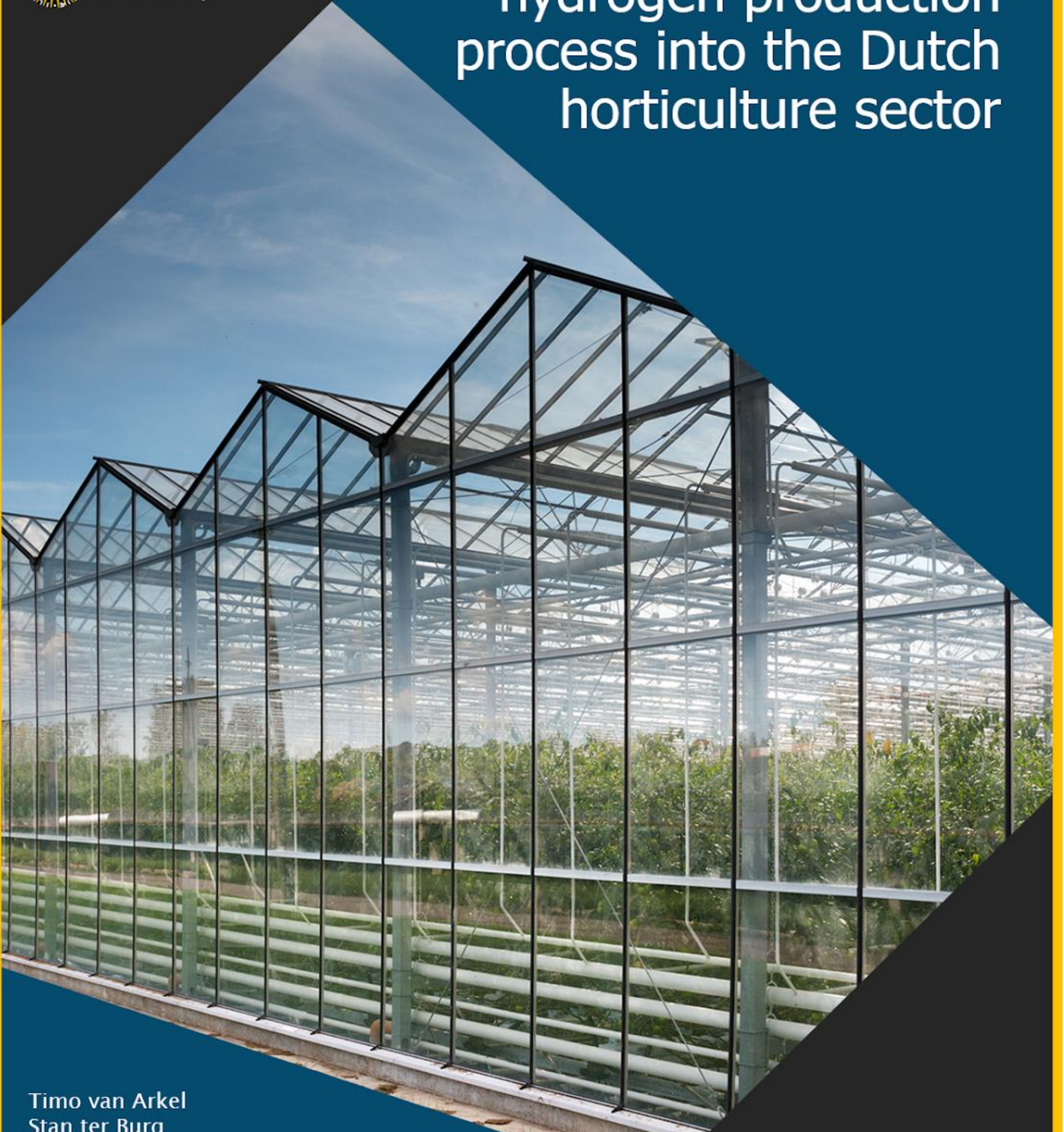
Solinoor
Innovative Energy Solutions

Utrecht University

Integrating the green hydrogen production process into the Dutch horticulture sector



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1st of July 2022

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Consultancy Project (GEO4-2007)

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Management advice

The partnership between Solinoor and Essent on the implementation of the green hydrogen production process provides many opportunities but also creates some challenges. It is for instance currently unclear what role this process could fulfil within various sectors. To provide Solinoor with a sense of directionality, this report assesses the implementation of the green hydrogen process within a major greenhouse gas emitting and energy-intensive sector in the Netherlands: the horticulture sector (CBS, n.d.). Accordingly, the central research question of this report is as follows:

"How could the green hydrogen production process enable a more sustainable heating system for the horticulture sector?"

To answer this question, this report uses a Multi-Criteria Analysis (MCA) to assess the financial and technological feasibility of specific applications related to the green hydrogen production process, namely: electric heat pumps, residual heat from electrolysers, hydrogen Combined Heat & Power (CHP) systems and hydrogen boilers. The MCA is conducted as this is an effective and acknowledged framework to compare alternatives on relevant criteria beyond mere financial criteria. Furthermore, a socio-technological analysis has been conducted to identify encompassing drivers and barriers affecting the development and implementation of the green hydrogen production process as a whole. Using the Technological Innovation System (TIS) framework, the fundamental innovation processes that influence technological development are considered in this study. These combined analyses form a comprehensive approach for assessing how the green hydrogen production process could enable a more sustainable horticulture sector. To collect the relevant data for these analyses, eleven interviews with relevant stakeholders have been conducted. In addition, desk research using newspapers and reports has been carried out to further substantiate the findings.

Of the four technological applications, we found that hydrogen CHPs are the most feasible to be applied within the horticulture sector. Based on financial and technological criteria, hydrogen CHPs scored 69 out of 100. An additional robustness analysis, considering various scenarios, showed that hydrogen CHPs were repeatedly still among the best-scoring alternatives. Hydrogen CHPs turned out to be rather applicable and compatible. Current CHPs can run up to 30% hydrogen mixed with natural gas and can be adapted to 100% hydrogen during regular maintenance services. Residual heat emerged as the second most feasible alternative, due to no additional investment costs and its high compatibility. Electric heat pumps are ranked third, as they require more extensive infrastructural modifications to implement within greenhouses. Hydrogen boilers are deemed the least feasible application, as they are less maturely developed and the most expensive.

Hydrogen CHPs are thus the most feasible to implement within the horticulture sector. These findings provide Solinoor with a substantiated and feasible direction on how they can implement the green hydrogen production process within individual greenhouses. In turn, this would contribute to making the Dutch horticulture sector more