of the tanks costs will be covered by the following consumer. For the purpose of the scope of this research, the costs for type IV hydrogen storage tanks are included and one days worth of tanks. Thus the assumption is made that tanks are returned to the farm within a day for reuse.

Price ranges for 700 bar hydrogen storage vary. A study done by Shin et al. found that the average price for a type IV of USD 656/kg H2 for temperature higher than 8 K, based on the market in 2018 [112]. Similarly, Li et al. found an average of USD 595/kg H2 for 700 bar hydrogen storage in a type IV tank, based on the market in 2023 [113].

Upon suggestion of Veritas BV, an average of €600/kg hydrogen should be taken to determine the price of a 994 L type IV storage tank. A 994 L tank of 700 bar hydrogen carries a hydrogen mass of 22,5 kg, as presented by Quantum Fuel Systems [111]. The price for a 994 L tank is thus estimated at €13500. This estimate was deemed plausible by experts at Veritas BV as well as an expert of the Centre of Expertise – Energy [18], [24].

The tank costs for every farm size in both locations is given in Table 54. These costs are notably high. The total farm costs could decreased in case the tank costs are removed by (partially) imposing them on the consumer or in case transportation is outsourced by a third party that will cover tank costs, or, in case the produced hydrogen can be transported using a hydrogen pipeline instead of tanks. A combination of pipeline and tank storage is another option to decrease the costs while maintaining a stable inflow of hydrogen into the pipeline.

Table 54: Tank costs for all farm sizes, based on the estimated €13.500 per type IV tank [18], [24], [111]–[113]

	Ínsua			Al Buraimi		
Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
Daily number of 994 L tanks (unit)	108	323	3230	133	400	4024
Tank cost (€)	1.453.000	4.360.000	43.600.000	1.800.000	5.410.000	54.330.000

6.2.4 Morphological chart

The morphological chart in Table 55 summarizes the means found for the three system functions of the hydrogen outflow system. The means for all system functions adhere to the functional constraints which were formulated in subsection 6.1. Due to these constraints, the on-site hydrogen collection system resulted with one suitable mean: carbon steel piping in a ring pipeline layout. Similarly, for centralized hydrogen storage, only type IV hydrogen tanks are deemed suitable. As for the compression technology, all methods comply to the functional constraints. Therefore, compression technology will be selected based on the non-functional constraints, functional – and non-functional objectives. This will be done in the following section (subsection 6.3).

Table 55: Morphological chart for the three system functions of the hydrogen outflow system.

Means ***System Function***					
On-site collection	Carbon steel piping - ring pipeline system				
Compression	Piston compression	Diaphragm compression	Centrifugal compression	Ionic liquid piston compression	Electrochemical compression
Storage	994 Liter type IV hydrogen tanks				

6.3 Design Selection

This section focuses on the compression technology as system function, as the means for the remaining system functions have resulted in previous sections. Non-functional constraints and objectives as well as functional objectives will be used to select a compression technology for each farm size (and for both locations). The remaining two system functions for which one plausible means has been found, will be touched upon briefly.

6.3.1 On-site hydrogen collection

Pipeline characteristics in terms of diameters, lengths, material and costs have been determined for all farm sizes in the previous section. As there is one mean selected for the system function, which complies with all posed functional and non-functional constraints, testing against the remainder of the objectives is redundant.

There is one specification that could influence especially the maintenance and cost aspect of the on-site collection pipeline system. The installation costs given in the previous section include welding. It is important to note that the pipelines can be placed without welding, which results in higher material costs for additional safety valves etc. More importantly, from a safety perspective this will require annual testing according to the ISO 22734 standards. All projects with lifetimes longer than 8 years benefit more from welded pipelines than that of annual inspection of each pipe, according to the Centre of Expertise – Energy [24].

This is especially the case as the Qualitative Risk Assessment (QRA) required for all hydrogen farms will be more costly for a farm based on multiple electrolyzers dispersed throughout the farm area. On a small-capacity based electrolyzer hydrogen farm, every electrolyzer has an individual risk radius. Overlap of risk radii requires additional testing on a yearly basis. This is reduced to once every five years in case the hydrogen pipeline system is welded, due to the decreased risk of leakage [24], [46]. For centralized hydrogen production (i.e., one large electrolyzer) there is only one large risk radius, and no overlap safety assessment is required.

For the carbon steel ring pipeline system for on-site hydrogen collection, a welded system is chosen for every farm size and location.

6.3.2 Hydrogen compression

Piston compressors, diaphragm -, centrifugal -, ionic liquid piston -, and electrochemical compressors are all technically suitable for compression of 45 or 46 bar hydrogen to 700 bar hydrogen of 99.5% purity. As posed in Table 52, electrochemical compression is least CAPEX intense and has the highest efficiency. Electrochemical compressors are being used in an increasing range of hydrogen projects for these reasons [24]. The amount of hydrogen to be compressed per farm size is given below in Table 56.

Table 56: Production flows for all three farm sizes on an hourly basis, quantities for compression. *hydrogen at 46 bar **hydrogen at 45 bar.

Farm sizes	***50 MW****	***150 MW****	***1,5 GW*****
Q - total farm production (kg/hour)	1052	3150	31500
Q - total farm production (m3/hour)	270	800	8000
Q daily Insua (m3/day)	5.900	17.750	177.500
Q daily Al Buraimi (m3/day)	7.300	22.000	220.000

As presented in the previous section and in Table 52, electrochemical compression is a highly efficient compression technology in terms of energy and costs that is currently used on an industrial level on the hydrogen market. Compared to the production volume per hour as presented above in Table 56 only the 50 MW farm falls within range of the electrochemical compressor capacity [21], [22]. Upon further investigation at hydrogen compressor suppliers such as HyET and Siemens Energy, practical experience has proven that piston compression has a higher efficiency in both energy and cost-effectiveness for flows larger than 5000 kg/day [23], [24]. Furthermore, as piston compression is the mostly used and advanced compression technology for hydrogen compression. It is suggested for all farm sizes by Bureau Veritas, Siemens Energym, Centre of Expertise – Energy, and SoluForce [18], [19], [23], [24]. Thus, piston compression will be used as compression technology for all farm sizes and for both locations.

Though most industrial hydrogen projects utilize piston compression, cost estimates and energy usage estimates are difficult to find and calculate.For most projects, piston compressors are tailored specifically to the flow rates, temperature, end-use of hydrogen, etc. Due to all adaptations and patents, even overarching CAPEX estimates are rarely given [23], [24].

Recent studies have published average CAPEX and energy usage of compressors, for hydrogen compression to 540 bar and for compression to 1000 bar. Both studies do not include state the compression technology nor the sources or compressor suppliers. The first study, by Solomon et al. from 2024 found that for hydrogen compression from 0 to 540 bar, the CAPEX of the compressor attributes to €0,07/kg hydrogen (as part of the LCOH) in case 10.000 kg of hydrogen is produced on a daily basis. When 30.000 kg is produced per day, the costs related to the compressor (including BoP) drop to €0,05/kg hydrogen [114].

The second study is done for a small scale hydrogen to transport trucking station in Norway, done in 2019. The study found that for production volumes of 21 kg/hour of hydrogen between 5 and 15 bar, compression to 200 – 450 bar translates to about EUR12/kg/hour of capital costs for compression (including BoP) [115]. For further compression from 200 – 450 bar to 700 – 1000 bar for flows of 20 kg/hour, it capital compression costs are about €6,50/kg/hour. Both studies fall within the large ranges given by Sdanghi et al. as presented in Table 52 [22].

A more specific range for compressors to 700 bar for all three farm sizes has been provided by experts at Siemens Energy. For all farm sizes multiple smaller piston compressors are required installed in series so that the desired pressure is achieved through incremental compression. A full turndown ratio is possible with the piston compressors, meaning that they can be operate at any flow between 0% (temporarily switched off) to 99%. The pressurizing capacity of the complete series of compressors is ± 1000 bar - the compressors increase pressure by 10 -, 5- or twofold. The additional pressurizing range of the compressor series provides system redundancy in case of operational failure of one of the compressors. The turndown ratio of the remaining compressors can then be decreased, allowing for a larger flow, and the desired pressure increased. In case multiple compressors fail to operate, the on-site collection system provides intermediate storage in the pipeline - the pipes allow for a larger mass flow than the production. Depending on the day and season, the on-site pipeline system can hold between one and two days worth of hydrogen production.

For a tailored piston compressor including BoP costs, the CAPEX estimate of €5.000.000 – 6.000.000 was quoted for the 50 MW farm, for compressing the hydrogen flow at 40-50 bar inlet pressure to 700 bar. For the 150 MW farm, €14.000.000 – 15.000.000 should be assumed and for the 1,5 GW farm €120.000.000 – 130.000.000 is a safe assumption [23]. For compressor OPEX, it is safe to assume that this covers 4% of the CAPEX specifically for Siemens Energy compressors [23]. Energy usage of the piston compressors was suggested to be taken as 5 kWh/kg hydrogen (to be compressed), which corresponds to values found in literature [21]–[23]. As these numbers have undergone expert validation, these will be used for further calculations. The numbers are presented in the tables below.

Table 57: Compressor CAPEX and OPEX for all farm sizes as given by Siemens Energy [23]

Farm sizes	***50 MW***	***150 MW***	***1,5 GW***
Piston compressor - CAPEX (eur)	5.000.000 - 6.000.000	14.000.000 - 15.000.000	120.000.000 - 130.000.000
Piston compressor - OPEX (eur/year)	200.000 - 300.000	560.000 - 600.000	4.800.000 - 5.200.000

Table 58: Minimal amount of solar panels required to support compressors per farm size, based on 0,6 kW solar panels, average ESH and estimated energy usage of 5 kWh/kg hydrogen.

	Insua - 5,65 ESH			***Al Buraimi - 7,0 ESH***		
Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
Total daily production (kg/day) 50 bar	5.920	17.750	177.500	7.350	22.000	220.000
Daily required kWh (5 kWh/kg)	29600	88750	887500	36750	110000	1100000
Maximal kwH per 0,6 kW solar panel	3,39	3,39	3,39	4,2	4,2	4,2
Minimal amount of solar panels required	8732	26180	261799	8750	26190	261905

6.3.3 Hydrogen storage

As the only means for centralized storage of the produced hydrogen available on the market is a type IV hydrogen storage tank, this is the selected method for the hydrogen outflow system storage for all farm sizes. As all farm sizes produce exceedingly sufficient hydrogen (compressed at 700 bar) to fill a multitude of the largest tanks available on the market, the 994 L tanks. The quantities and costs of the tanks given in in Table 54 will be used for further evaluation.

6.3.4 System design overview

In this section, the selected means for the system functions are summarized and evaluated. In addition, the acquired data is specified in how it has been validated, and the same is done to verify the calculation. In terms of system design, as the previous sections show, the hydrogen outflow system does not vary in means for any of the system functions. However, an option will be explored without hydrogen storage as the sole storage method is not practically viable for a 150 MW farm or for the 1,5 GW farm, at either location. Even for the smallest farm size, hydrogen storage in tanks is logistically exhaustive. Without hydrogen tanks as predefined storage method, and no consideration for pipelines and their required operating pressure, there is no direct need for hydrogen compression to 700 bar other than the system boundary. For pragmatic purposes, the hydrogen outflow system will be evaluated including and excluding compression as well. Plausible hydrogen outflow system designs are depicted in Figure 29.

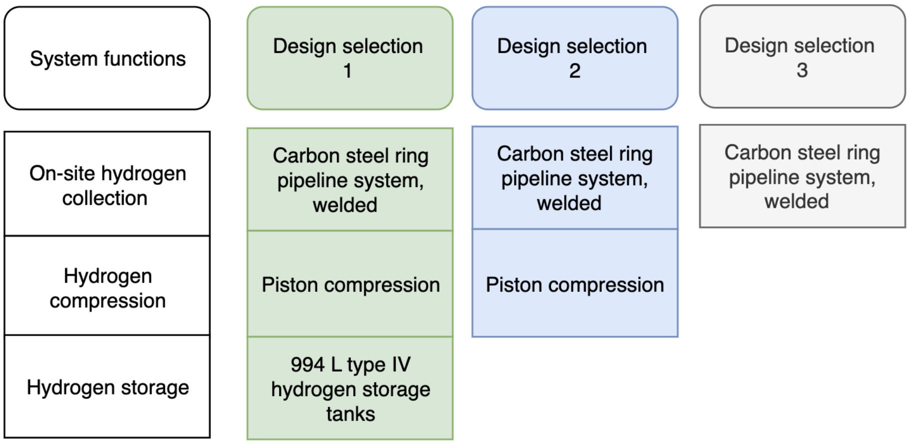


Figure 29: Means for the system functions of the hydrogen outflow system design selections

6.3.5 Discussion - critical design components, system redundancy and flexibility

The hydrogen outflow system consists of one, two or three system functions, depending on the design selection. The on-site hydrogen collection system is a ring pipeline system made of welded carbon steel. The cost assumptions include production and transport, welding and installation (including testing for safety). Equal factors for these costs were used for both locations. In reality the transport and expertise required for installation will differ between the locations. A larger investment might be needed for ensuring safety and expertise for the installment and testing of the on-site collection pipeline system.

The ring pipeline system offers redundancy in case one of the row columns or column pipelines forms an interruption. Furthermore, the diameters of the collection system, as mentioned, have a larger mass flow capacity than the production rate of the electrolyzers. It form as intermediate storage for the produced hydrogen prior to compression or any other form of disposal (e.g., pipeline) in case required.

The series of compressors are a relatively novel construction, especially for the larger farm size. Their coupling provides system redundancy as the total pressurizing capacity and flow capacity is larger than that required for the farm. In case one compressor completely fails, the remaining compressors can sustain compression of the produced hydrogen - for a duration that depends on the seasonality and production. In case multiple compressors have disruptions, more than a days worth of hydrogen production can be stored in the ring pipeline collection system.

Tanks for storage even for the 50 MW farm form a logistical challenge more than 100 tanks per day assuming average ESH per location. Though not in the system boundary for this research, transport of hydrogen by tanks relies on the availability of trucks licensed to transport such tanks. The availability at capacity of more than 100 tanks per day at either location has not been assessed. It is beneficial for the hydrogen not to require that much transport: to be produced near he (intermediate) consumer.

6.3.6 Data validation and calculation validation

Throughout the previous sections, various calculations and estimations have been done. Sources and data used for the calculations – found in literature or project reports or given by experts – have been mentioned in the sections as well. An overview of the data validation for these calculations is presented in the list that will follow below. As for verification on the calculations, all calculations have been checked based on their input parameters and computational coherence. Underlying assumptions and bench marking against theoretical ranges is presented in the list for data validation as well, in addition to expert verification of the outcomes.

All calculations have been done based on input data that was either found in literature and validated by an expert in the field – or (ranges of data) delivered by experts in the field. The expertise given is based on practical experience with hydrogen production farms or segments hereof. Furthermore, all data given has been validated by at least two independent experts.

Where factors have been used – as for the pipeline system estimations - it must be said that the factors taken for production, welding and installation are estimated factors. Though these factors are used for projects by companies such as Bureau Veritas and SoluForce B.V. based on the farm size, it should be noted that the costs are influenced by the farm location (country) as well.

OPEX or operation and maintenance costs are deemed negligible or minimal. Corrosion, fluid impact and third party damage of slidings or earth movements must be supervised, though measures for these are taken upon installation. Additional sensors etc., are negligible compared to the initial investment cost, as is their energy usage [19]. Below follows a list of main calculations with inputs specified and validation elaborated upon, as well as their output.

- Pipeline diameters and flow rates under set pressure losses by Weymouth, Panhandle A, and Panhandle B equations
    - Input: Pipeline diameter, length, inlet and outlet pressure as presented in Table 42
    - Data validation: LMNO calculator - Engineering, Research, and Software, Ltd approved [107], Peter Cloos – SoluForce B.V [19], SoluForce B.V. – factsheet on hydrogen pressure loss [19]
    - Output: Resulting mass flow rate and velocities for plausible column and row pipeline sizes, for 50 MW (Table 43 and Table 44), 150 MW (Table 45 and Table 46), and 1,5 GW (Table 47 and Table 48). Appropriate diameter for all pipelines and farm sizes summarized in Table 49
- Pipeline costs, including production, welding and installation costs
    - Input: Pipeline diameters and lengths, as well as farms sizes (Table 49), steel costs and factors for production, welding installment.
    - Data validation: Steel costs by Pipedata – source used by Bureau Veritas and SoluForce B.V [18]–[20], adjustment factors as used by SoluForce and Aqualeap B.V [15], [19]
    - Output:Costs for pipelines of different diameters (Table 50) and total costs for pipelines per farm size (Table 51) – output verified by experts at SoluForce [19]
- Daily production quantity of 700 bar hydrogen for all farm sizes, assuming full conversion under the ideal gas law at constant temperature
    - Input: Hourly production per electrolyzer as given in the methodology (Table 2), average ESH per farm location, initial pressure of 50 bar.
    - Data validation: Data as received by ZEF [12], [13], conversion method as done by Aqualeap B.V. and SoluForce B.V [15], [19]
    - Output: Daily production volumes of 700 bar hydrogen for all farm sizes (in kg, m3 and L) and the required number of 994 L tanks for storage(Table 53 and Table 56)
- Tank costs

  - Input: Determined tank quantity requirements (Table 53), average price for a type IV hydrogen tank of €600/kg hydrogen - €13500 per 994 L tank [18], [113]
  - Data validation: Average based on the market in 2023 and the average recommended by Bureau Veritas [18], [113], hydrogen mass per 994 L tank by Quantum Fuel Systems [111]
  - Output: Tank costs for all farm sizes (Table 54), estimates deemed plausible by experts at Veritas BV as well as an expert of the Centre of Expertise – Energy [18], [24]
- Compression OPEX and CAPEX
  - Input: CAPEX range for piston compressors for all farm sizes, used to determine OPEX range as percentage of CAPEX
  - Data validation: CAPEX ranges given by expert at Siemens Energy [23], order of magnitude falls within range of CAPEX estimates in literature by Sdanghi et al [22]
  - Output: CAPEX and OPEX ranges for 50 MW, 150 MW and 1,5 GW farms in Table 57

6.3.7 Cost estimation and discussion

For the three design selections, a cost estimation has been made which covers the CAPEX and OPEX (total over the 30 year lifetime). The costs are estimated based on previously determined values. It should be noted that the costs have been corrected based on the 30-year lifetime and account for a 5 % discount rate.

For the on-site hydrogen collection system, the cost for a ring pipeline system of carbon steel, including welding and installation of Table 51. As mentioned, no OPEX or energy usage is taken for the on-site hydrogen collection system [19].

For hydrogen compression, maximal price estimates for piston compressors for farm sizes as presented in Table 57 have been used for the CAPEX of the compressor. The OPEX was determined based on the given percentages based on CAPEX, from Table 57. For the energy usage of the compressor(s), estimated costs for solar panels based on the amount of panels required per farm (Table 58) and the costs per solar panel (€163,86 for Ínsua and €130,36 for Al Buraimi [13]) were used. Once again, these costs include procurement, transportation, installment, land costs, solar tracker costs, and installation hereof (i.e.full BoP).The OPEX for solar panels based on the amount of panels required per farm (Table 58) and the OPEX per year per solar panel (€2,57 for Ínsua and €1,14 for Al Buraimi [13]), and lifetime of 30 years.

For hydrogen storage, costs for the daily amount of type IV 994 L tanks for compressed hydrogen at 700 Bar as calculated in Table 54 were taken as CAPEX. The 994 L type IV hydrogen storage tank by Quantum Fuels has a lifetime of 15 years without (negligible and insured) maintenance. Therefore, no OPEX is taken for hydrogen storage.

It should be noted that for the timeline of this research, no design includes battery or energy storage, which will be required for operating the compressors according to the production of the electrolyzers. The total CAPEX and OPEX for the design selections are given in Table 60, Table 61, and Table 62, respectively. The tables include the interest over CAPEX as an OPEX cost: assuming that at least 85% of the total CAPEX will be funded through bank loans at an interest rate of 3% for both locations, as done in prior studies for the ZEF electrolyzer [12], [13]. The determined cost per kg hydrogen is determined based on the discounted hydrogen production per farm size, which is based on the values and formula presented in section 4, Table 2 and Table 56. The resulting corrected production quantities are given in Table 59.

Hydrogen compression is the largest cost component for the hydrogen outflow system when included in the design. Aside of being highest in CAPEX, it is the sole component with OPEX (significant enough to include), and demanding in terms of energy – which leads to additional CAPEX and OPEX. This can be deducted from Table 60 and Table 61. The on-site collection system is the lowest CAPEX contributor for 50 and 150 MW farm sizes. Due to the diameter sizes required for the 1,5 GW farm, it's contribution to the overall cost increases. For the 50 MW farm – the only farm size where hydrogen storage in tanks is practically feasible – hydrogen storage contributes twice as much as the on-site collection system does. Depending on the consumer needs and consumer location, it could be beneficial to transport hydrogen through pipelines for this farm size as well.

The results show that for all design selections, the hydrogen outflow system is most costly for the largest farm size, compared to the smaller sizes at the respective location. The decrease in costs for all farm sizes when eliminating hydrogen storage in tanks (difference between Table 60 and Table 61), that the hydrogen storage cost increases quite linear with the farm size.

The difference between on-site hydrogen collection with and without compression (Table 61 and Table 62), shows that compression takes up more than half of the cost for the largest farm size and more than 90 % of the cost for the two smaller farm sizes. As expected, design selection three (on-site collection only) has the largest cost per kg hydrogen for the 1,5 GW farm as the cost for steel pipelines scales more than linear for longer and larger pipelines (and thus for larger farms). This can also be seen when increasing the farm size from 50 MW to 150 MW with a slight increase in cost for the hydrogen collection system.

The comparison between the design selections also shows that hydrogen compression, though large in total costs, has benefits in terms of economies of scale for the 150 MW farm. This can be seen as the total cost per kg hydrogen decreases as the farm size increases from 50 MW to 150 MW. The costs for compression increase with approximately a factor of 2,5 (2.400.000 to 6.000.000) while the farm size increases with a factor 3.

For the 1,5 GW farm, the quoted costs for compression increase by a factor of 8,67 while the farm size increases with a factor 10. This is a larger percentile increase than that of the 50 MW to the 150 MW farm. According to experts at Siemens Energy this is because the farm size is both unprecedented and extremely large. Therefore the quote given includes the Lang factor for its production. Even so it was advised to account for a possibly higher cost for compression as the coupling of multiple compressor units at this scale has not been done before by Siemens Energy [23].

Table 59: Discounted production quantities for all farm sizes based on a 5% discount rate.

	Insua			Al Buraimi		
Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
Total yearly production (kg/year) 50 bar	2.160.800	6.478.750	64.787.500	2.682.750	8.030.000	80.300.000
Discounted production 30 years - 50 bar	33.216.792	99.594.267	995.942.671	41.240.442	123.440.782	1.234.407.817
Total yearly production (kg/year) 700 bar	1.423.699	4.271.098	42.724.282	1.756.339	5.295.629	53.222.400
Discounted production 30 years - 700 bar	21.885.746	65.657.239	656.776.927	26.999.238	81.406.794	818.158.737

Table 60: Total CAPEX and OPEX for design selection one, for all farm sizes and both locations.

		Insua - 5,65 ESH			***Al Buraimi - 7,0 ESH***		
	Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
CAPEX							
	On-site hydrogen collection system	763.000	2.400.000	138.540.000	763.000	2.400.000	138.540.000
	Hydrogen compression	6.000.000	15.000.000	130.000.000	6.000.000	15.000.000	130.000.000
	Hydrogen storage	1.453.000	4.360.000	43.600.000	1.800.000	5.410.000	54.330.000
	Solar panels - energy for hydrogen compression	1430754	4289845	42898451	1140650	3414190	34141905
OPEX	Hydrogen compression	7.200.000	18.000.000	156.000.000	7.200.000	18.000.000	156.000.000
	Solar panels - energy for hydrogen compression	673.766	2.020.158	20.201.585	675.188	2.020.971	20.209.714
	Interest over CAPEX	245.992	664.271	9.053.481	247.443	668.771	9.103.804
	Total - discounted	4.160.686	10.599.013	94.927.481	4.162.158	10.601.707	94.957.433
TOTAL	incl. discounted OPEX	13.807.440	36.648.858	449.965.932	13.865.808	36.825.898	451.969.337
Cost per kg hydrogen (€/kg)		0,63	0,56	0,69	0,51	0,45	0,55

Table 61: Total CAPEX and OPEX for design selection two, for all farm sizes and both locations.

		Insua - 5,65 ESH			***Al Buraimi - 7,0 ESH***		
	Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
CAPEX							
	On-site hydrogen collection system	763.000	2.400.000	138.540.000	763.000	2.400.000	138.540.000
	Hydrogen compression	6.000.000	15.000.000	130.000.000	6.000.000	15.000.000	130.000.000
	Solar panels - energy for hydrogen compression	1430754	4289845	42898451	1140650	3414190	34141905
OPEX	Hydrogen compression	7.200.000	18.000.000	156.000.000	7.200.000	18.000.000	156.000.000
	Solar panels - energy for hydrogen compression	673.766	2.020.158	20.201.585	675.188	2.020.971	20.209.714
	Interest over CAPEX	208.941	553.091	7.941.681	201.543	530.762	7.718.389
	Total - discounted	4.141.700	10.599.013	94.927.481	4.162.158	10.601.707	94.957.433
TOTAL	incl. discounted OPEX	12.335.454	32.288.858	406.365.932	12.065.808	31.415.898	397.639.337
Cost per kg hydrogen (€/kg)		0,56	0,49	0,62	0,45	0,39	0,49

Table 62: Total CAPEX and OPEX for design selection three, for all farm sizes and both locations.

		Insua - 5,65 ESH			***Al Buraimi - 7,0 ESH***		
	Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
CAPEX							
	On-site hydrogen collection system	763.000	2.400.000	138.540.000	763.000	2.400.000	138.540.000
OPEX	Interest over CAPEX	19.457	61.200	3.532.770	19.457	61.200	3.532.770
	Total - discounted	9.970	31.360	1.810.244	9.970	31.360	1.810.244
TOTAL	incl. discounted OPEX	772.970	2.431.360	140.350.244	772.970	2.431.360	140.350.244
Cost per kg hydrogen (€/kg)		0,02	0,02	0,14	0,02	0,02	0,11

6.4 Conclusion

The analysis has showed that a hydrogen outflow system, when consisting of on-site hydrogen collection, compression and centralized storage, contributes to the LCOH with less than €1/kg (Table 60, Table 61, Table 62).

On-site hydrogen collection can only be done using (welded) steel pipes. The defined designs include a ring pipeline system to increase the redundancy of the system. Welding is advised for all hydrogen pipelines with an anticipated lifetime of 8 years or longer, to minimize the risk of leakages and to minimize the safety testing required. The pipeline system can be positioned underneath the solar panels on the tracker system, as mentioned. In this way, the pipes are not exposed to UV and more importantly, excavation is no longer required for underground installment. The on-site collection system is the smallest cost contributor to the LCOH.

The compression system, which in case included in the system design, consists of multiple piston compressors, is most the largest cost contributor of the hydrogen outflow system. The piston compressors provide flexibility and redundancy of the system due to their large turndown ratios. Compressing 99.5% pure hydrogen to 700 bar will likely not be required by the market. This as 700 bar is the pressure hydrogen is used at for the (land) transport market, and for this market, hydrogen of higher purity is required. Compression to 500 bar is suggested by experts, for which the number of piston compressors remains equal.

Hydrogen storage in 994 L tanks is not feasible in practice for the 150 MW and 1,5 GW farm sizes and logistically exhaustive for the 50 MW farm. Storage in tanks will only be considered for further analysis of the 50 MW farm sizes. The tank costs contribute for €0,63 and €0,51 to the LCOH for Ínsua and Al Buraimi, respectively.

7 Combined system evaluation: LCOH

The previous chapters have resulted in design selections for a water supply system and a hydrogen outflow system. In this chapter, combinations of the design selections will be made to form a complete hydrogen farm design. The LCOH will be determined for all farm sizes, for each resulting hydrogen farm design. To this end, the costs for the electrolyzers and supporting solar panels (and infrastructure) will be determined first, based on CAPEX and OPEX results from previous research at ZEF for the 6 kW electrolyzer. The LCOH for the complete hydrogen farm design will then be calculated based on the cost estimations of the design selections that resulted from section 5 and section 6.

7.1 Hydrogen farm designs

The water supply system design led to systems utilizing grid water and urban waste water for Ínsua, and to utilizing grid water and treated urban and industrial waste water for Al Buraimi. As indicated in section 5, the 50 MW farms will utilize grid water as water source, and for both locations the larger two farm sizes will utilize (treated or untreated) waste water.

The hydrogen outflow system led to design options based on on-site hydrogen collection, with or without compression to 700 bar – and with or without hydrogen storage at 700 bar. As aforementioned, storage of hydrogen in tanks (the only option with centralized storage as system boundary) is not practically feasible for farm sizes larger than 50 MW, and is already logistically exhaustive for the 50 MW farm. Therefore, the only farm size that will be considered to include hydrogen storage is the 50 MW farm for both locations.

Designs without compression do not comply with the system boundary of 700 bar. In practicality, depending on the presence of a hydrogen backbone and the pressure requirements hereof, 700 bar compression might not be needed. Considering both the system boundary of 700 bar and the practicality of hydrogen suppliers, the LCOH will be calculated for systems with and without compression to 700 bar. For each location, seven design configurations result, depicted in the following overview in Table 63.

	Ínsua			Al Buraimi		
Farm size	50 MW	150 MW	1,5 GW	50 MW	150 MW	1,5 GW
Water system	Grid water	-	-	Grid water	-	-
Hydrogen outflow system	Collection, compression, storage	-	-	Collection, compression, storage	-	-
Water system	Grid water	Urban waste water	Urban waste water	Grid water	Treated urban and industrial waste water	Treated urban and industrial waste water
Hydrogen outflow system	Collection, compression	Collection, compression	Collection, compression	Collection, compression	Collection, compression	Collection, compression
Water system	Grid water	Urban waste water	Urban waste water	Grid water	Treated urban and industrial waste water	Treated urban and industrial waste water
Hydrogen outflow system	Collection	Collection	Collection	Collection	Collection	Collection

Table 63: Hydrogen farm design configurations for LCOH calculations

7.2 CAPEX and OPEX for PV-6 kW electrolyzer system

The previous study for ZEF assessed i.a. the corrected CAPEX and OPEX for the electrolyzer and solar panel (including tracker system equipment) for both Ínsua and Al Buraimi. The estimates include transportation, installation, and other BoP costs. The CAPEX and OPEX for electrolyzer and solar panel equipment are posed in Table 64. The solar panel costs include procurement, transportation, installment, land costs, and solar tracker (installation, equipment, transport, etc.) costs. This data is used in combination with the number of electrolyzers required per farm as defined throughout this research and the assumption that 10 solar panels are coupled to one electrolyzer, to determine the total CAPEX and OPEX for each farm size at each location. For a 30 year-lifetime, an electrolyzer is replaced twice as it has a lifetime of 10 years. Its OPEX includes shipping, transport, installation, etc. which is why no additional replacement costs are considered.

The interest over CAPEX is considered as well. For both locations, a 3% interest rate is considered for 85% - assuming that 85% of the CAPEX is financed through bank loans, while the remaining 15% is funded by the company's own resources. This assumption is equal for both locations. Again, for OPEX, a 5% discount rate throughout the 30-year lifetime is accounted for. The results are posed in Table 65. For Ínsua, for all three farm sizes, the electrolyzer contributes to ± 82% of the costs, and PV accounts for ± 18%. For Al Buraimi, this is ± 84% and ± 16%, respectively.

Table 64: CAPEX and OPEX for PV (including equipment) and electrolyzer cost (including BoP, installation and transportation) as determined in the previous TIL study and provided by ZEF. [12], [13]

	Ínsua	**Al Buraimi**
Solar CAPEX/panel (€/unit)	163,86	130,36
Solar OPEX/panel (€/unit)	2,57	1,03
Electrolyzer CAPEX (€/unit)	2.800	2.600
Electrolyzer OPEX /unit/year(€/unit/year)	46,02	37,82

Table 65: CAPEX and OPEX for PV (including equipment) and electrolyzer cost (including BoP, installation and transportation) as determined in the previous TIL study and provided by ZEF. [12], [13]

	Insua			Al Buraimi		
Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
Number of electrolyzer microplants (unit)	8400	25000	250000	8400	25000	250000
Number of solar panels	84000	250000	2500000	84000	250000	2500000
CAPEX solar	€ 13.764.240	€ 40.965.000	€ 409.650.000	€ 10.950.240	€ 32.590.000	€ 325.900.000
CAPEX/electrolyzer-microplant	€ 70.560.000	€ 210.000.000	€ 2.100.000.000	€ 65.520.000	€ 195.000.000	€ 1.950.000.000
OPEX electrolyzer	€ 11.597.040	€ 34.515.000	€ 345.150.000	€ 9.530.640	€ 28.365.000	€ 283.650.000
OPEX - interest over CAPEX	€ 2.150.268	€ 6.399.608	€ 63.996.075	€ 1.949.991	€ 5.803.545	€ 58.035.450
OPEX solar	€ 6.481.807	€ 19.291.091	€ 192.910.909	€ 2.601.785	€ 7.743.409	€ 77.434.091
OPEX - total discounted	€ 10.365.702	€ 30.850.305	€ 308.503.050	€ 7.216.042	€ 21.476.315	€ 214.763.154
TOTAL (€) - incl. discounted OPEX	€ 94.689.942	€ 281.815.305	€ 2.818.153.050	€ 83.686.282	€ 249.066.315	€ 2.490.663.154
Cost per kg hydrogen - 45/46 bar (€/kg)	€ 2,85	€ 2,83	€ 2,83	€ 2,03	€ 2,02	€ 2,02
Cost per kg hydrogen - 700 bar (€/kg)	€ 4,30	€ 4,27	€ 4,27	€ 3,10	€ 3,06	€ 3,04
Electricity cost (€/kWh)	€ 0,013	€ 0,013	€ 0,013	€ 0,007	€ 0,007	€ 0,007

7.3 LCOH calculation

From the design selections, a total of seven designs results per location. All designs with a minimal lifetime of 30 years as specified in the design requirements. For each selected design configuration (as defined in Table 63), the LCOH is calculated based on the CAPEX and OPEX of the water supply system, of the PV-electrolyzers, and for the hydrogen outflow system. The results are posed in Table 66 and in Table 67.

Table 66: LCOH calculation for all selected hydrogen farm design configurations for Ínsua.

	Ínsua					
Farm size	***50 MW***	***Costs***	***150 MW***	***Costs***	***1,5 GW***	***Costs***
Water system	Grid water	€ 3.801.353	-	-	-	-
Hydrogen outflow system	Collection, compression, storage	€ 13.807.440	-	-	-	-
PV-electrolyzers		€ 94.689.942	-	-	-	-
LCOH - 700 bar		**€ 5,10**	-	-	-	-
Water system	Grid water	€ 3.801.353	Urban waste water	€ 5.924.174	Urban waste water	€ 27.009.582
Hydrogen outflow system	Collection, compression	€ 12.335.454	Collection, compression	€ 32.288.858	Collection, compression	€ 406.365.932
PV-electrolyzers		€ 94.689.942		€ 281.815.305		€ 2.818.153.050
LCOH - 700 bar		**€ 5,04**		**€ 4,85**		**€ 4,93**
Water system	Grid water	€ 3.801.353	Urban waste water	€ 5.924.174	Urban waste water	€ 27.009.582
Hydrogen outflow system	Collection	€ 772.970	Collection	€ 2.431.360	Collection	€ 140.350.244
PV-electrolyzers		€ 94.689.942		€ 281.815.305		€ 2.818.153.050
LCOH - 45/46 bar		**€ 2,99**		**€ 2,91**		**€ 3,00**

Table 67: LCOH calculation for all hydrogen farm design configurations for Al Buraimi.

	Al Buraimi					
Farm size	**50 MW**	**Costs**	**150 MW**	**Costs**	**1,5 GW**	**Costs**
Water system	Grid water	€ 3.836.664	-	-	-	-
Hydrogen outflow system	Collection, compression, storage	€ 13.865.808	-	-	-	-
PV-electrolyzers		€ 83.686.282	-	-	-	-
LCOH		**€ 3,76**	-	-	-	-
Water system	Grid water	€ 3.836.664	Treated urban and industrial waste water	€ 5.895.643	Treated urban and industrial waste water	€ 26.796.357
Hydrogen outflow system	Collection, compression	€ 12.065.808	Collection, compression	€ 31.415.898	Collection, compression	€ 397.639.337
PV-electrolyzers		€ 83.686.282		€ 249.066.315		€ 2.490.663.154
LCOH		**€ 3,69**		**€ 3,52**		**€ 3,55**
Water system	Grid water	€ 3.836.664	Treated urban and industrial waste water	€ 5.895.643	Treated urban and industrial waste water	€ 26.796.357
Hydrogen outflow system	Collection	€ 772.970	Collection	€ 2.431.360	Collection	€ 140.350.244
PV-electrolyzers		€ 83.686.282		€ 249.066.315		€ 2.490.663.154
LCOH		**€ 2,14**		**€ 2,09**		**€ 2,15**

7.3.1 Discussion

The resulting tables show that the LCOH differs most based on location and as anticipated, with the number of processes included (higher LCOH when storage and compression is included than if not). The size of the farm has less influence on the LCOH, than the location and included processes. This is mainly attributable to the majority of the LCOH being made up of the PV-electrolyzer CAPEX and OPEX, which, respectively to the water supply and hydrogen outflow system, increase in costs linearly as the farm size expands. I.e., due to the modular design of the PV-electrolyzer system, its costs provide less benefits in terms of economies of scale than the centrally built water supply - and hydrogen outflow system.

The determined LCOHs for all system designs fall out on the rather low end compared to values found throughout literature, which range from €4 - 15/kg hydrogen. [11], [35], [55], [56] Compared to the TNO report (totalling

€14/kg), it is mainly due to two cost aspects. The first is the electrolyzer cost. For the 6 kW electrolyzer it is between ± € 430 - 466/kW compared to €3000/kW for a large centralized electrolyzer (based on a 100 - 200 MW farm size). The second main difference is the electricity cost, which amounts to nearly €6/kg of hydrogen. The direct coupling of PV to the electrolyzer avoids nearly all of these costs and results in either €0,013 or €0,007 per kg of hydrogen for Ínsua and Al Buraimi, respectively (Table 65) [11].

The contribution of the water supply system, the hydrogen outflow system and the PV-electrolyzer aspect of the farm to the total costs, is visualized in Figure 30. The figure shows the cost breakdown for the 50 MW farms of Ínsua and Al Buraimi when the hydrogen outflow system only entails on-site hydrogen collection. The figure and tables reinforce that the Al Buraimi farms result in lower costs for both water supply and PV-electrolyzer parts of the farm.

Additionally, is it shown that the largest cost contributor (by far) is the PV-electrolyzer system - with more than 95% for all farms, all sizes and both locations. Note that the electrolyzers contribute to 84-64% of the PV-electrolyzer costs. Despite this, the designed farms seem to provide financial benefit. The electrolyzer costs found by TNO in their most recent study of €3050/kW amount to ± €152.500.000 for electrolyzers on a 50MW farm. The PV-electrolyzer cost of the designed farms of this research result in a lower total.

However, PV-electrolyzers being the main cost contributor is in alignment with the statement in section 2: that the high electrolyzer costs must be covered in relatively little running hours, which is done more in the Al Buraimi farms where more running hours are anticipated (more ESH). Moreover, as PV takes up a relatively small part of the costs, it supports the choice to implement oversizing of PV to allow for more production - thereby lowering the electrolyzer cost per kg hydrogen produced.

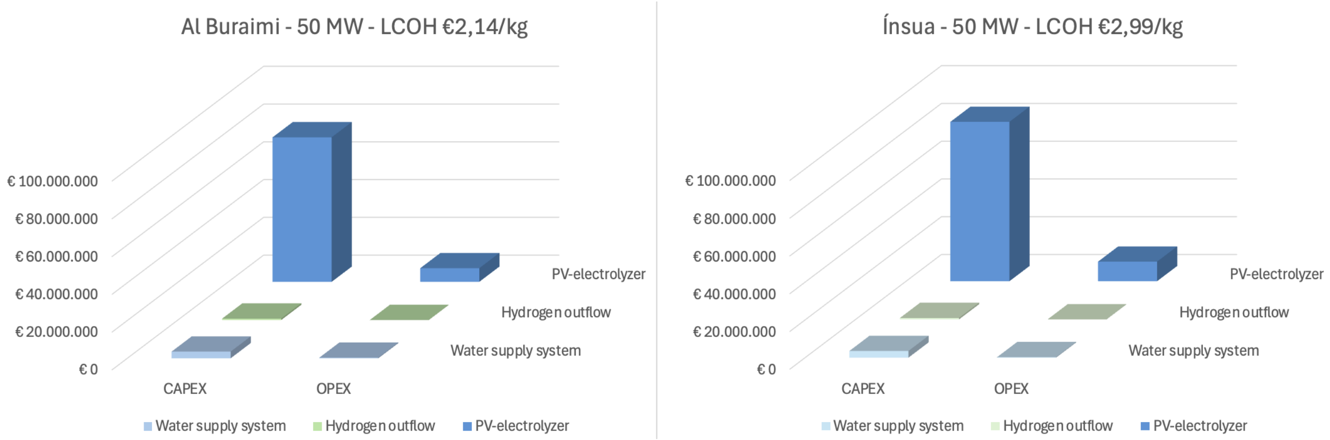


Figure 30: CAPEX and OPEX contribution to total costs per subsystem, for 50 MW farm sizes of Al Buraimi and Ínsua which include only on-site hydrogen collection as hydrogen outflow system.

7.4 LCOH sensitivity

The reflection on the critical processes, redundancy and flexibility of the design selections included various uncertainties of the system components or underlying assumptions. The LCOH will therefore be calculated for all design selections while accounting for these uncertainties - a critical scenario evaluation. To estimate these costs, different Lang factors are used for the CAPEX of systems. As mentioned, the Lang factor is a factor by which the estimated and true costs of an industrial plant differ that is mainly due to overhead BoP, installation, testing, safety, manufacturing, etc. costs that were underestimated. The Lang factor scales with availability and maturity of technologies and materials [27].

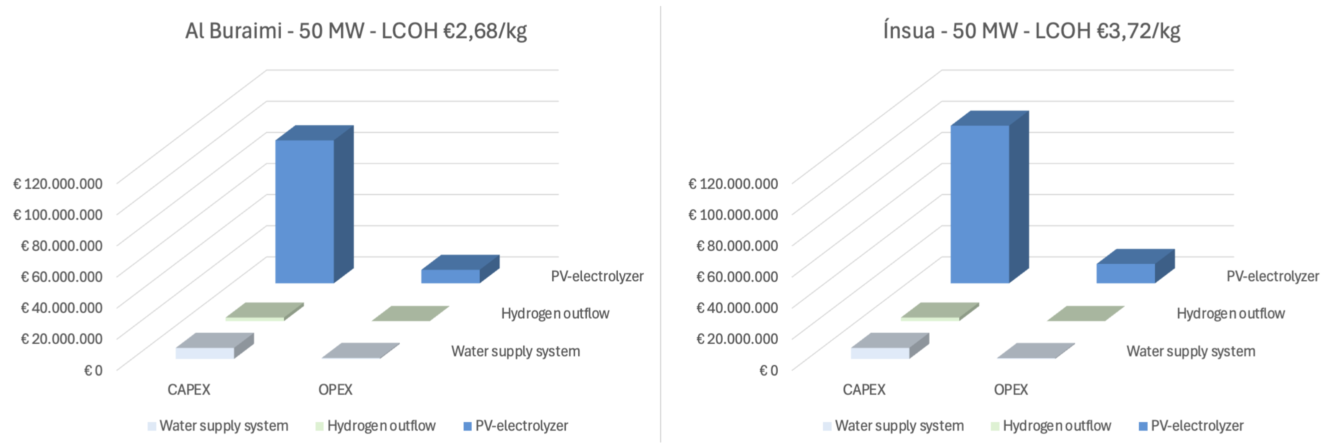
For the water supply system, mature technologies and materials are used. To account for higher installation, safety and transportation costs, a Lang factor of 2 is used. The same holds for the on-site collection system of hydrogen: carbon steel welding and manufacturing. For the compression of the hydrogen outflow system a Lang factor of 3 is used for the two smaller farm sizes. Due to the extreme novelty of a compressor system for the 1,5 GW farm size, a Lang factor of 4 is used [23]. For the PV-electrolyzer system, an overestimated price was taken for transport and installation in the initial (reference LCOH) calculation in the previous section. To allow for higher costs of raw materials and additional maintenance, both CAPEX and OPEX for the PV-electrolyzer system is increased by 20%. The results are posed in Table 68 and Table 69. As done for the first LCOH calculation, the CAPEX and OPEX contribution per subsystem is given for the 50 MW farms of Ínsua and Al Buraimi (with only on-site hydrogen collection) in Figure 31.

Table 68: LCOH calculation considering higher Lang factors for all selected hydrogen farm design configurations for Ínsua.

	Ínsua					
Farm size	**50 MW**	**Costs**	**150 MW**	**Costs**	**1,5 GW**	**Costs**
Water system	Grid water	€ 7.602.707	-	-	-	-
Hydrogen outflow system	Collection, compression, storage	€ 41.422.320	-	-	-	-
PV-electrolyzers		€ 113.627.931	-	-	-	-
LCOH - 700 bar		**€ 7,39**	-	-	-	-
Water system	Grid water	€ 7.602.707	Urban waste water	€ 11.848.348	Urban waste water	€ 54.019.163
Hydrogen outflow system	Collection, compression	€ 37.006.363	Collection, compression	€ 96.866.573	Collection, compression	€ 1.625.463.728
PV-electrolyzers		€ 113.627.931		€ 338.178.366		€ 3.381.783.660
LCOH - 700 bar		**€ 7,19**		**€ 6,77**		**€ 7,67**
Water system	Grid water	€ 7.602.707	Urban waste water	€ 11.848.348	Urban waste water	€ 54.019.163
Hydrogen outflow system	Collection	€ 2.318.909	Collection	€ 7.294.079	Collection	€ 561.400.978
PV-electrolyzers		€ 113.627.931		€ 338.178.366		€ 3.381.783.660
LCOH - 45/46 bar		**€ 3,72**		**€ 3,59**		**€ 4,01**

Table 69: LCOH calculation considering higher Lang factors for all selected hydrogen farm design configurations for Al Buraimi.

	Al Buraimi					
Farm size	**50 MW**	**Costs**	**150 MW**	**Costs**	**1,5 GW**	**Costs**
Water system	Grid water	€ 7.673.329	-	-	-	-
Hydrogen outflow system	Collection, compression, storage	€ 41.597.425	-	-	-	-
PV-electrolyzers		€ 100.423.538	-	-	-	-
LCOH - 700 bar		**€ 5,54**	-	-	-	-
Water system	Grid water	€ 7.673.329	Treated urban and industrial waste water	€ 11.791.286	Treated urban and industrial waste water	€ 53.592.714
Hydrogen outflow system	Collection, compression	€ 36.197.425	Collection, compression	€ 94.247.693	Collection, compression	€ 1.590.557.349
PV-electrolyzers		€ 100.423.538		€ 298.879.578		€ 2.988.795.785
LCOH - 700 bar		**€ 5,34**		**€ 4,97**		**€ 5,65**
Water system	Grid water	€ 7.673.329	Treated urban and industrial waste water	€ 11.791.286	Treated urban and industrial waste water	€ 53.592.714
Hydrogen outflow system	Collection	€ 2.318.909	Collection	€ 7.294.079	Collection	€ 561.400.978
PV-electrolyzers		€ 100.423.538		€ 298.879.578		€ 2.988.795.785
LCOH - 45/46 bar		**€ 2,68**		**€ 2,58**		**€ 2,92**


Al Buraimi - 50 MW - LCOH €2,68/kg

Ínsua - 50 MW - LCOH €3,72/kg

Figure 31: CAPEX and OPEX contribution to total costs per subsystem including critical Lang factors, for 50 MW farm sizes of Al Buraimi and Ínsua which include only on-site hydrogen collection as hydrogen outflow system.

7.4.1 Discussion

The figure and tables show that the increase in total costs and LCOH for all farm sizes are steeper for Ínsua and Al Buraimi - which is expected as these were higher in the reference calculations of the previous sections. In addition, the main cost contributor (with over 90% for all farm sizes of both locations) remains the PV-electrolyzer system of the farm.

The results also show that the doubling of the water supply system costs and tripling or quadrupling of the hydrogen outflow system costs, despite this, results in a market competitive LCOH on the lower end of LCOH ranges found in literature (€4 - 15/kg hydrogen [11], [35], [55], [56]). There remains a margin available to cover costs in case these result even higher than the chosen Lang factors, with which the LCOH can still remain within a market competitive range. This is especially the case for farms that do not include compression and storage. This margin can also be used for i.a., installation or connection to a hydrogen pipeline, either connected to the consumer or hydrogen network.

8 Conclusions

This thesis aimed to evaluate the potential of an off-grid and photovoltaic powered hydrogen farm that is based on multiple small-capacity electrolyzers. The main research question was posed as follows: *What system* ***size*** *and* ***geographical location requirements*** *are necessary to achieve a* ***market-competitive*** *Levelized Cost of Hydrogen for an off-grid, photovoltaic and 6 kW electrolyzer hydrogen production process?*

This thesis found that for the 6 kW electrolyzer hydrogen farms assessed in Ínsua and Al Buraimi, that 50 MW, 150 MW and 1,5 GW farm sizes have technical feasibility, and, all can result in market-competitive LCOHs. The lowest and therefore most market-competitive LCOH was found for a 50 MW farm in Al Buraimi.

The hydrogen farms were based on a 6 kW electrolyzer that is directly coupled to solar panels as hydrogen production component. The technical feasibility of the hydrogen farms was assessed by first completing the farm design with a water supply system and with a hydrogen outflow system based on available technologies on the market and expert input. Alternatives for each system were determined and evaluated, after which the best-performing alternatives were selected, combined and used for LCOH calculation.

Water supply system design alternatives

All found alternatives for the water supply system are based on distant water sources. This is due to the fact that no technologies to obtain the required amount of water locally are currently available for industrial usage on the market. The usage of (any) distant water source, for the required volumes of water for all evaluated farm sizes, demands a pipeline for its transport to the hydrogen farm. This results that the hydrogen farms are not fully off-grid.

Depending on the location - Ínsua, Portugal or Al Buraimi, Oman - various water sources of different water quality, are available. Qualitative evaluation led to the design choice for usage the water grid and treated (industrial and urban) wastewater. Water sources as surface- or rainwater and groundwater have been eliminated due to low reliability in availability, high competition with other local or industrial users, more water (filtering) treatment required, lower perceives social acceptance and higher complexity of the permitting process.

The water supply system based on water from the grid requires less water treatment than that based on water from WWTPs - it only requires reverse osmosis. Ínsua's urban wastewater requires fine screening, ultrafiltration, and reverse osmosis whereas Al Buraimi's urban and industrial wastewater only requires ultrafiltration and reverse osmosis. Conversely, the water cost is higher for water from the water grid than that of WWTPs.

For the 150 MW and 1,5 GW for both locations it was found that the lower water cost of waste water (€/m3) compensates for the additional water treatment. Due to the lower amount of water required for the 50 MW farms, the high investment costs for additional treatment are not outweighed, and usage of grid water prevails.

The remainder of the water design in terms of equipment was equal for both locations and farm sizes - PVC pipelines in a ring pipeline system, with utilization of pumps, water storage tanks and PV (battery is suggested by experts but not included in the design).

Hydrogen outflow system design alternatives and challenges

The expected challenges for the hydrogen system was the on-site hydrogen collection system, for safely transporting 50 bar hydrogen to a centralized point at minimal pressure loss. The found pressure loss for a welded carbon steel ring pipeline system for all farm sizes has proved minimal pressure loss (4-5 bar) while using minimal diameter size pipelines. Safety regarding risk of leakage can be mitigated by using a welded pipeline system. Material degradation, embrittlement, corrosion and thermal effects are mitigated through the pipeline placement: on the tracker system below the solar panels, close to the electrolyzer, without direct exposure to UV.

In addition to the on-site collection of hydrogen, an alternative is to include compression in the hydrogen outflow system. A system boundary was set at 700 bar hydrogen. However, regarding the usage of hydrogen at 99.5% purity, it is not viable on the transport market - where 700 bar is common. The design for compression, made of piston compressors installed in serie supports compression to 500 bar as well, which was advised for the purity of the hydrogen by experts [23], [24]. Hydrogen compression takes up the majority of the total costs of the hydrogen outflow system.

The third alternative for the hydrogen outflow system, is to include storage of the compressed hydrogen in type IV 994 L hydrogen cylinder tanks. For the amount of hydrogen produced, it is logistically exhaustive to facilitate this for the smallest farm size of 50 MW. Therefore, this alternative is not considered for the 150 MW and 1,5 GW farm sizes for both locations. For these farm sizes, an alternative method transporting the produced hydrogen to the following consumer/pipeline will be required. Pipeline transport to the consumer or hydrogen network (possibly in combination with partial storage in tanks) is an option, but is excluded from the scope of this research.

System LCOH for resulting design configurations

Selected alternatives for the water supply and hydrogen outflow system were combined to form a complete design for an off-grid photovoltaic and 6 kW electrolyzer-based hydrogen farm. For these farms, the LCOH was determined and evaluated alongside the design choices of the resulting farm configurations to answer the main research question.

Per location, seven hydrogen farm configurations resulted for which the LCOHs were determined. In addition, a Lang factor - factor by which the estimated and true costs of an industrial plant differ that is mainly due to overhead project costs and technical maturity - was assigned to each subsystem (water supply, PV-electrolyzer and hydrogen outflow) to determine a critical scenario LCOH for sensitivity purpose. The results are recapitulated in Table 70.

Table 70: Reference LCOH and LCOH including critical Lang factors for all selected hydrogen farm configurations.

			Ínsua		Al Buraimi	
Farm size	**Water supply system**	**Hydrogen outflow system**	**LCOH**	**LCOH - critical Lang factors**	**LCOH**	**LCOH - critical Lang factors**
50 MW	Water grid	Collection, compression, tank storage	€ 5,10	€ 7,39	€ 3,76	€ 5,54
50 MW	Water grid	Collection, compression	€ 5,04	€ 7,19	€ 3,69	€ 5,34
150 MW	Waste water	Collection, compression	€ 4,85	€ 6,77	€ 3,52	€ 4,97
1,5 GW	Waste water	Collection, compression	€ 4,93	€ 7,67	€ 3,55	€ 5,65
50 MW	Water grid	Collection	€ 2,99	€ 3,72	€ 2,14	€ 2,68
150 MW	Waste water	Collection	€ 2,91	€ 3,59	€ 2,09	€ 2,58
1,5 GW	Waste water	Collection	€ 3,00	€ 4,01	€ 2,15	€ 2,92

The results show that for farms that do not include compression or storage, the LCOH is on the lower end of the ranges found in literature for PV-electrolysis hydrogen which is between € 4-15/kg hydrogen, and therefore deemed market competitive [11], [35], [55], [56]. In comparison to these ranges, farms that include compression (and storage) perform reasonably considering an LCOH near the midst of these ranges. For all farm configurations, Al Buraimi farms result in lower LCOHs than Ínsua, which is due to the lower costs for the systems in Al Buraimi and due to more running hours for Al Buraimi (larger average ESH used) and thus a larger production quantity.

The lowest and thus most market competitive LCOH is achieved with a system consisting of less system components - including only on-sire hydrogen collection in the hydrogen outflow system - and with smaller farm sizes. The PV-electrolyzer system was identified as the main contributor to the LCOH. This system, in contrary to the water supply and hydrogen outflow system, scales linearly in costs with the farm size. For all farm sizes and locations, both the water supply system and the hydrogen outflow system account for less than 5% of the LCOH. The market-competitiveness of the off (energy) grid photovoltaic and 6 kW electrolyzer-based hydrogen farm thus depends on mainly the electrolyzer cost and secondly on the PV costs.

Despite this, the cost of the 6 kW electrolyzer of €433 - 500 /kW is much lower than cited costs of up to €3.000 /kW in recent studies for centralized PV-electrolysis based hydrogen production farms [11]–[13]. Additionally, the electricity cost for designed farms are either €0,007 or 0,013/kWh (Al Buraimi and Ínsua, respectively). The electricity and energy grid-related cost in the most recent TNO study for PV-electrolysis based hydrogen production amounts to nearly half the LCOH. It can thus be concluded that remaining off energy grid, provides a financial benefit and results in a lower LCOH for small-capacity electrolyzer based production process. The designed farms being off-grid implies limited running hours. This can be mitigated by oversizing PV and/or usage of batteries.

It was found that a smaller farm size is favoured from a practical perspective as well. Due to the novelty of a PV and small-capacity electrolyzer based hydrogen farm, a smaller farm size allows for improved oversight and flexibility for mitigation or trial and error - as advised by experts [18], [24].

The presented research is based on various assumptions and simplifications - as specified in the discussion and Appendix III. These have been partially compensated for by using critical Lang factors that double, triple or quadruple the costs of subsystems. The results show that, both Ínsua and Al Buraimi are suitable locations and 50, 150 MW and 1,5 GW are all farm sizes that can lead to market-competitive LCOHs. The critical advantages of the off-energy-grid PV and 6 kW electrolyzer farms are the low electrolyzer and low electricity costs. The lowest LCOH is realised for the 50 MW farm based utilizing the water grid while operating most running hours tested, and includes on-site hydrogen collection of hydrogen at 46 bar in Al Buraimi.

The performed evaluation shows that there is potential for off-energy-grid PV and small-capacity electrolyzers based hydrogen farms in terms of technical feasibility and a market-competitive LCOH. Utilization of small-capacity electrolyzer connected directly to PV and being disconnected from the energy grid can reduce the LCOH by nearly 80% (€2,92 vs €13,69). Technical feasibility and market competitiveness are highest for the smallest farm size - 50 MW. Market-competitiveness is further improved when running hours of the farm are increased - in Al Buraimi. Implications for future research, including limitations of the presented research, are discussed in the following chapter.

9 Discussion

The conclusion section underlines that the findings of this thesis strongly support the technical feasibility and resulting market-competitiveness of hydrogen produced by an off-energy-grid photovoltaic and small-capacity based electrolyzer production process. This research is a case study for the 6 kW electrolyzer as designed by ZEF. This section discusses the limitations of this research, a reflection on the methodology, and provides recommendations for future research.

9.1 Limitations

This thesis is an initial evaluation of the potential for an off-grid PV and small-capacity electrolyzer based hydrogen production farm and therefore intentionally simplified. The scope, simplifications, and assumptions form the main limitations of this thesis.

Research scope

The scope of this research includes obtaining water, production of hydrogen with 6 kW electrolyzers directly coupled to PV, and a form of hydrogen collection with plausible compression and storage. Compression and storage are not included in the farm design with lowest LCOH. In practice, some cost will arise for the producer to facilitate export of the produced hydrogen from the farm, which will increase the costs and LCOH. This is not accounted for in the presented research.

In addition to that, this research and its scope is project oriented and focuses on the current availability of systems and equipment on the market. For the water supply system, this eliminates upcoming technologies which are not yet available on the market or industrial scale. This constricts the method for water transport to pipeline transport - causing all farms to include a grid-like structure for obtaining water and no longer be fully off grid. Contrarily, without market availability or data provided by suppliers, estimating the systems LCOH is more complex.

Lastly, the scope of this research does not include the cost or size estimation of a battery. The usage of a battery is strongly advised by experts to ensure energy for water supply and hydrogen outflow system i.e. in case water tanks should be filled more to ensure sufficient water for the following day, or during (short) maintenance intermittence, etc. The inclusion of batteries will require direct to alternating current control (DC/AC and AC/DC) on the farm and will have implications on installation, costs, expertise required, etc. and have not been considered in this thesis.

Simplifications and assumptions

There are many simplifications and assumptions used throughout this research (as listed is Appendix III). Using a fixed number of solar panels coupled to an electrolyzer at either location overly simplifies the setup of the farm as well as the LCOH calculations. In reality, the number of solar panels will depend on the solar irrandiance of the farm location. To add to this, oversizing of PV is likely to be implemented on the farms to increase and stabilize energy production. The number of solar panels, depending on the location and including oversizing, is not estimated in this thesis. Inclusion hereof will lead to different costs and LCOHs. Given the time frame of this research, scenarios with different numbers of solar panels were not included when analyzing the sensitivity of the designed farms.

The production of the electrolyzers is simplified in this research as it is based on the average ESH in combination with the average production per ESH. In reality, production will vary as the energy production fluctuates on an hourly, daily and seasonal basis. This influence on the production subsequently influences the LCOH, which is not accounted for in this research. In terms of over and underproduction, intermediate storage of hydrogen in pipelines and emptiness of pipelines is considered - pipelines of the on-site hydrogen collection system allow for a much larger mass flow than the production; up to two days worth of hydrogen considering the average production quantity, as described in section 6. Less production does not impede on the carbon-steel pipeline to collect hydrogen, as verified by experts [18], [24].

The used equipment costs are largely based on an in depth paper on electrolysis-based hydrogen production by Simoes et al., its supporting materials, and are further supported by quotations received by suppliers. Especially for the water supply system, not many recent quotations were found. As a result, equipment costs differ marginally in price between the two farm locations. In reality, the costs to obtain, transport and install the complete systems will differ more between locations. From a practical perspective, both locations have experience with industrial scale water filtration especially with RO and the EDI methods. Expertise in these fields is not a factor that differentiates the locations. Safety and risk mitigation can be of influence. However considering that the water supply system is much less a risk factor than the electrolyzer or hydrogen compression area, these aspects are not likely to indicate preference of location.

The largest simplification and overestimation is that of the water transport pipeline to obtain water at the farms. Only one reliable estimate for a complete pipeline construction was obtained for an underground welded steel pipeline of 10 km. This estimate was used for all farms, even though the diameters of such a pipeline can be smaller for a 50 MW farm, and, distances to water sources or a connection point to their existing network, vary per location.

Lastly, no land costs for the water treatment area and the hydrogen compression area are considered in this research - though these areas will be significantly smaller than the PV-electrolyzer area for which land costs are included in the CAPEX.

9.2 Reflection on methodology

The methodology of determining water supply - and hydrogen outflow system to complete the hydrogen farm has resulted in technical and practically feasible farm designs, and allows for LCOH calculation.

Due to the extensive list of defined functional and non-functional constraints and objectives in the first design step, the design space is quite limited. Expanding the scope of the research to allow for technologies that are not yet available on the market would have allowed for more flexibility in design - i.e., allowing for a plausibly fully off-grid farm design. Because there are a finite number of available technologies and equipment for the defined system functions, testing against requirements other than the functional constraints, in most cases, became obsolete.

A specific aspect of the methodology for selecting the water source of the water supply included qualitative assessment of water sources. The defined criteria and ranking methods are well-adopted and used throughout literature. Though the equal weights for the scoring method was followed as designed by Catarino et al. and used by Simoes et al., the inquiry pertains to whether equal weights should be assigned to them. Climactic effects or social acceptance could for example achieve a higher weight in case local policies aimed at industrial water usage reflect these interests. The assignment of weights to the qualitative criteria should be based on a more in depth evaluation of the importance of the criteria from i.e. a socio-demographic and/or local policy perspective.

Two aspects that the resulting farm designs could have been tested against are system safety and system redundancy. Safety protectives and ISO standards are named, and the subsystem alternatives have been verified to comply with these based on the experience and advice given by experts and suppliers. However, no separate overview is given of the required QRA to be done for every farm, nor has the safety testing procedure been given in this thesis.

System redundancy is assessed for the equipment and infrastructure of the resulting design alternatives i.a., storage tanks, extra holding space in water and hydrogen pipelines, ring pipeline systems, turndown ratio of compressors, etc. Though the water supply - and hydrogen outflow system were designed with an eye on system redundancy, no standard for system redundancy was investigated, set, or used to deem either systems sufficiently redundant.

9.3 Recommendations for future research

This thesis provides an initial evaluation of the potential for an off-grid PV and small-capacity electrolyzer based hydrogen production farm. Based on the results, limitations and reflection of the methodology, several recommendations are made to improve and expand upon this research:

1. *Incorporate fluctuations of solar irradiance.* Modelling or incorporating the fluctuation of solar irradiance to approximate both hydrogen production quantities as well as the number of solar panels required more accurately.
2. *Optimization for oversizing PV.* Possibly in combination with the previous recommendations, optimization of the required PV and the extent to which PV can be oversized for off-energy-grid hydrogen farms that still result in market-competitive LCOHs can be assessed.
3. *Investigate the threshold production quantity.* This study shows that for the smallest assessed farm size, the LCOH can be market-competitive. Investigating the production quantity that is the threshold for a hydrogen production farm can advocate for piloting smaller hydrogen production farms, which can possibly be fully off-grid due to lower volumes of water being required. Similarly, investigating the threshold electrolyzer unit cost (€/kW) can lead to valuable insights for off-energy-grid hydrogen production.
4. *Expand the scope of the research* . Increasing the design flexibility can be done by including novel technologies that are not (yet) available on the market - i.e. AWG. Expansion of the scope can also take form by incorporating the export of produced hydrogen from the farm: pipeline transport, conversion to intermediaries such as methanol, etc.
5. *Expand on qualitative analysis and cost estimation.* Incorporate qualitative assessments for design choices - as mentioned in the reflection of the methodology for selecting water sources. Assign accurate weights to qualitative criteria for design selection. In combination, expansion on the cost estimations will lead to improved accuracy of the LCOH.

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10 Appendices

10.1 Appendix I: Water supply system cost breakdown for all farms

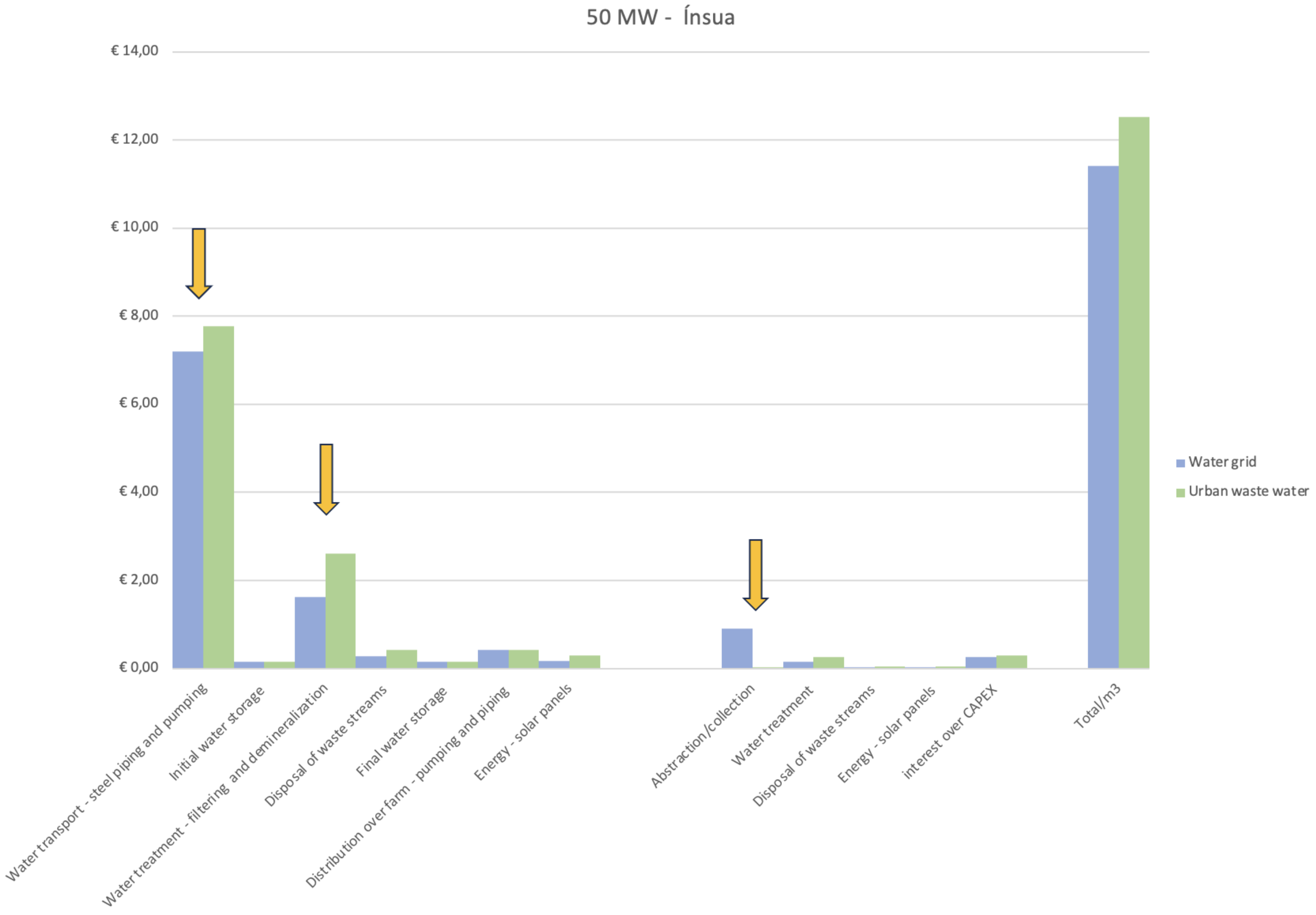


Figure 32: Cost breakdown for the 50 MW farm in Ínsua for water grid and urban waste water

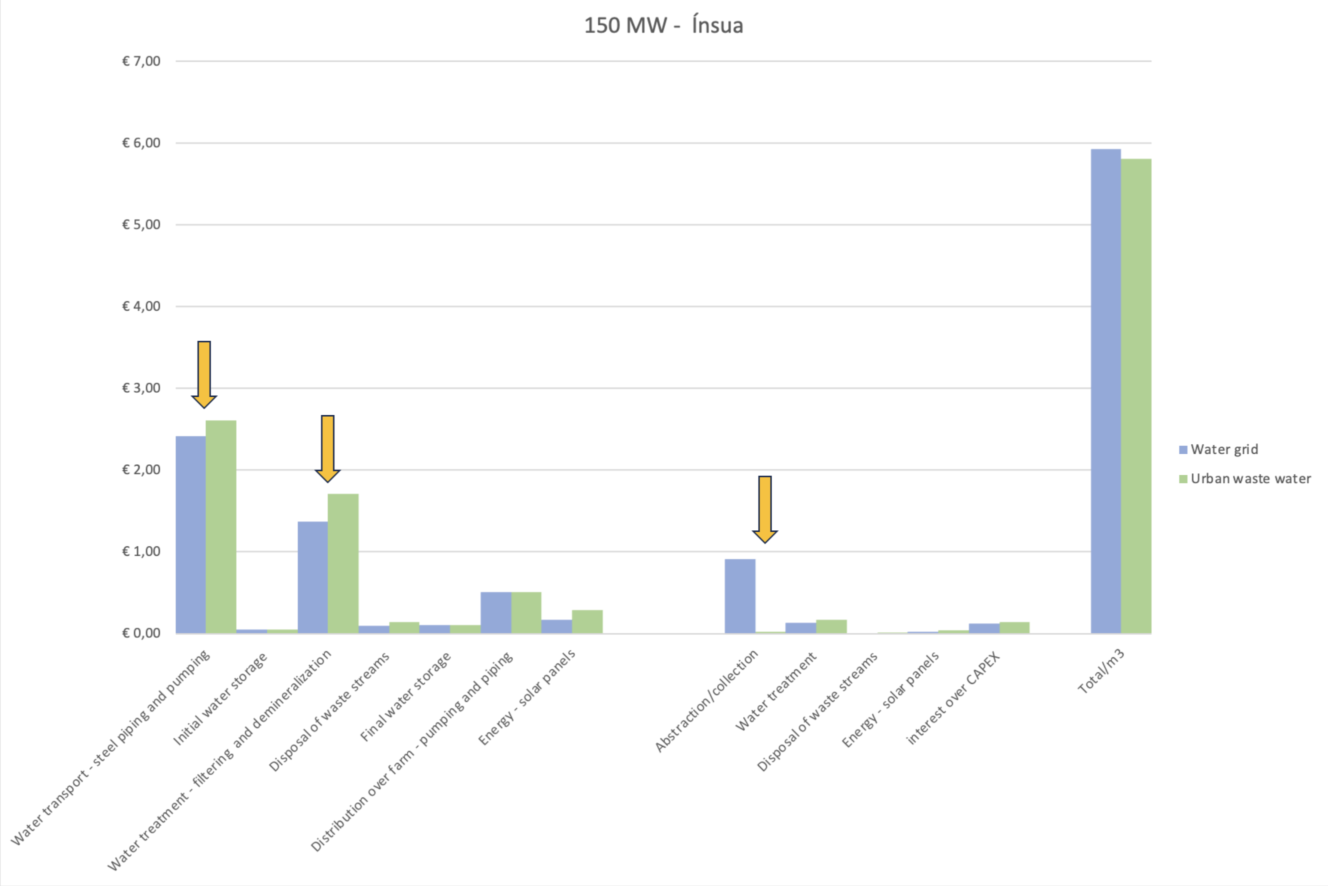


Figure 33: Cost breakdown for the 150 MW farm in Ínsua for water grid and urban waste water

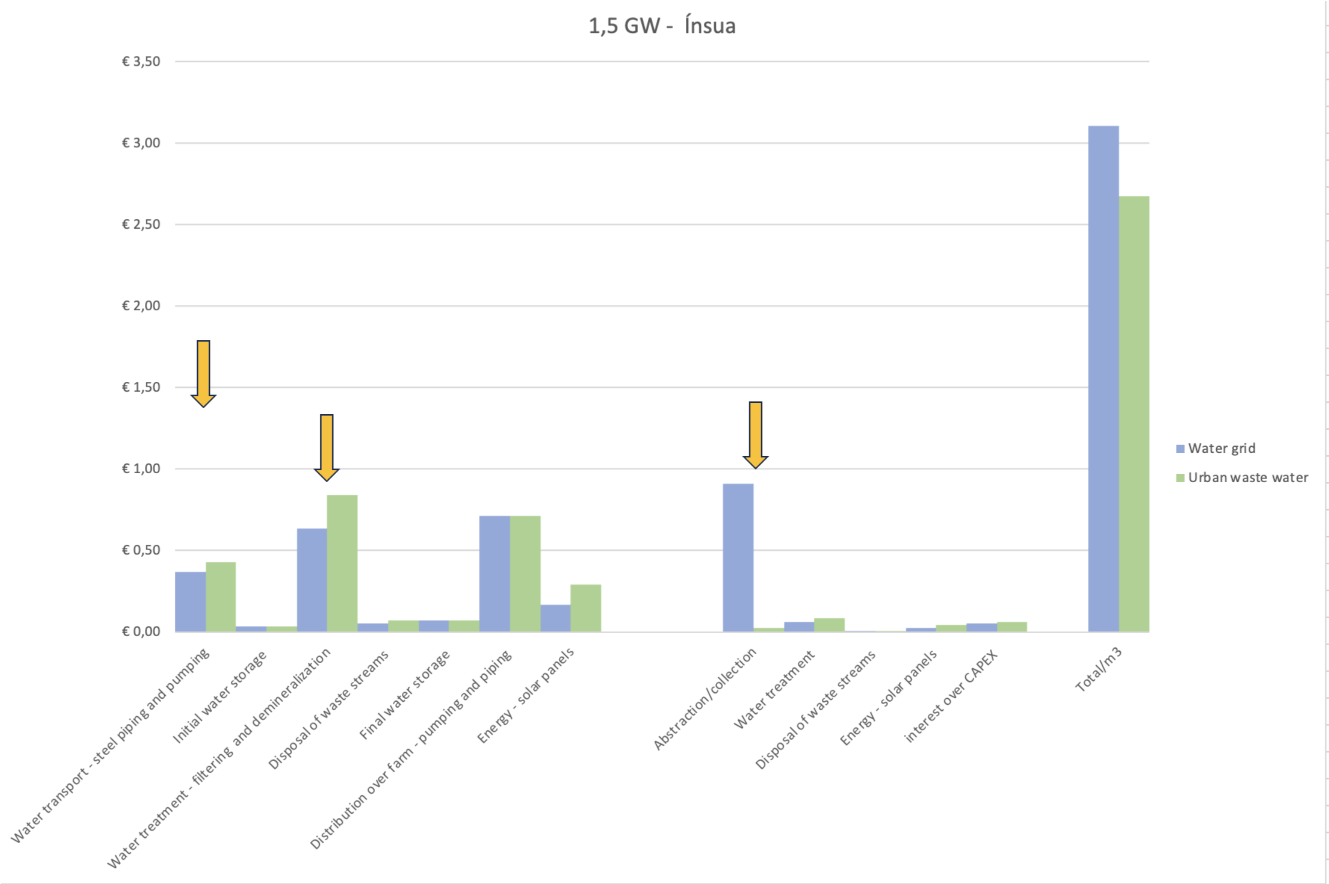


Figure 34: Cost breakdown for the 1,5 GW farm in Ínsua for water grid and urban waste water

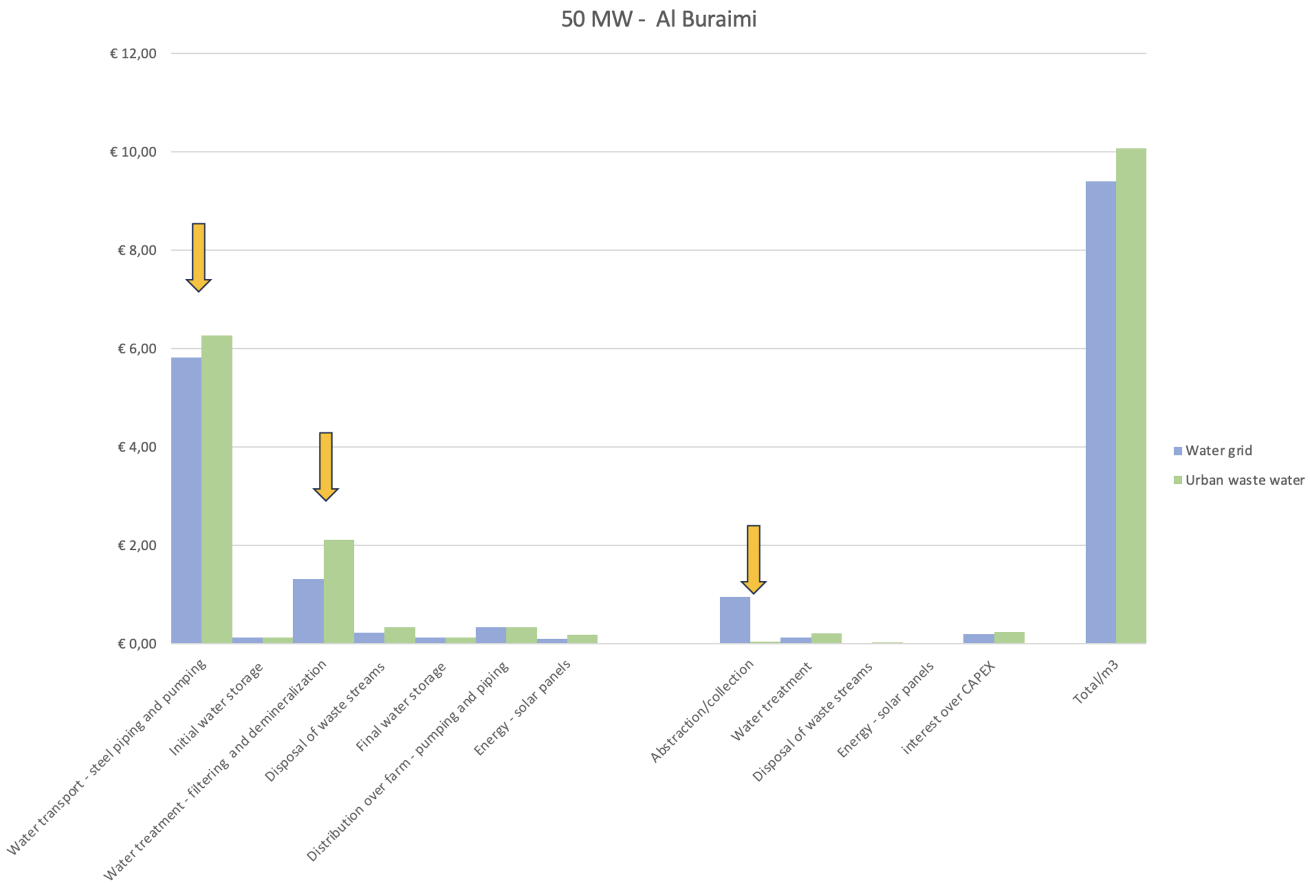


Figure 35: Cost breakdown for the 50 MW farm in Al Buraimi for water grid and urban waste water

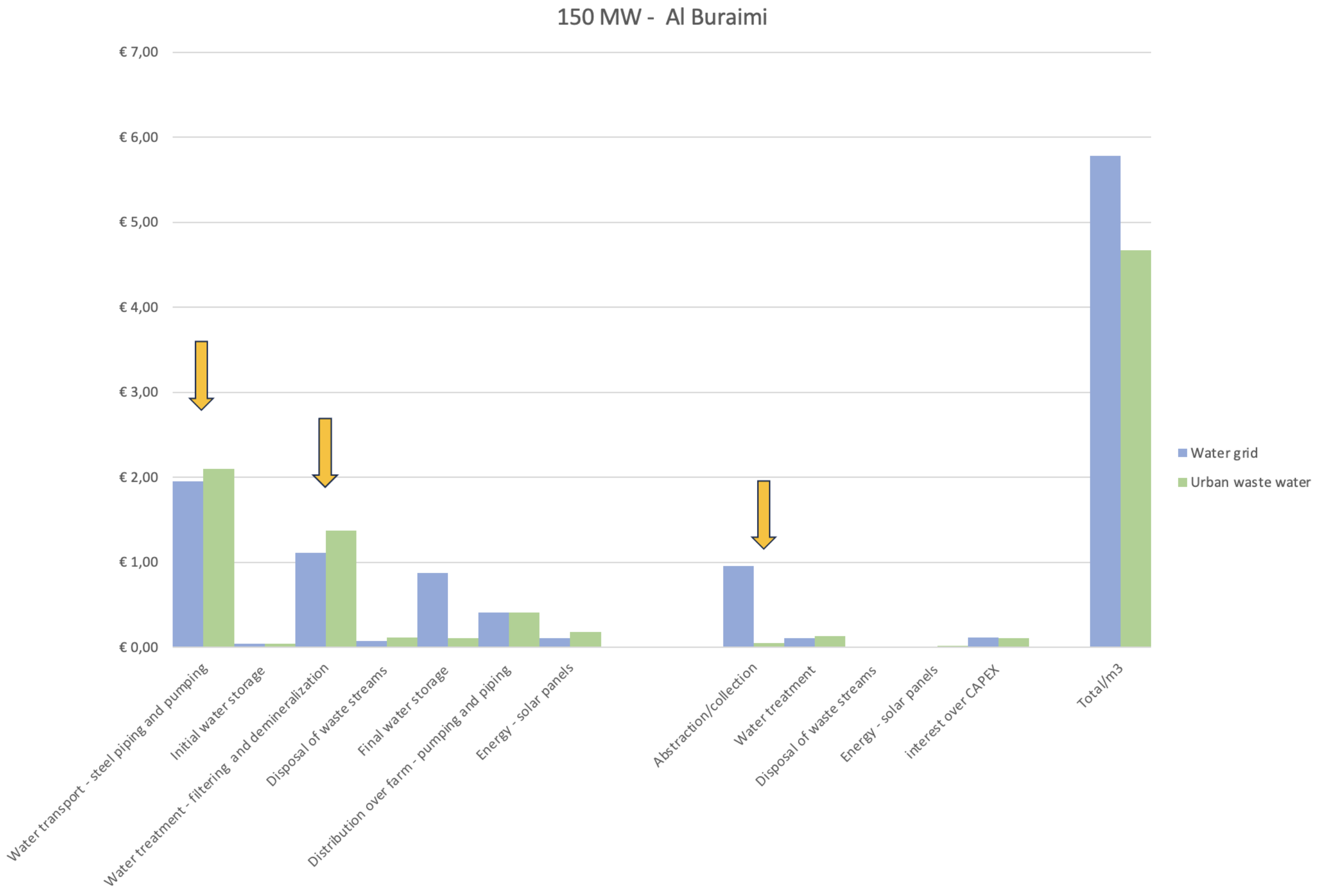


Figure 36: Cost breakdown for the 150 MW farm in Al Buraimi for water grid and urban waste water

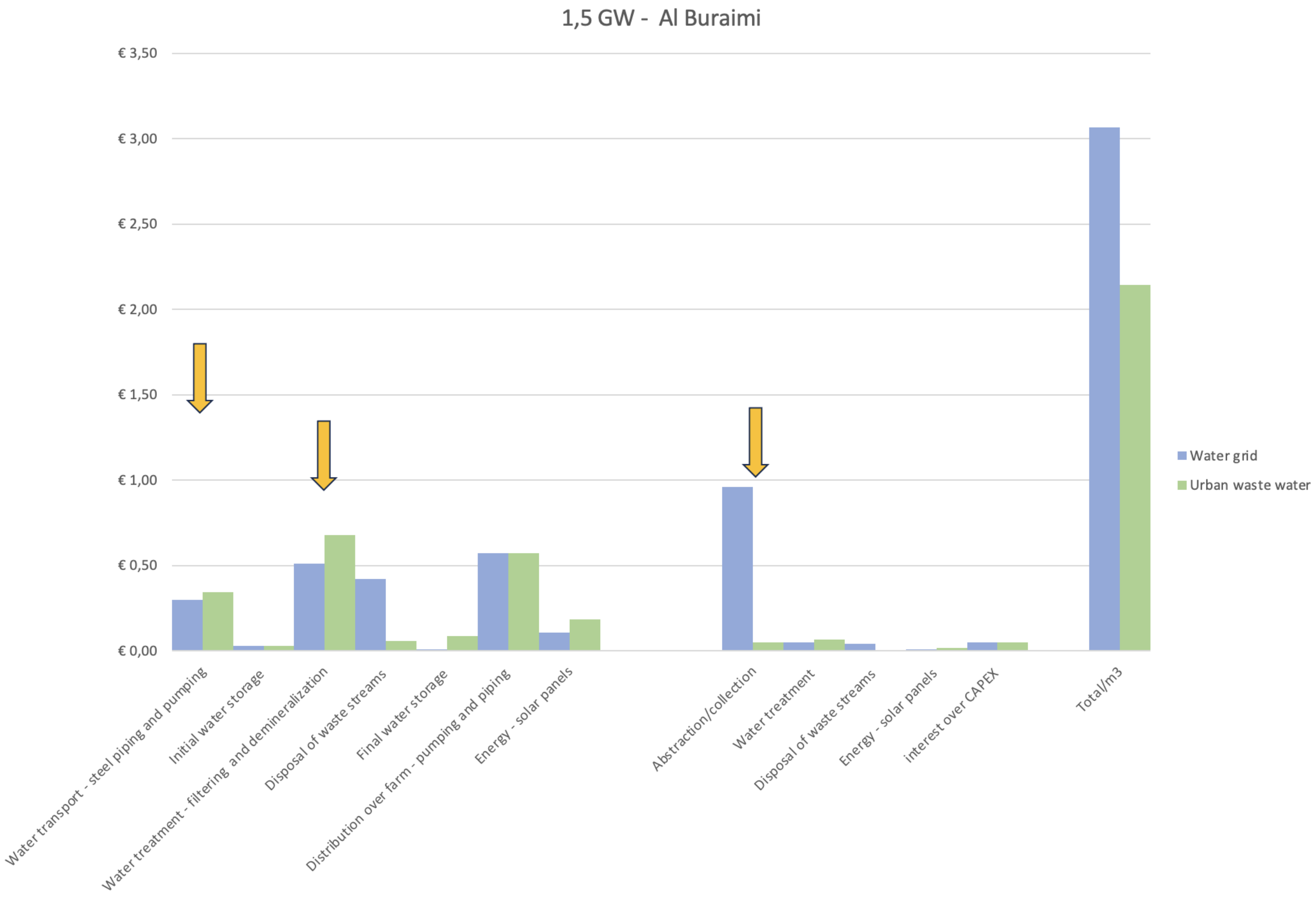
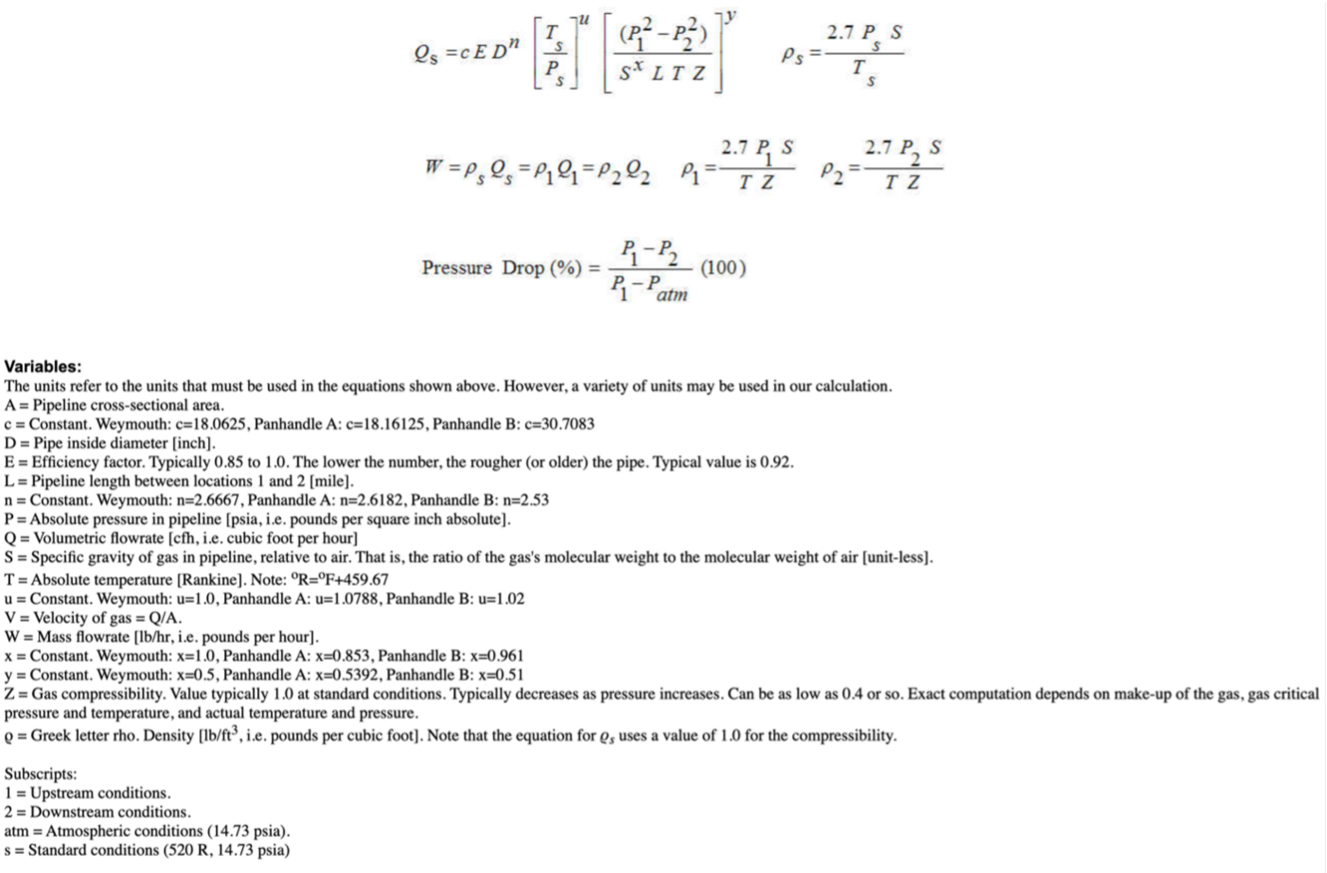


Figure 37: Cost breakdown for the 1,5 GW farm in Al Buraimi for water grid and urban waste water

10.2 Appendix II: Weymouth, Panhandle A, and Panhandle B equations

The LMNO calculator used for determining the pressure loss and mass flow rate for the hydrogen outflow system is based on the following equations:



$$Q_s = c\,E\,D^n \left[\frac{T_s}{P_s}\right]^u \left[\frac{(P_1^2 - P_2^2)}{S^x\,L\,T\,Z}\right]^y \qquad \rho_s = \frac{2.7\,P_s\,S}{T_s}$$

$$W = \rho_s\,Q_s = \rho_1\,Q_1 = \rho_2\,Q_2 \qquad \rho_1 = \frac{2.7\,P_1\,S}{T\,Z} \qquad \rho_2 = \frac{2.7\,P_2\,S}{T\,Z}$$

$$\text{Pressure Drop (\%)} = \frac{P_1 - P_2}{P_1 - P_{atm}}\,(100)$$

Variables:

The units refer to the units that must be used in the equations shown above. However, a variety of units may be used in our calculation.

A = Pipeline cross-sectional area.

c = Constant. Weymouth: c=18.0625, Panhandle A: c=18.16125, Panhandle B: c=30.7083

D = Pipe inside diameter [inch].

E = Efficiency factor. Typically 0.85 to 1.0. The lower the number, the rougher (or older) the pipe. Typical value is 0.92.

L = Pipeline length between locations 1 and 2 [mile].

n = Constant. Weymouth: n=2.6667, Panhandle A: n=2.6182, Panhandle B: n=2.53

P = Absolute pressure in pipeline [psia, i.e. pounds per square inch absolute].

Q = Volumetric flowrate [cfh, i.e. cubic foot per hour]

S = Specific gravity of gas in pipeline, relative to air. That is, the ratio of the gas's molecular weight to the molecular weight of air [unit-less].

T = Absolute temperature [Rankine]. Note: $^oR = {}^oF + 459.67$

u = Constant. Weymouth: u=1.0, Panhandle A: u=1.0788, Panhandle B: u=1.02

V = Velocity of gas = Q/A.

W = Mass flowrate [lb/hr, i.e. pounds per hour].

x = Constant. Weymouth: x=1.0, Panhandle A: x=0.853, Panhandle B: x=0.961

y = Constant. Weymouth: x=0.5, Panhandle A: x=0.5392, Panhandle B: x=0.51

Z = Gas compressibility. Value typically 1.0 at standard conditions. Typically decreases as pressure increases. Can be as low as 0.4 or so. Exact computation depends on make-up of the gas, gas critical pressure and temperature, and actual temperature and pressure.

ρ = Greek letter rho. Density [lb/ft^3, i.e. pounds per cubic foot]. Note that the equation for ρ_s uses a value of 1.0 for the compressibility.

Subscripts:

1 = Upstream conditions.

2 = Downstream conditions.

atm = Atmospheric conditions (14.73 psia).

s = Standard conditions (520 R, 14.73 psia)

Figure 38: Weymouth, Panhandle A, and Panhandle B equations for pressure loss calculations, used in the LMNO calculator

10.3 Appendix III: List of Assumptions

This Appendix provides the full list of assumptions that are used throughout this thesis. They are listed per system or component that they are used for

PV-electrolyzer

Number of solar panels coupled to one electrolyzer is a fixe parameter set at 10. This is equal for both farm locations. Optimization of amount of PV is not included in this research.

- Solar panels of 620 Watt are assumed, for which an effective energy generation of 600 Watt is used
- Oversizing of PV is not considered in this research
- Fluctuations of solar irradiance and subsequent fluctuations in hydrogen production are not considered
- PV-electrolyzer CAPEX provided by ZEF include production, transport, installation, farm land costs and safety testing [12], [13]
- Battery inclusion on the farm is suggested by experts and named in designs, however, size estimations and costs (and/or optimization) are not included in this research
- Lifetime of solar panels is assumed as 30 years
- Lifetime of the electrolyzers is assumed as 10 years, requiring to be replaced twice throughout the farm lifetime set at 30 years
- Electrolyzers produced 0,125 kg of 50 bar hydrogen at 99.5% purity per running hour
- Running hours are equal to the average ESH per location - 5,65 for Ínsua and 7,0 for Al Buraimi
- For interest over CAPEX, it is assumed that 85% is financed through loans with a 3% interest rate. The remaining 15% of the costs are covered by the company's own resources.

Water supply system

- Water usage is not discounted throughout the years
- Only technologies and water sources readily available (on the market) are included
- Optimization of tank sizes is not included
- Weights for qualitative assessment of the water source are taken as equal [16], [17]
- For interest over CAPEX, it is assumed that 85% is financed through loans with a 3% interest rate. The remaining 15% of the costs are covered by the company's own resources.
- For all tank sizes, only one pipeline cost is assumed which is

Hydrogen outflow system

- Hydrogen production is considered continuous as mentioned previously
- The density of hydrogen is used as 3,949 kg/m3 at 50 bar and as 42 kg/m3 at 700 bar [19]
- Full conversion (no partial reactions) is assumed at constant/controlled temperature of 25 °C for hydrogen compression
- For interest over CAPEX, it is assumed that 85% is financed through loans with a 3% interest rate. The remaining 15% of the costs are covered by the company's own resources.

10.4 Appendix IV: Research Paper

Decentralized off-grid PV hydrogen production based on small-capacity electrolyzers

Determining the System LCOH - a case study for 6 kW electrolyzers

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Abstract

Hydrogen is emerging as plausible energy carrier to decrease the global dependency on fossil fuels. Hydrogen production based on renewable energy and electrolysis is a technically mature and well-researched production process. Production processes based on large electrolyzers result in varying and relatively high (between €4/kg and up to ± €14/kg) levelized costs of hydrogen - attributable to high electrolyzer and electricity costs. This research evaluates the potential of an off-energy-grid PV and small-capacity electrolyzer based hydrogen production process. The assessed smaller-capacity electrolyzers result in less than a quarter of most electrolyzer costs (€/kW). The cost reduction combined with the avoided electricity costs due to grid connection, allow for market competitive LCOHs within the range of ± €2,15-5/kg hydrogen depending on the hydrogen outflow system chosen for the farm. This research shows that the low electrolyzer and electricity costs of an off-energy-grid PV and small-capacity electrolyzer based hydrogen farm - with running hours limited to the average sun equivalent hours while including a water supply system (source, treatment, distribution across farms, etc.) and a hydrogen outflow system (collection across farm, possible compression) - has technical feasibility and market potential.

Keywords: Off-grid hydrogen production, PV, small-capacity electrolyzer, LCOH, electrolyzer

1. Introduction

The increasing global energy demand in combination with the depletion of fossil fuels has created a demand for more sustainable energy carriers and hydrogen, is a prospective candidate (Sharma et al., 2023; NWP, 2022). Various production routes are known and upcoming for the production of hydrogen. Hydrogen production through electrolysis - splitting water into hydrogen and oxygen - is one of the most mature technologies. Electrolysis driven by solar or wind energy is predominantly used by industrial scale hydrogen producers, which have farms operating large electrolyzers ranging from 10-200 MW in daily production capacity (Amrani et al., 2023; Shin et al., 2023; Nasser and Hassan, 2023; Eblé and Weeda, 2023; Jochen et al., 2024).

The resulting Levelized Cost of Hydrogen (LCOH) determined for such projects in techno-economic evaluations and project reports, vary from €4 to €15 per kg of hydrogen produced based on solar energy specifically (Amrani et al., 2023; Shin et al., 2023; Nasser and Hassan, 2023; Eblé and Weeda, 2023). Minimization of the LCOH is sought after in to bring it within market-competitive range. The main cost contributor to the LCOH throiughout literature, is the electrolyzer cost - ranging from €1000-3050/kW - and the LCOE - the Levelized Cost of Eletricity - which can make up to half of the LCOH (Shin et al., 2023; Eblé and Weeda, 2023). Anticipated decreases in electrolyzer cost due to technical advancement is not expected to lead to a sufficient decrease in LCOH (Eblé and Weeda, 2023).

A novel, small-capacity electrolyzer, specifically a 6 kW alkaline electrolyzer by Zero Emission Fuels (ZEF), is estimated to cost between €400-500/kW (while producing hydrogen at 50 bar of 99.5% purity). The designed electrolyzers allow for direct coupling to photovoltaic (PV) panels, thereby allowing to operate off of the energy grid and reducing the LCOE. This research aims to evaluate the potential of a PV off-energy-grid hydrogen farm based on small-capacity electrolyzers, as it is currently unexplored throughout literature and project reports.

1.1. Scope

This research evaluates the potential of hydrogen farms based on PV and small-capacity electrolyzers without connection to the energy grid, in terms of technical feasibility and market-competitiveness of the resulting LCOH. The scope of this research includes the design of a water supply system and hydrogen outflow system to complete the hydrogen farm, in order to determine the LCOH. Therefore the first system boundary is set at the water source. Three end-of-line hydrogen configurations are taken as final system boundary: centrally collected hydrogen on the farm; centrally collected and compressed hydrogen on the farm; and centrally collected, compressed and stored hydrogen on the farm. Compression to 700 bar is considered throughout this research. Two possible farm locations and three plausible farm sizes are assessed: Ínsua, Portugal and Al Buraimi, Oman; and 50 MW, 150 MW and 1,5 GW farm sizes.

As an initial evaluation for the potential of a PV off-grid small-capacity electrolyzer based farm, simplifications were made in terms of average production (0,125 kg of 50 bar hydrogen per ESH per electrolyzer), running hours (ESH of location) and PV required (10 solar panels per electrolyzer). These simplifications are based on previous research of the ZEF electrolyzer.

1.2. Research question

The following research question and sub questions are posed in order to complete the hydrogen production process, to evaluate the technical feasibility and market-competitiveness:

*What system **size** and **geographical location requirements** are necessary to achieve a **market-competitive** Levelized Cost of Hydrogen for an off-grid, photovoltaic and 6 kW electrolyzer hydrogen production process?*

1. What are the alternatives for a water supply system for a decentralized electrolysis-PV hydrogen production farm, considering different farm sizes and locations?
2. What are the challenges and alternatives for the hydrogen outflow system for a decentralized electrolysis-PV hydrogen production farm, considering different farm sizes and locations?
3. What is the LCOH of an off-grid photovoltaic 6 kW hydrogen production farm considering the possible configurations of water supply system and hydrogen outflow system for different farm sizes and locations?

2. Methodology

To complete the hydrogen farm with a water supply and hydrogen outflow system, the Delft Design Guide was used to formulate the design and evaluation steps for each system. An overview of the methodology is given below in Figure 1.

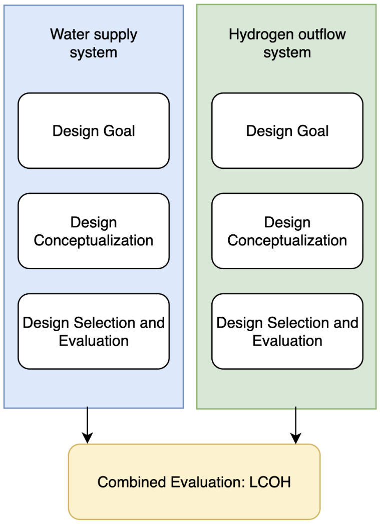


Figure 1: Overview of the methodology

2.1. Design Goal

In the first step of the design process, the system is described, subsystems are defined and functional and non-functional constraints and objectives are posed. Functional constraints and objectives reflect what the system must or preferably should do, non-functional constraints and objectives reflect what the system must or preferably should have. These constraints and objectives are used for design selection and evaluation.

2.2. Design Conceptualization

In design conceptualization, means for the defined subsystems are found that comply with the functional constraints. The means are found through literature review, project reports and expert interviews. The technical feasibility of the means is thereby guaranteed. Dimensioning of the means for the various farm sizes as well as obtaining reliable cost estimates is done in this design step as well. Sets of means for all subsystems result in different design alternatives of the water supply or hydrogen outflow system.

2.3. Design Selection and Evaluation

Design alternatives are selected based on non-functional constraints, and functional - and non-functional objectives as well as they are based on expert opinions. Technical performance is tested. The best performing design alternatives based on location and farm size are selected as final system design alternatives.

2.4. Combined Evaluation: LCOH

Resulting water supply system designs and hydrogen outflow system designs are combined so that the LCOH of complete hydrogen farm designs can be calculated according to:

$$LCOH = \frac{I + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1+i)^t}} \tag{1}$$

Where:

- I - Initial investment for the system in €

  These costs entail the capital expenditures (CAPEX) of PV and electrolyzers - including balance of pant (BoP), land cost, transport, installation - and water supply system (pipelines, pumping, water treatment equipment, etc.) and hydrogen outflow system (pipelines, compressors, storage).

- A_t - Annual costs in year t in €.

  These costs consist of the operational expenditures (OPEX) for PV, electrolyzers, water supply system and hydrogen outflow system. Variable costs of the water supply system cover water costs, maintenance for subsystems and waste streams, and interest over CAPEX, and water costs (location and source dependent). For the hydrogen system this includes maintenance and interest over CAPEX as well. For interest over CAPEX, it is assumed that 85% is covered through loans with a 3% interest rate.

- H_t - Hydrogen production of year t in kg.

  As hydrogen density is pressure dependent, the production differs based on the pressure of the end-product. The hydrogen production is discounted, implying that the production decreases every year.

- i - Discount rate in % (taken as 5 % for all farms)

- n - System lifetime in years.

  The system lifetime is taken as 30 years for all the scenarios as it is the standard lifetime for PV. The designed electrolyzers by ZEF have a lifetime of 10 years and will be replaced twice throughout the farm lifetime.

- t - Time in years

Data validation and verification take place at this stage as well.

3. Water supply system design

The water supply system must supply all electrolyzers dispersed across the farm with the amount and quality of water. Prior to the system design, the number of electrolyzers and water required was defined for all farm sizes. This estimation is based on an average hourly production rate per electrolyzer and an average number of running hours per location. The number of running hours corresponds to the average daily equivalent sun hours (ESH) found for both farm locations, which is 5,65 for Ínsua and 7,0 for Al Buraimi.

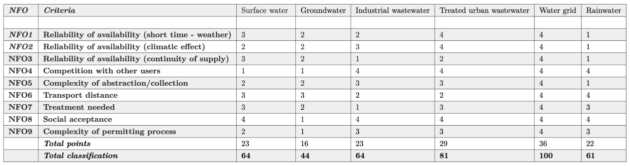
To define the design requirements, the functional- and non-functional constraints and objectives, the water supply system is categorized into subsystems. The full list requirements can be found in Appendix A. Per section, the key requirements, plausible and best performing means of the subsystem are presented. The defined subsystems for the water supply system are:

- Water source
- Water purity and pressure
- Water quantity
- Infrastructure
- Energy
- Transportation

3.1. Water source

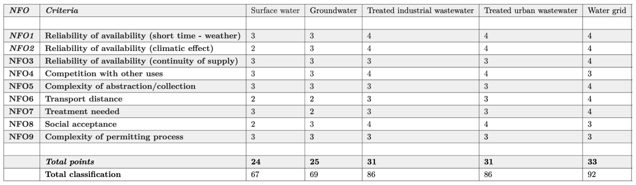
Mainly qualitative requirements are formulated for the water source. Ideally, the water source can provide sufficient water from a short (as short as possible) distance to the farm, preferably available on-site so that the farm can remain off-grid. Social acceptance and interference or competition with other local and/or industrial users is considered as well. For Ínsua, the available water sources are surface water, groundwater, industrial wastewater, urban wastewater, water grid and rainwater (Council, 2012; do Rosário de Jesus, 2015; Waterbase - UWWTD: Urban Waste Water Treatment Directive, 2022). Less water sources are available for Al Buraimi: surface and groundwater, treated industrial and urban wastewater, and water grid (Zidi et al., 2020, 2017; Al-Awadhi and Mansour, 2015; Khaliq et al., 2017; NAMA, 2021).

The available sources are evaluated based on the qualitative criteria utilizing performance indicators identified by Catarino et al. (Catarino et al., 2011). Results are posed in Figure 2 and Figure 3. They show that for both locations, water grid performs best, with urban wastewater following for Ínsua and urban and industrial wastewater following for Al Buraimi - which can be retrieved from the same waste water treatment plant (WWTP). Thus water grid and urban wastewater are taken for further design steps for Ínsua and water grid and treated urban and industrial wastewater are considered for Al Buraimi.



NFO	*Criteria*	Surface water	Groundwater	Industrial wastewater	Treated urban wastewater	Water grid	Rainwater
NFO1	Reliability of availability (short time - weather)	3	2	2	4	4	1
NFO2	Reliability of availability (climatic effect)	2	2	3	4	4	1
NFO3	Reliability of availability (continuity of supply)	3	2	1	2	4	1
NFO4	Competition with other users	1	1	4	4	4	4
NFO5	Complexity of abstraction/collection	2	2	3	3	4	1
NFO6	Transport distance	3	3	2	2	4	4
NFO7	Treatment needed	3	2	1	3	4	3
NFO8	Social acceptance	4	1	4	4	4	4
NFO9	Complexity of permitting process	2	1	3	3	4	3
	Total points	23	16	23	29	36	22
	Total classification	**64**	**44**	**64**	**81**	**100**	**61**

Figure 2: Qualitative assessment for water sources available for industrial usage in Ínsua



NFO	*Criteria*	Surface water	Groundwater	Treated industrial wastewater	Treated urban wastewater	Water grid
NFO1	Reliability of availability (short time - weather)	3	3	4	4	4
NFO2	Reliability of availability (climatic effect)	2	3	4	4	4
NFO3	Reliability of availability (continuity of supply)	3	3	3	3	4
NFO4	Competition with other uses	3	3	4	4	3
NFO5	Complexity of abstraction/collection	3	3	3	3	4
NFO6	Transport distance	2	2	3	3	4
NFO7	Treatment needed	3	2	3	3	4
NFO8	Social acceptance	2	3	4	4	3
NFO9	Complexity of permitting process	3	3	3	3	3
	Total points	**24**	**25**	**31**	**31**	**33**
	Total classification	67	69	86	86	92

Figure 3: Qualitative assessment for water sources available for industrial usage in Al Buraimi

3.2. Water purity and pressure

The alkaline electrolyzer requires demineralized to minimize the interference of metals or ions of the water with metals or ions in of the electrolyzer and alkaline medium (van Kranendonk and Vroegindeweij, 2023). To obtain demineralized water, demineralization must be included as water treatment step in the water supply system. The main requirements for the method of demineralization are maintainable equipment for a lifetime of 30 years, minimal energy usage, market availability, minimal waste stream production and minimal equipment components. Based on literature on demineralization processes used for electrolysis and expert input, electrodeionization (EDI) in combination with a mixed bed filter is selected as demineralization method (Khan et al., 2023; Madsen, 2022).

Prior to demineralization, water filtration of physical and chemical components is required for water from WWTPS and the water grid. Water grid for both locations requires removal of chemical components, for which reverse osmosis is most suitable (Council, 2012; Al-Awadhi and Mansour, 2015). Ínsua's urban wastewater requires fine screening and ultrafiltration in addition to reverse osmosis, as is entails larger solid components (Waterbase - UWWTD: Urban Waste Water Treatment Directive, 2022). For Al Buraimi, ultrafiltration and reverse osmosis is sufficient treatment prior to demineralization (NAMA, 2021).

Regarding water pressure, the electrolyzer requires the in-feed water to be between 1 and 5 bar, which is ensured through the pipeline infrastructure defined in following sections.

3.3. Water quantity

The amount of water required for the farm is based on the hourly usage per electrolyzer, in combination with a safety margin of 20%. Furthermore, the leakages that unavoidably arise from processing in the water treatment. Leakage percentages have been incorporated as found in literature (Khan et al., 2023; Madsen, 2022; Simoes et al., 2021). The amounts of water determined for each farm size and location are presented in Appendix B.

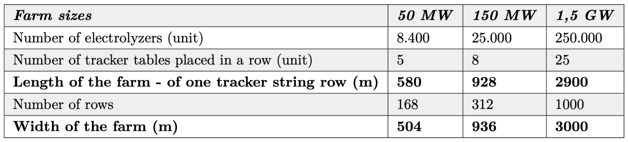
3.4. Infrastructure

All mentioned systems require equipment and supporting infrastructure. Aside of the water treatment equipment, the farm is designed to have an initial water storage tank prior to treatment. This tank is a buffer to account for interference prior to acquiring water at the farm. The required volume is dependent on the method of transportation of water to the farm. Another water tank, subsequent to the water treatment system is included in the design as well: so that there is a storage buffer for demineralized water. This tank is required to hold up to a days worth of water - for safety and redundancy purposes or interference that can happen in the treatment process, etc.

Regarding water delivery to the dispersed electrolyzers, PVC pipelines were deemed best suitable for all farm sizes by experts, especially considering the farm sizes, material costs and pressure range (Kanaar, 2024). The required diameters for a PVC pipeline system and maximal pressure are investigated by i) assuming the farm layouts based on minimal distance between PV-electrolyzers systems - which are solar panel tracker systems with their own distance requirements, ii) dividing the farms in rows of solar panel tracker strings where all strings support a set number of electrolyzers, iii) determine the mass flow rate required per row set - the amount of water required per row and assessing what diameter size of PVC pipeline allows such a rate, iv) determine the pressure loss across the length of the PVC pipeline of a specific diameter (Kanaar, 2024). It should be noted that alongside pipelines for each row set, two overarching pipelines are included in the design to allow for a ring-system, increasing its redundancy.

The determined farm sized are depicted below.

The flow rates per row set an be found alongside the overall water quantities in Appendix B. The maximal found pressure loss for the 50 MW farm is 5,2 bar. For the 150 MW farm this is 7,4 bar and for the 1,5 GW this is 10,8 bar when using minimal diameter size pipelines per row set. The maximal pressure that can be help by PVC pipes is 16 bar (Kanaar, 2024). The maximal pressure drop falling within this pressure holding range, no intermediate pumping is required throughout the farm.

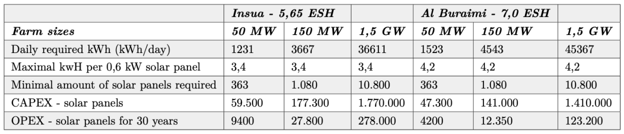


Farm sizes	***50 MW***	***150 MW***	***1,5 GW***
Number of electrolyzers (unit)	8.400	25.000	250.000
Number of tracker tables placed in a row (unit)	5	8	25
Length of the farm - of one tracker string row (m)	**580**	**928**	**2900**
Number of rows	168	312	1000
Width of the farm (m)	**504**	**936**	**3000**

Figure 4: Farm lengths and widths for all farm sizes for both locations

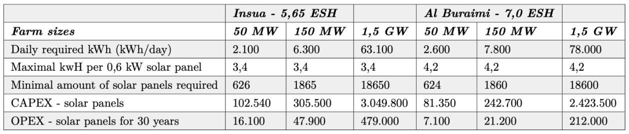
3.5. Energy

To supply the water supply system with energy on an off-energy-grid farm, additional PV is selected as energy source. Energy requirements of all water treatment equipment and expert input is used as basis to calculate the number of additional solar panels required on the hydrogen farm (Khan et al., 2023; Madsen, 2022; Simoes et al., 2021; Kanaar, 2024). Based on the PV cost given by ZEF - which include transport, land costs, installation, etc. Depending on the water source and thus required treatment on the farm and based on 600 Watt assumed as effective energy produced per ESH alongside the average ESH per farm location, the following results are derived:



	Insua - 5,65 ESH			***Al Buraimi - 7,0 ESH***		
Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
Daily required kWh (kWh/day)	1231	3667	36611	1523	4543	45367
Maximal kwH per 0,6 kW solar panel	3,4	3,4	3,4	4,2	4,2	4,2
Minimal amount of solar panels required	363	1.080	10.800	363	1.080	10.800
CAPEX - solar panels	59.500	177.300	1.770.000	47.300	141.000	1.410.000
OPEX - solar panels for 30 years	9400	27.800	278.000	4200	12.350	123.200

Figure 5: PV required and corresponding CAPEX and OPEX - Water grid as water source



	Insua - 5,65 ESH			***Al Buraimi - 7,0 ESH***		
Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
Daily required kWh (kWh/day)	2.100	6.300	63.100	2.600	7.800	78.000
Maximal kwH per 0,6 kW solar panel	3,4	3,4	3,4	4,2	4,2	4,2
Minimal amount of solar panels required	626	1865	18650	624	1860	18600
CAPEX - solar panels	102.540	305.500	3.049.800	81.350	242.700	2.423.500
OPEX - solar panels for 30 years	16.100	47.900	479.000	7.100	21.200	212.000

Figure 6: PV required and corresponding CAPEX and OPEX - Water from WWTPs as water source

A battery is suggested by experts as safety measure - earlier operations possible for water treatment, covering for maintenance of other interference, etc. - however - defining the battery size and its evaluation is this not included in the scope of this research.

3.6. Transportation

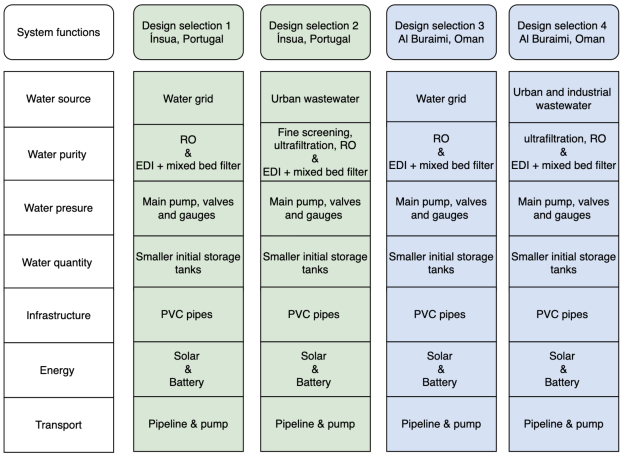
Transportation is needed to acquire water at the hydrogen farm. Ideally the transportation method is flexible, minimal in costs, available on the market and logistically feasible. The two possible means are truck or pipeline transport for the selected water sources. The water quantity for even the smallest farm size of 50 WM eliminates the possibility of truck transport as this would be logistically exhaustive to achieve, and impossible for the larger farm sizes. Pipeline transport connects the farm to a grid-like structure: the farm is no longer fully off-grid. As it is the only appropriate method for transporting the required volumes of water to the farm from either water source in either farm location, it is selected as only transportation method.

Cost estimations for a water pipeline are challenging to acquire. The estimates used are based on a 50 cm diameter pipeline of 10 km for every farm size and location, as it is the only estimate found (Simoes et al., 2021). These were originally made for a 175 MW farm size. The pipeline diameter does allow the required volume of water for the 1,5 GW farm size with additional pumping (Wiersma, 2024). For the 50 MW farm size, this cost and pipeline is an overestimation, especially considering the distance of 10 km taken for the pipelines cost.

3.7. Selected design alternatives

The resulting overall cost estimates per farm are given in Appendix C. The majority of the costs are attributed to the water transport and water treatment plant. The pipeline for water transport taken as equal for all farm sizes poses a disadvantage for the smaller farm size. Moreover, water treatment equipment can provide benefits in terms of economies of scale. The equipment scales less than linearly when the farm size increases, which poses an advantage for the larger farm sizes.

The cost of water (€/m3) from the grid is higher than that of water from the WWTPs in either location. It can be seen that for the two larger farm sizes, a lower water costs outweighs the higher water treatment costs required for filtering. For the smaller farm sizes, due to the water treatment costs being spread over a lower amount of water, it is beneficial from a cost perspective to use water dependent from the grid. As the previous design steps ensure technical feasibility, the water sources are selected for the different farm sizes and locations based on the determined costs. The four water supply systems that result from this analysis - are shown in Figure 7.



System functions	Design selection 1 Ínsua, Portugal	Design selection 2 Ínsua, Portugal	Design selection 3 Al Buraimi, Oman	Design selection 4 Al Buraimi, Oman
Water source	Water grid	Urban wastewater	Water grid	Urban and industrial wastewater
Water purity	RO & EDI + mixed bed filter	Fine screening, ultrafiltration, RO & EDI + mixed bed filter	RO & EDI + mixed bed filter	ultrafiltration, RO & EDI + mixed bed filter
Water presure	Main pump, valves and gauges	Main pump, valves and gauges	Main pump, valves and gauges	Main pump, valves and gauges
Water quantity	Smaller initial storage tanks	Smaller initial storage tanks	Smaller initial storage tanks	Smaller initial storage tanks
Infrastructure	PVC pipes	PVC pipes	PVC pipes	PVC pipes
Energy	Solar & Battery	Solar & Battery	Solar & Battery	Solar & Battery
Transport	Pipeline & pump	Pipeline & pump	Pipeline & pump	Pipeline & pump

Figure 7: Overview of the resulting water supply system design alternatives. Design option 1 and 3 hold for 50 MW farms and design option 2 and 4 hold for 150 MW and 1,5 GW farm sizes for both locations.

4. Hydrogen outflow system design

The hydrogen outflow system must provide a system which collects the produced hydrogen from each electrolyzer, includes an option for compression of the hydrogen to 700 bar and includes an option for centralized storage of 700 bar hydrogen on the farm. The following sections the key requirements of the subsystems are presented as well as the available and selected means. The full list of requirements can be found in Appendix D. The following subsystems have been formulated for the hydrogen outflow system:

- On-site hydrogen collection
- Hydrogen compression
- Compressed hydrogen storage

4.1. On-site hydrogen collection

Hydrogen produced by electrolyzers is to be collected to a central point on the farm which is to be done using a pipeline system. The key requirements for such a pipeline system are safety, ability to hold 50 bar hydrogen, 30 year lifetime, redundancy, minimal costs, etc. Literature and expert input has resulted in a welded carbon-steel pipeline being most suitable for the on-site collection of hydrogen (Reuderink, 2024; Wildenberg, 2024). It is the only material that can hold 50 bar hydrogen while complying to ISO safety standards for hydrogen transport (the International Organization for Standardization, 2020, 2019).

As hydrogen is produced at 50 bar and dispersed across the farm, this pressure can be used to drive the hydrogen to the collection point by setting the pressure lower at this point - hydrogen flows from high to low pressure (Wild and Davis, 2023). At the same time, the pressure loss is to be minimized in case compression to 700 bar is done after collection. On the other hand, the cost of the pipeline is ideally minimized, implying that minimal diameter sizes are used for hydrogen transport. However, minimal diameter sizes causes relatively more interaction and friction and thus a higher loss of pressure of the hydrogen.

To estimate the pressure loss while using minimal diameter size pipelines, first the production of hydrogen is quantified in the same row and tracker system (defined as column) as done for the water supply system. The quantities are posed in Figure 8.

Farm sizes	***50 MW***	***150 MW***	***1,5 GW***
Number of electrolyzer microplants (unit)	8334	25000	250000
Units per column	50	80	250
Rows per farm	167	313	1000
Q - production per column (kg/hour)	6,3	10,08	31,5
Q - total farm production (kg/hour)	1052	3155	31500
Farm length (km) - column pipeline	0,58	0,93	2,9
Farm width (km) – row pipeline	0,5	0,94	3

Figure 8: Hydrogen production quantities per farm size for both locations on an hourly basis

Pipeline diameters were tested for the mass flow rate they allow while maintaining a minimal flow rate between 2 and 10 m/s, at a maximal pressure loss of 4 to 5 bar. The Weymouth, Panhandle A, and Panhandle B equations are used through the LMNO calculator for compressible gas (Edwards, 2012). All minimal pipelines allowed for minimal pressure losses while allowing for a much higher (in most cases up to at least 5 times as much of a) mass flow rate than produced by the electrolyzers. The resulting diameter sizes and final pressures are given in Figure 9 (Cloos, 2024; Reuderink, 2024).

Farm size	***50 MW***	***150 MW***	***1,5 GW***
Column pipeline length (km)	0,58	0,93	2,9
Column pipeline diameter (mm)	20	20	50
Row pipeline length (km)	0,5	0,94	3
Row pipeline diameter (mm)	50	80	200
Final pressure (bar)	46	46	45

Figure 9: Pipeline lengths and sizes for all farms and the final pressure of hydrogen prior to compression.

As advised by experts, the costs are approximated based on carbon steel prices per kg by Pipedata (Cloos, 2024; Reuderink, 2024; Pipedata, 2024). The base cost is multiplied by a factor 2 for production and 1,5 for transport (Reuderink, 2024; Cloos, 2024). The column pipeline is acquired twice to result in a ring pipeline system which increases the redundancy and offers additional intermediate storage for produced hydrogen.

4.2. Hydrogen compression

As 700 bar compressed hydrogen is a system boundary, the hydrogen compression subsystem must be able to compress the collected hydrogen to (up to) 700 bar. The key requirements are once again safety, market availability, minimal energy usage, flexibility in operations, etc. The flexibility in operations is key as in reality, the production is not an hourly average but will fluctuate with the solar irradiance of the location. Compressors available on the market for compressing hydrogen to up to 700 bar are centrifugal, piston, diaphragm and ionic liquid compressors (Sdanghi et al., 2020, 2019).

As advised by experts at Siemens Energy B.V., piston compressors are most advanced on the market, least costly in terms of investment, and require minimal maintenance. Piston compressors have a complete turndown ratio, meaning that they can be operate at any flow between 0% (temporarily switched off) to 99% and thus handle fluctuating production quantities (Okhuijsen, 2024). Two compressors are required at a minimum, depending on the farm size - each compressor to increase the pressure by a factor 2, 5 or 10 (Okhuijsen, 2024).

The energy required for the compression system and additional PV required for its supply is given below in Figure 10.

	Insua - 5,65 ESH			***Al Buraimi - 7,0 ESH***		
Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
Total daily production (kg/day) 50 bar	5.920	17.750	177.500	7.350	22.000	220.000
Daily required kWh (5 kWh/kg)	29600	88750	887500	36750	110000	1100000
Maximal kwH per 0,6 kW solar panel	3,39	3,39	3,39	4,2	4,2	4,2
Minimal amount of solar panels required	8732	26180	261799	8750	26190	261905

Figure 10: Minimal amount of solar panels required to support compressors per farm size, based on 0,6 kW solar panels, average ESH and estimated energy usage of 5 kWh/kg hydrogen

4.3. Hydrogen storage

The key requirements for hydrogen storage are that it must be done according to safety standards, in a transportable manner that ideally can respond to fluctuation in production quantities. The only means to this end that is currently available on the market is a type IV hydrogen cylinder tank - types I, II and III can not hold the 700 bar pressure (Reuderink, 2024; Cendejas; Langmi et al., 2022).

The number of required tanks of 994 L - which is the largest size tank available on the market - is estimated using the ideal gas law, assuming constant temperature (at 25 degrees Celsius as advised (Reuderink, 2024)) and full conversion. Results are given in Figure 11.

	Insua - 5,65 ESH			Al Buraimi - 7,0 ESH		
Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
Electrolyzers (units)	8.400	25.000	250.000	8.400	25.000	250.000
Total daily production (kg/day) 50 bar	5.920	17.750	177.500	7.350	22.000	220.000
Total daily production (m3/day) 50 bar	1.499	4.495	44.948	1.861	5.571	55.710
Total daily production (L/day) 50 bar	1.499.114	4.494.809	44.948.088	1.861.231	5.571.031	55.710.306
Total daily production (L/day) 700 bar	107.000	321.000	3.211.000	132.000	398.000	4.000.000
Daily number of 994 L tanks required	108	323	3230	133	400	4024
Hourly number of 994 L tanks required	19	57	572	19	57	575

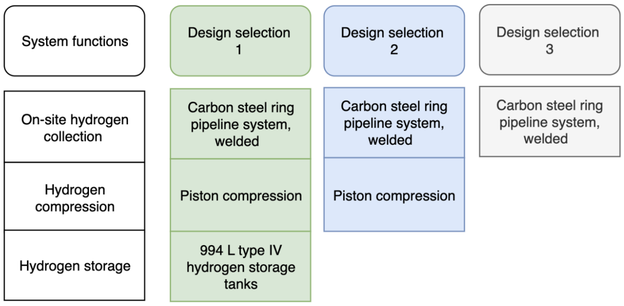
Figure 11: Daily production quantities for all farm sizes in both locations determined with the average ESH, assuming complete compression (100% conversion) and the ideal gas law at a constant temperature of 25 C, required number of 994 L storage tanks are given for a daily and hourly rate according to the average ESH.

As can be seen and as concluded by experts at SoluForce B.V., for the smallest size, the filling, loading and unloading of tanks is logistically exhaustive. It is impossible to do at the scale of the 150 MW and 1,5 GW farm size. Hydrogen storage in 994 L type IV tanks is therefore only considered for 50 MW farm sizes for both locations.

4.4. Selected design alternatives

The hydrogen outflow system has on-site hydrogen collection through welded carbon-steel ring pipeline system. Hydrogen compression to 700 bar is possible for all farm sizes. Its necessity however, is debatable. 700 bar hydrogen is the common standard in the transport sector. This sector requires hydrogen at 99.9% purity, which is higher than produced by the assessed small-capacity electrolyzers by ZEF. The compression system has the ability to compress to lower pressures as well for negligible difference in energy usage (500-700 bar nearly equal energy usage).

Hydrogen storage with the aim of exportation of the hydrogen from the farm is only possible in the form of 994 L type IV hydrogen tanks, which is only possible for the 50 MW farm sizes from a logistical perspective. Other options for hydrogen exportation from the farm could include pipeline transport to the customer, possible combined with partial storage in tanks to levelize the pipeline influx. This however, is out of scope for this research. The resulting design alternatives for the hydrogen outflow system are posed in Figure 12. The resulting cost overview for all systems can be found in Appendix E. The results show that the compression takes up majority of the costs, even though it scales less than linear as the farm size increases - still providing benefits in terms of economies of scale.



System functions	Design selection 1	Design selection 2	Design selection 3
On-site hydrogen collection	Carbon steel ring pipeline system, welded	Carbon steel ring pipeline system, welded	Carbon steel ring pipeline system, welded
Hydrogen compression	Piston compression	Piston compression	
Hydrogen storage	994 L type IV hydrogen storage tanks		

Figure 12: Overview of the resulting design alternatives for the hydrogen outflow systems. Design selection 1 is only applicable for the 50 MW farms for both locations, design selections 2 and 3 are applicable for all farms.

5. System evaluation - LCOH

To evaluate complete hydrogen farm designs, the PV and electrolyzer costs are determined. The solar and electrolyzer CAPEX and OPEX are used as provided by ZEF and stated below in Figure 13.

	Ínsua	**Al Buraimi**
Solar CAPEX/panel (€/unit)	163,86	130,36
Solar OPEX/panel (€/unit)	2,57	1,03
Electrolyzer CAPEX (€/unit)	2.800	2.600
Electrolyzer OPEX /unit/year(€/unit/year)	46,02	37,82

Figure 13: CAPEX and OPEX for PV (including equipment) and electrolyzer cost (including BoP, installation and transportation) as provided by ZEF. (van Kranendonk and Vroegindeweij, 2023)

The resulting costs related to PV and electrolyzers are given in Appendix F, which show that the electricity cost for Ínsua farms is €0,013/kWh and €0,007/kWh for Al Buraimi.

The resulting combinations of the selected designs result in seven configurations per location - fourteen in total. Based on the discounted hydrogen production quantities as posed in Figure 14, the LCOH is calculated for each hydrogen farm configuration. The results are given in Figure 16. An overview of the allocation of CAPEX an OPEX to the total farm cost for the 50 MW farm sizes - including only on-site hydrogen collection - is given in Figure 15.

	Insua			Al Buraimi		
Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
Total yearly production (kg/year) 50 bar	2.160.800	6.478.750	64.787.500	2.682.750	8.030.000	80.300.000
Discounted production 30 years - 50 bar	33.216.792	99.594.267	995.942.671	41.240.442	123.440.782	1.234.407.817
Discounted production 30 years - rounded 50 bar	33.220.000	99.600.000	996.000.000	41.240.000	123.500.000	1.235.000.000
Total yearly production (kg/year) 700 bar	1.423.699	4.271.098	42.724.282	1.756.339	5.295.629	53.222.400
Discounted production 30 years - 700 bar	21.885.746	65.657.239	656.776.927	26.999.238	81.406.794	818.158.737
Discounted production 30 years - rounded 700 bar	22.000.000	66.000.000	660.000.000	27.000.000	81.400.000	820.000.000

Figure 14: Hydrogen production quantities based on an annual discount of 5%

5.1. Sensitivity

To account for simplifications, time-frames of data and unavoidable uncertainties of the system components or underlying assumptions, a critical scenario calculation is done for all configurations as well. A so-called Lang factor is used as multiplier for the CAPEX of the designed systems. The Lang factor is a multiplier for the based on the technology readiness level (TRL) of a system thus scaling with the maturity of a technology or system (Saur et al., 2019).

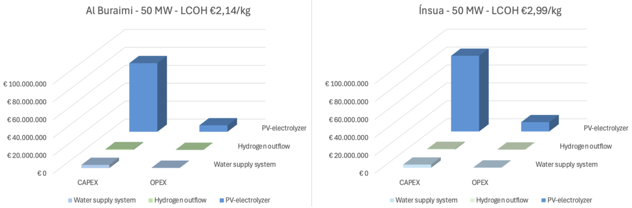


Figure 15: CAPEX and OPEX contribution to total costs per subsystem, for 50 MW farm sizes of Al Buraimi and Insua which include only on-site hydrogen collection as hydrogen outflow system.

Based on expert input and maturity of technologies based on the literature available for the systems, the Lang factors are adopted as 2 for the water supply system; 3 for the hydrogen outflow system of the 50 and 150 MW farms and 4 for the 1,5 GW farm (due to the novelty of the technology in combination with the scale). For the PV-electrolyzer system, a 20% increase is taken for both CAPEX and OPEX. The results are given in Figure 16. Again, an overview of the allocation of CAPEX an OPEX to the total farm cost for the 50 MW farm sizes - including only on-site hydrogen collection - is given in Figure 17.

			Ínsua		Al Buraimi	
Farm size	**Water supply system**	**Hydrogen outflow system**	**LCOH**	**LCOH - critical Lang factors**	**LCOH**	**LCOH - critical Lang factors**
50 MW	Water grid	Collection, compression, tank storage	€ 5,10	€ 7,39	€ 3,76	€ 5,54
50 MW	Water grid	Collection, compression	€ 5,04	€ 7,19	€ 3,69	€ 5,34
150 MW	Waste water	Collection, compression	€ 4,85	€ 6,77	€ 3,52	€ 4,97
1,5 GW	Waste water	Collection, compression	€ 4,93	€ 7,67	€ 3,55	€ 5,65
50 MW	Water grid	Collection	€ 2,99	€ 3,72	€ 2,14	€ 2,68
150 MW	Waste water	Collection	€ 2,91	€ 3,59	€ 2,09	€ 2,58
1,5 GW	Waste water	Collection	€ 3,00	€ 4,01	€ 2,15	€ 2,92

Figure 16: Reference LCOH and LCOH including critical Lang factors for all selected hydrogen farm configurations.

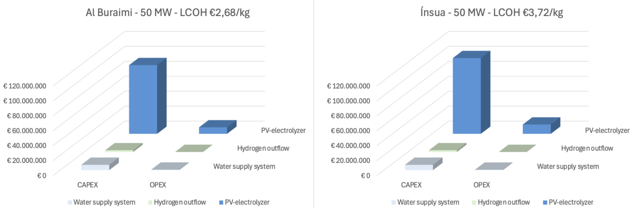


Figure 17: CAPEX and OPEX contribution to total costs per subsystem including critical Lang factors, for 50 MW farm sizes of Al Buraimi and Insua which include only on-site hydrogen collection as hydrogen outflow system.

6. Discussion

This research provides an evaluation of the potential of off-energy-grid PV and small-capacity electrolyzer based hydrogen farms. As an initial exploration, assumptions and simplifications are made that undoubtedly influence the results.

Firstly, no fluctuations of solar irradiance and thus production is taken into account. In reality, the production will vary on an hourly, daily, and seasonal basis. Though the simplification of the production was necessary for initial assessment, it is recommended to include this fluctuation in future research. The solar irradiance influences the amount of PV required to supply the electrolyzers (and other systems) with energy as well - which is another influence on the total costs. Optimization of PV regarding solar irradiance can lead to an improvement of the LCOH - especially when considering the possibility of oversizing PV with or without usage of a battery, to increase the energy generation, which is excluded from the scope of this research. The research scope also limits the inclusion of a battery - or assessment of the required size and pricing, which inevitably influence the system costs.

Additionally, the design space was limited by excluding upcoming technologies that are not available on the market yet. Disregarding novel technologies that can generate water off-grid eliminates the possibility of a fully off-grid farm design. Such technologies are encouraged to be considered in future research, especially considering the fact that this research is based on a novel electrolyzer.

Moreover, no hydrogen export is included for farms where on-site collection is the only function of the hydrogen outflow system. In truth, even when using an existing pipeline, equipment will be required and costs will arise for feeding the produced hydrogen into the pipeline - if not, they will for any other method for exportation of the produced hydrogen. Furthermore, no purification step was included, which is required in case hydrogen is to be used at 700 bar and thus by the transport sector.

Regarding the methodology and outcomes of specific parts of the design steps, there are some point to mention as well. In the qualitative evaluation for water source selection equal weights were used for all criteria. Though this follows the method as designed by Catarino et al. and used by Simoes et al., the inquiry pertains to whether equal weights should be assigned to them. Climactic effects or social acceptance could for example achieve a higher weight in case local policies aimed at industrial water usage reflect these interests. The evaluation of the importance of the criteria for choice of water source is therefore recommended to be assessed from a local and/or policy perspective in further depth.

For water transport to the farms, steel pipeline assumed for all farms is an uncertainty for two reasons. First is that the pipeline diameter is too large for the smallest size and due to steep steel pricing, the total is certainly overestimated for this farm size. Second, the length of the pipeline is 10 km. It is dependent on the location of the farm what the distance to the chosen water source is, however for the water grid, and thus again for the smaller farm size, it is likely that a connection point to the water grid is within closer proximity than 10 km.

Lastly, though expert opinions have been used as input and for verification of (ranges) of quantities and costs, it should be noted that the information comes forth from their respective projects and experience. The input of e.g. larger firms or firms with different project and methods can lead to different input for the evaluation.

7. Conclusion

This thesis found that for the 6 kW electrolyzer hydrogen farms assessed in Ínsua and Al Buraimi, that 50 MW, 150 MW and 1,5 GW farm sizes have technical feasibility, and, all can result in market-competitive LCOHs. The lowest LCOH was found for a 50 MW farm in Al Buraimi.

The emerged water supply system is a centralized system that provides benefits in terms of economies of scale which favours larger farms in terms of levelized cost. The same holds for compression of the hydrogen. The on-site collection of the hydrogen system increases with farm size - favouring smaller farms sizes. The influence of these systems is minimal compared to that of the main cost contributor: the PV-electrolyzer system and more specifically, the electrolyzer costs. These account for at least 85% of the LCOH, of which 85% is attributed to electrolyzer costs. As this systems costs scale linearly with the farm size, benefiting smaller farm sizes, the final system shows lowest costs for the smallest farm size of 50 MW. This remains the case when the critical Lang factors are incorporated. The water supply - and hydrogen outflow system remain to take up at most 13% of the total farm costs.

The findings show that even with limited running hours, the low cost per kW of the electrolyzer in combination with the relatively low costs of water supply and hydrogen outflow system, the off-energy-grid PV and 6 kW electrolyzer farms lead to an LCOH that forms only ± 20% of the calculated LCOH for a centralized and grid connected PV-electrolyzer process (Eblé and Weeda, 2023).

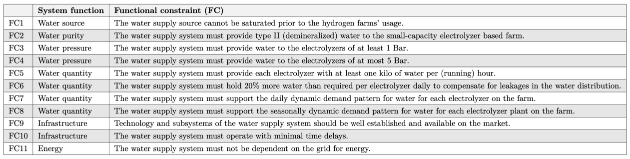
Furthermore, not being connected to the grid results in an extremely low electricity cost compared to that found in recent studies for a centralized and grid connected PV-electrolyzer process by TNO. The found electricity costs in this study consist of the price of electricity (€ 0,075/kWh), the electricity tax (€ 0,01 per kg hydrogen), and the electricity grid tariff (€ 2,31 /kg hydrogen) - amount to € 7,50/ kg hydrogen. These costs are avoided in the designed off-energy-grid hydrogen farm.

The critical advantages of the off-energy-grid PV and 6 kW electrolyzer farms are the low electrolyzer and low electricity costs. Even with limited running hours, and the electrolyzer cost taking up most of the total costs, the addition of a water supply and hydrogen outflow system do not jeopardize the market-competitiveness of the resulting LCOH.

The presented research is based on various assumptions and simplifications - as specified in the discussion. These have been partially compensated for by using critical Lang factors that double, triple or quadruple the costs of subsystems. The results show that, both Ínsua and Al Buraimi are suitable locations and 50 MW, 150 MW and 1,5 GW are all farm sizes that can lead to market-competitive LCOHs. The lowest LCOH is realised for the 50 MW farm based utilizing the water grid while operating most running hours tested, and includes on-site hydrogen collection of hydrogen at 46 bar in Al Buraimi.

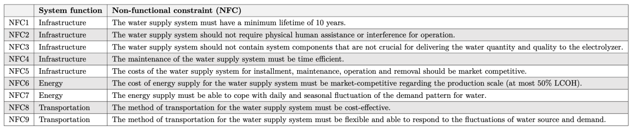
Based on the considered 6 kW electrolyzer in combination with found alternatives for a water supply system and hydrogen outflow system, for either Ínsua or Al Buraimi, for all assessed farm sizes, the findings of this research strongly support the technical feasibility and resulting market-competitiveness of hydrogen produced by an off-energy-grid photovoltaic and small-capacity based electrolyzer production process - and its further consideration for research.

Appendix A. Requirements for the water supply system



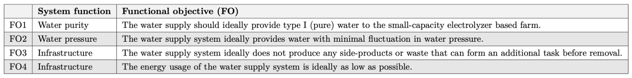
	System function	**Functional constraint (FC)**
FC1	Water source	The water supply source cannot be saturated prior to the hydrogen farms' usage.
FC2	Water purity	The water supply system must provide type II (demineralized) water to the small-capacity electrolyzer based farm.
FC3	Water pressure	The water supply system must provide water to the electrolyzers of at least 1 Bar.
FC4	Water pressure	The water supply system must provide water to the electrolyzers of at most 5 Bar.
FC5	Water quantity	The water supply system must provide each electrolyzer with at least one kilo of water per (running) hour.
FC6	Water quantity	The water supply system must hold 20% more water than required per electrolyzer daily to compensate for leakages in the water distribution.
FC7	Water quantity	The water supply system must support the daily dynamic demand pattern for water for each electrolyzer on the farm.
FC8	Water quantity	The water supply system must support the seasonally dynamic demand pattern for water for each electrolyzer plant on the farm.
FC9	Infrastructure	Technology and subsystems of the water supply system should be well established and available on the market.
FC10	Infrastructure	The water supply system must operate with minimal time delays.
FC11	Energy	The water supply system must not be dependent on the grid for energy.

Figure A.18: Functional constraints for the subsystems of the water supply system



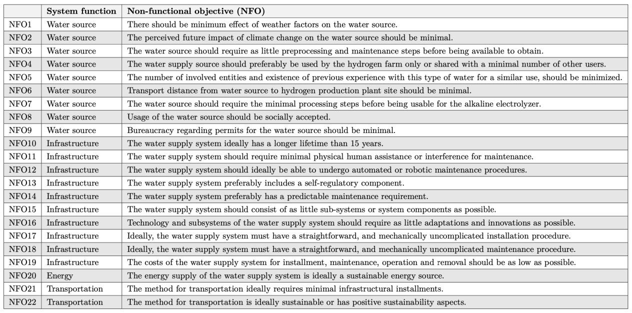
	System function	**Non-functional constraint (NFC)**
NFC1	Infrastructure	The water supply system must have a minimum lifetime of 10 years.
NFC2	Infrastructure	The water supply system should not require physical human assistance or interference for operation.
NFC3	Infrastructure	The water supply system should not contain system components that are not crucial for delivering the water quantity and quality to the electrolyzer.
NFC4	Infrastructure	The maintenance of the water supply system must be time efficient.
NFC5	Infrastructure	The costs of the water supply system for installment, maintenance, operation and removal should be market competitive.
NFC6	Energy	The cost of energy supply for the water supply system must be market-competitive regarding the production scale (at most 50% LCOH).
NFC7	Energy	The energy supply must be able to cope with daily and seasonal fluctuation of the demand pattern for water.
NFC8	Transportation	The method of transportation for the water supply system must be cost-effective.
NFC9	Transportation	The method of transportation for the water supply system must be flexible and able to respond to the fluctuations of water source and demand.

Figure A.19: Non-functional constraints for the subsystems of the water supply system



	System function	**Functional objective (FO)**
FO1	Water purity	The water supply should ideally provide type I (pure) water to the small-capacity electrolyzer based farm.
FO2	Water pressure	The water supply system ideally provides water with minimal fluctuation in water pressure.
FO3	Infrastructure	The water supply system ideally does not produce any side-products or waste that can form an additional task before removal.
FO4	Infrastructure	The energy usage of the water supply system is ideally as low as possible.

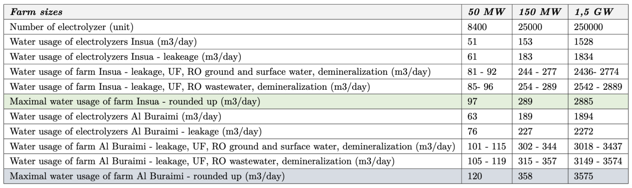
Figure A.20: Functional objectives for the subsystems of the water supply system



	System function	**Non-functional objective (NFO)**
NFO1	Water source	There should be minimum effect of weather factors on the water source.
NFO2	Water source	The perceived future impact of climate change on the water source should be minimal.
NFO3	Water source	The water source should require as little preprocessing and maintenance steps before being available to obtain.
NFO4	Water source	The water supply source should preferably be used by the hydrogen farm only or shared with a minimal number of other users.
NFO5	Water source	The number of involved entities and existence of previous experience with this type of water for a similar use, should be minimized.
NFO6	Water source	Transport distance from water source to hydrogen production plant site should be minimal.
NFO7	Water source	The water source should require the minimal processing steps before being usable for the alkaline electrolyzer.
NFO8	Water source	Usage of the water source should be socially accepted.
NFO9	Water source	Bureaucracy regarding permits for the water source should be minimal.
NFO10	Infrastructure	The water supply system ideally has a longer lifetime than 15 years.
NFO11	Infrastructure	The water supply system should require minimal physical human assistance or interference for maintenance.
NFO12	Infrastructure	The water supply system should ideally be able to undergo automated or robotic maintenance procedures.
NFO13	Infrastructure	The water supply system preferably includes a self-regulatory component.
NFO14	Infrastructure	The water supply system preferably has a predictable maintenance requirement.
NFO15	Infrastructure	The water supply system should consist of as little sub-systems or system components as possible.
NFO16	Infrastructure	Technology and subsystems of the water supply system should require as little adaptations and innovations as possible.
NFO17	Infrastructure	Ideally, the water supply system must have a straightforward, and mechanically uncomplicated installation procedure.
NFO18	Infrastructure	Ideally, the water supply system must have a straightforward, and mechanically uncomplicated maintenance procedure.
NFO19	Infrastructure	The costs of the water supply system for installment, maintenance, operation and removal should be as low as possible.
NFO20	Energy	The energy supply of the water supply system is ideally a sustainable energy source.
NFO21	Transportation	The method for transportation ideally requires minimal infrastructural installments.
NFO22	Transportation	The method for transportation is ideally sustainable or has positive sustainability aspects.

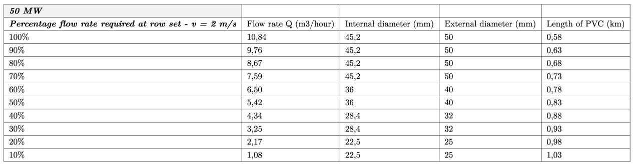
Figure A.21: Non-functional objectives for the subsystems of the water supply system

Appendix B. Water Quantities



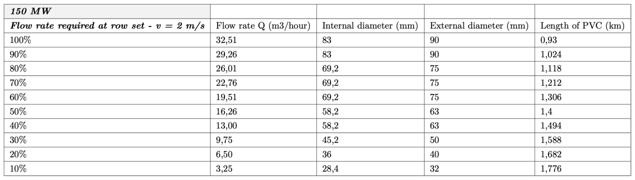
Farm sizes	***50 MW***	***150 MW***	***1,5 GW***
Number of electrolyzer (unit)	8400	25000	250000
Water usage of electrolyzers Insua (m3/day)	51	153	1528
Water usage of electrolyzers Insua - leakeage (m3/day)	61	183	1834
Water usage of farm Insua - leakage, UF, RO ground and surface water, demineralization (m3/day)	81 - 92	244 - 277	2436- 2774
Water usage of farm Insua - leakage, UF, RO wastewater, demineralization (m3/day)	85- 96	254 - 289	2542 - 2889
Maximal water usage of farm Insua - rounded up (m3/day)	97	289	2885
Water usage of electrolyzers Al Buraimi (m3/day)	63	189	1894
Water usage of electrolyzers Al Buraimi - leakage (m3/day)	76	227	2272
Water usage of farm Al Buraimi - leakage, UF, RO ground and surface water, demineralization (m3/day)	101 - 115	302 - 344	3018 - 3437
Water usage of farm Al Buraimi - leakage, UF, RO wastewater, demineralization (m3/day)	105 - 119	315 - 357	3149 - 3574
Maximal water usage of farm Al Buraimi - rounded up (m3/day)	120	358	3575

Figure B.22: Water quantities for farm sizes at both locations - accounting for leakages and losses of treatment processes



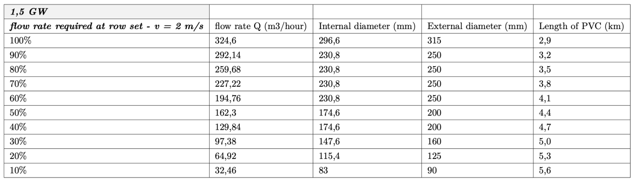
50 MW				
Percentage flow rate required at row set - v = 2 m/s	Flow rate Q (m3/hour)	Internal diameter (mm)	External diameter (mm)	Length of PVC (km)
100%	10,84	45,2	50	0,58
90%	9,76	45,2	50	0,63
80%	8,67	45,2	50	0,68
70%	7,59	45,2	50	0,73
60%	6,50	36	40	0,78
50%	5,42	36	40	0,83
40%	4,34	28,4	32	0,88
30%	3,25	28,4	32	0,93
20%	2,17	22,5	25	0,98
10%	1,08	22,5	25	1,03

Figure B.23: PVC pipes required per row set for the 50 MW farm, including the length of the PVC pipe covering the row set



150 MW				
Flow rate required at row set - v = 2 m/s	Flow rate Q (m3/hour)	Internal diameter (mm)	External diameter (mm)	Length of PVC (km)
100%	32,51	83	90	0,93
90%	29,26	83	90	1,024
80%	26,01	69,2	75	1,118
70%	22,76	69,2	75	1,212
60%	19,51	69,2	75	1,306
50%	16,26	58,2	63	1,4
40%	13,00	58,2	63	1,494
30%	9,75	45,2	50	1,588
20%	6,50	36	40	1,682
10%	3,25	28,4	32	1,776

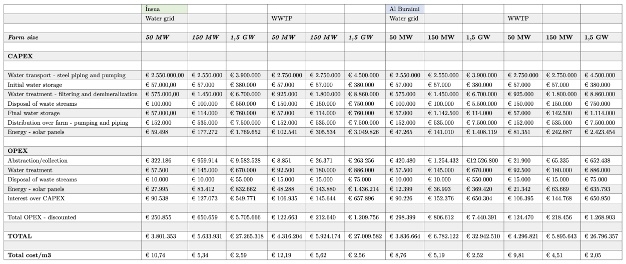
Figure B.24: PVC pipes required per row set for the 150 MW farm, including the length of the PVC pipe covering the row set



1,5 GW				
flow rate required at row set - v = 2 m/s	flow rate Q (m3/hour)	Internal diameter (mm)	External diameter (mm)	Length of PVC (km)
100%	324,6	296,6	315	2,9
90%	292,14	230,8	250	3,2
80%	259,68	230,8	250	3,5
70%	227,22	230,8	250	3,8
60%	194,76	230,8	250	4,1
50%	162,3	174,6	200	4,4
40%	129,84	174,6	200	4,7
30%	97,38	147,6	160	5,0
20%	64,92	115,4	125	5,3
10%	32,46	83	90	5,6

Figure B.25: PVC pipes required per row set for the 1,5 GW farm, including the length of the PVC pipe covering the row set

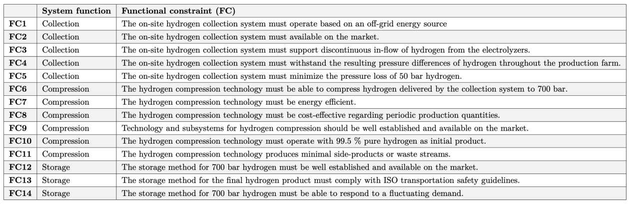
Appendix C. Cost calculations for all water supply system alternatives



	Ínsua						Al Buraimi					
	Water grid			WWTP			Water grid			WWTP		
Farm size	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***	**50 MW**	**150 MW**	**1,5 GW**	**50 MW**	**150 MW**	**1,5 GW**
CAPEX												
Water transport - steel piping and pumping	€ 2.550.000,00	€ 2.550.000	€ 3.900.000	€ 2.750.000	€ 2.750.000	€ 4.500.000	€ 2.550.000	€ 2.550.000	€ 3.900.000	€ 2.750.000	€ 2.750.000	€ 4.500.000
Initial water storage	€ 57.000,00	€ 57.000	€ 380.000	€ 57.000	€ 57.000	€ 380.000	€ 57.000	€ 57.000	€ 380.000	€ 57.000	€ 57.000	€ 380.000
Water treatment - filtering and demineralization	€ 575.000,00	€ 1.450.000	€ 6.700.000	€ 925.000	€ 1.800.000	€ 8.860.000	€ 575.000	€ 1.450.000	€ 6.700.000	€ 925.000	€ 1.800.000	€ 8.860.000
Disposal of waste streams	€ 100.000	€ 100.000	€ 550.000	€ 150.000	€ 150.000	€ 750.000	€ 100.000	€ 100.000	€ 5.500.000	€ 150.000	€ 150.000	€ 750.000
Final water storage	€ 57.000,00	€ 114.000	€ 760.000	€ 57.000	€ 114.000	€ 760.000	€ 57.000	€ 1.142.500	€ 114.000	€ 57.000	€ 142.500	€ 1.114.000
Distribution over farm - pumping and piping	€ 152.000	€ 535.000	€ 7.500.000	€ 152.000	€ 535.000	€ 7.500.000	€ 152.000	€ 535.000	€ 7.500.000	€ 152.000	€ 535.000	€ 7.500.000
Energy - solar panels	€ 59.498	€ 177.272	€ 1.769.652	€ 102.541	€ 305.534	€ 3.049.826	€ 47.265	€ 141.010	€ 1.408.119	€ 81.351	€ 242.687	€ 2.423.454
OPEX												
Abstraction/collection	€ 322.186	€ 959.914	€ 9.582.528	€ 8.851	€ 26.371	€ 263.256	€ 420.480	€ 1.254.432	€12.526.800	€ 21.900	€ 65.335	€ 652.438
Water treatment	€ 57.500	€ 145.000	€ 670.000	€ 92.500	€ 180.000	€ 886.000	€ 57.500	€ 145.000	€ 670.000	€ 92.500	€ 180.000	€ 886.000
Disposal of waste streams	€ 10.000	€ 10.000	€ 55.000	€ 15.000	€ 15.000	€ 75.000	€ 10.000	€ 10.000	€ 550.000	€ 15.000	€ 15.000	€ 75.000
Energy - solar panels	€ 27.995	€ 83.412	€ 832.662	€ 48.288	€ 143.880	€ 1.436.214	€ 12.399	€ 36.993	€ 369.420	€ 21.342	€ 63.669	€ 635.793
interest over CAPEX	€ 90.538	€ 127.073	€ 549.771	€ 106.935	€ 145.644	€ 657.896	€ 90.226	€ 152.376	€ 650.304	€ 106.395	€ 144.768	€ 650.950
Total OPEX - discounted	€ 250.855	€ 650.659	€ 5.705.666	€ 122.663	€ 212.640	€ 1.209.756	€ 298.399	€ 806.612	€ 7.440.391	€ 124.470	€ 218.456	€ 1.268.903
TOTAL	€ 3.801.353	€ 5.633.931	€ 27.265.318	€ 4.316.204	€ 5.924.174	€ 27.009.582	€ 3.836.664	€ 6.782.122	€ 32.942.510	€ 4.296.821	€ 5.895.643	€ 26.796.357
Total cost/m3	€ 10,74	€ 5,34	€ 2,59	€ 12,19	€ 5,62	€ 2,56	€ 8,76	€ 5,19	€ 2,52	€ 9,81	€ 4,51	€ 2,05

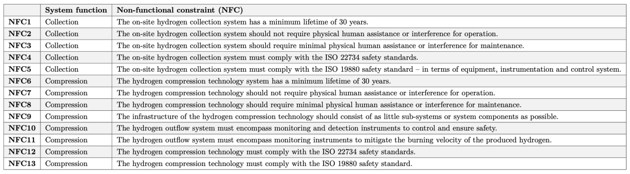
Figure C.26: Determined costs per m3 of water used for each designed water supply system

Appendix D. Requirements for the hydrogen outflow system



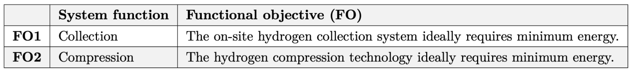
	System function	**Functional constraint (FC)**
FC1	Collection	The on-site hydrogen collection system must operate based on an off-grid energy source
FC2	Collection	The on-site hydrogen collection system must available on the market.
FC3	Collection	The on-site hydrogen collection system must support discontinuous in-flow of hydrogen from the electrolyzers.
FC4	Collection	The on-site hydrogen collection system must withstand the resulting pressure differences of hydrogen throughout the production farm.
FC5	Collection	The on-site hydrogen collection system must minimize the pressure loss of 50 bar hydrogen.
FC6	Compression	The hydrogen compression technology must be able to compress hydrogen delivered by the collection system to 700 bar.
FC7	Compression	The hydrogen compression technology must be energy efficient.
FC8	Compression	The hydrogen compression technology must be cost-effective regarding periodic production quantities.
FC9	Compression	Technology and subsystems for hydrogen compression should be well established and available on the market.
FC10	Compression	The hydrogen compression technology must operate with 99.5 % pure hydrogen as initial product.
FC11	Compression	The hydrogen compression technology produces minimal side-products or waste streams.
FC12	Storage	The storage method for 700 bar hydrogen must be well established and available on the market.
FC13	Storage	The storage method for the final hydrogen product must comply with ISO transportation safety guidelines.
FC14	Storage	The storage method for 700 bar hydrogen must be able to respond to a fluctuating demand.

Figure D.27: Functional constraints for the subsystems of the hydrogen outflow system



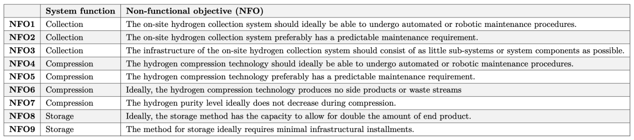
	System function	**Non-functional constraint (NFC)**
NFC1	Collection	The on-site hydrogen collection system has a minimum lifetime of 30 years.
NFC2	Collection	The on-site hydrogen collection system should not require physical human assistance or interference for operation.
NFC3	Collection	The on-site hydrogen collection system should require minimal physical human assistance or interference for maintenance.
NFC4	Collection	The on-site hydrogen collection system must comply with the ISO 22734 safety standards.
NFC5	Collection	The on-site hydrogen collection system must comply with the ISO 19880 safety standard – in terms of equipment, instrumentation and control system.
NFC6	Compression	The hydrogen compression technology system has a minimum lifetime of 30 years.
NFC7	Compression	The hydrogen compression technology should not require physical human assistance or interference for operation.
NFC8	Compression	The hydrogen compression technology should require minimal physical human assistance or interference for maintenance.
NFC9	Compression	The infrastructure of the hydrogen compression technology should consist of as little sub-systems or system components as possible.
NFC10	Compression	The hydrogen outflow system must encompass monitoring and detection instruments to control and ensure safety.
NFC11	Compression	The hydrogen outflow system must encompass monitoring instruments to mitigate the burning velocity of the produced hydrogen.
NFC12	Compression	The hydrogen compression technology must comply with the ISO 22734 safety standards.
NFC13	Compression	The hydrogen compression technology must comply with the ISO 19880 safety standard.

Figure D.28: Non-functional constraints for the subsystems of the hydrogen outflow system



	System function	**Functional objective (FO)**
FO1	Collection	The on-site hydrogen collection system ideally requires minimum energy.
FO2	Compression	The hydrogen compression technology ideally requires minimum energy.

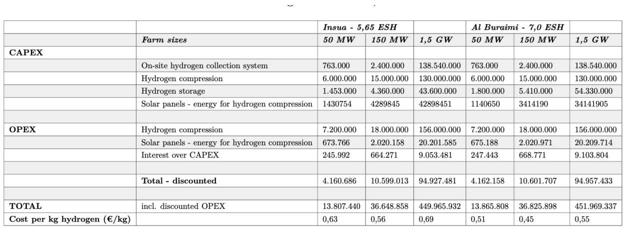
Figure D.29: Functional objectives for the subsystems of the hydrogen outflow system



	System function	**Non-functional objective (NFO)**
NFO1	Collection	The on-site hydrogen collection system should ideally be able to undergo automated or robotic maintenance procedures.
NFO2	Collection	The on-site hydrogen collection system preferably has a predictable maintenance requirement.
NFO3	Collection	The infrastructure of the on-site hydrogen collection system should consist of as little sub-systems or system components as possible.
NFO4	Compression	The hydrogen compression technology should ideally be able to undergo automated or robotic maintenance procedures.
NFO5	Compression	The hydrogen compression technology preferably has a predictable maintenance requirement.
NFO6	Compression	Ideally, the hydrogen compression technology produces no side products or waste streams
NFO7	Compression	The hydrogen purity level ideally does not decrease during compression.
NFO8	Storage	Ideally, the storage method has the capacity to allow for double the amount of end product.
NFO9	Storage	The method for storage ideally requires minimal infrastructural installments.

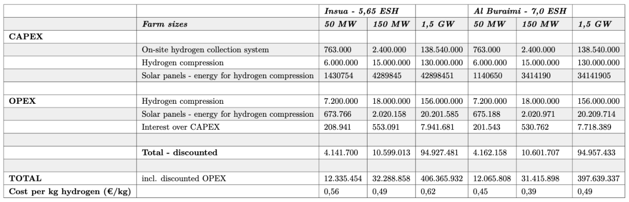
Figure D.30: Non-functional objectives for the subsystems of the hydrogen outflow system

Appendix E. Cost calculations for all hydrogen outflow system alternatives



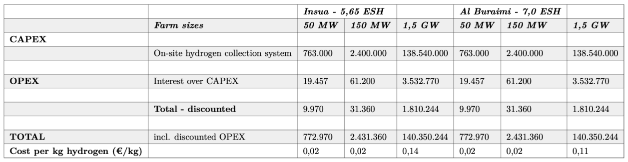
		Insua - 5,65 ESH			***Al Buraimi - 7,0 ESH***		
	Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
CAPEX							
	On-site hydrogen collection system	763.000	2.400.000	138.540.000	763.000	2.400.000	138.540.000
	Hydrogen compression	6.000.000	15.000.000	130.000.000	6.000.000	15.000.000	130.000.000
	Hydrogen storage	1.453.000	4.360.000	43.600.000	1.800.000	5.410.000	54.330.000
	Solar panels - energy for hydrogen compression	1430754	4289845	42898451	1140650	3414190	34141905
OPEX	Hydrogen compression	7.200.000	18.000.000	156.000.000	7.200.000	18.000.000	156.000.000
	Solar panels - energy for hydrogen compression	673.766	2.020.158	20.201.585	675.188	2.020.971	20.209.714
	Interest over CAPEX	245.992	664.271	9.053.481	247.443	668.771	9.103.804
	Total - discounted	4.160.686	10.599.013	94.927.481	4.162.158	10.601.707	94.957.433
TOTAL	incl. discounted OPEX	13.807.440	36.648.858	449.965.932	13.865.808	36.825.898	451.969.337
Cost per kg hydrogen (€/kg)		0,63	0,56	0,69	0,51	0,45	0,55

Figure E.31: CAPEX and OPEX calculation for hydrogen outflow system design selection one



		Insua - 5,65 ESH			***Al Buraimi - 7,0 ESH***		
	Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
CAPEX							
	On-site hydrogen collection system	763.000	2.400.000	138.540.000	763.000	2.400.000	138.540.000
	Hydrogen compression	6.000.000	15.000.000	130.000.000	6.000.000	15.000.000	130.000.000
	Solar panels - energy for hydrogen compression	1430754	4289845	42898451	1140650	3414190	34141905
OPEX	Hydrogen compression	7.200.000	18.000.000	156.000.000	7.200.000	18.000.000	156.000.000
	Solar panels - energy for hydrogen compression	673.766	2.020.158	20.201.585	675.188	2.020.971	20.209.714
	Interest over CAPEX	208.941	553.091	7.941.681	201.543	530.762	7.718.389
	Total - discounted	4.141.700	10.599.013	94.927.481	4.162.158	10.601.707	94.957.433
TOTAL	incl. discounted OPEX	12.335.454	32.288.858	406.365.932	12.065.808	31.415.898	397.639.337
Cost per kg hydrogen (€/kg)		0,56	0,49	0,62	0,45	0,39	0,49

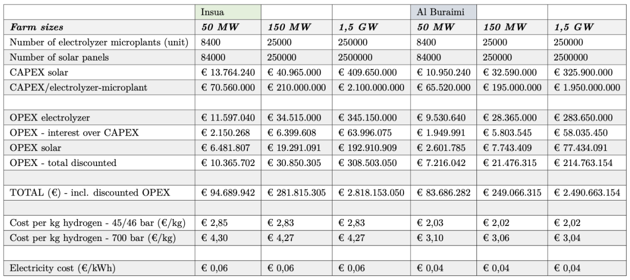
Figure E.32: CAPEX and OPEX calculation for hydrogen outflow system design selection two



		Insua - 5,65 ESH			***Al Buraimi - 7,0 ESH***		
	Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
CAPEX							
	On-site hydrogen collection system	763.000	2.400.000	138.540.000	763.000	2.400.000	138.540.000
OPEX	Interest over CAPEX	19.457	61.200	3.532.770	19.457	61.200	3.532.770
	Total - discounted	9.970	31.360	1.810.244	9.970	31.360	1.810.244
TOTAL	incl. discounted OPEX	772.970	2.431.360	140.350.244	772.970	2.431.360	140.350.244
Cost per kg hydrogen (€/kg)		0,02	0,02	0,14	0,02	0,02	0,11

Figure E.33: CAPEX and OPEX calculation for hydrogen outflow system design selection three

Appendix F. Cost calculations for PV-electrolyzer systems for all farm sizes in both locations



	Insua			Al Buraimi		
Farm sizes	***50 MW***	***150 MW***	***1,5 GW***	***50 MW***	***150 MW***	***1,5 GW***
Number of electrolyzer microplants (unit)	8400	25000	250000	8400	25000	250000
Number of solar panels	84000	250000	2500000	84000	250000	2500000
CAPEX solar	€ 13.764.240	€ 40.965.000	€ 409.650.000	€ 10.950.240	€ 32.590.000	€ 325.900.000
CAPEX/electrolyzer-microplant	€ 70.560.000	€ 210.000.000	€ 2.100.000.000	€ 65.520.000	€ 195.000.000	€ 1.950.000.000
OPEX electrolyzer	€ 11.597.040	€ 34.515.000	€ 345.150.000	€ 9.530.640	€ 28.365.000	€ 283.650.000
OPEX - interest over CAPEX	€ 2.150.268	€ 6.399.608	€ 63.996.075	€ 1.949.991	€ 5.803.545	€ 58.035.450
OPEX solar	€ 6.481.807	€ 19.291.091	€ 192.910.909	€ 2.601.785	€ 7.743.409	€ 77.434.091
OPEX - total discounted	€ 10.365.702	€ 30.850.305	€ 308.503.050	€ 7.216.042	€ 21.476.315	€ 214.763.154
TOTAL (€) - incl. discounted OPEX	€ 94.689.942	€ 281.815.305	€ 2.818.153.050	€ 83.686.282	€ 249.066.315	€ 2.490.663.154
Cost per kg hydrogen - 45/46 bar (€/kg)	€ 2,85	€ 2,83	€ 2,83	€ 2,03	€ 2,02	€ 2,02
Cost per kg hydrogen - 700 bar (€/kg)	€ 4,30	€ 4,27	€ 4,27	€ 3,10	€ 3,06	€ 3,04
Electricity cost (€/kWh)	€ 0,06	€ 0,06	€ 0,06	€ 0,04	€ 0,04	€ 0,04

Figure F.34: CAPEX and OPEX for PV (including equipment) and electrolyzer cost (including BoP, installation and transportation) as provided by ZEF. (van Kranendonk and Vroegindeweij, 2023)

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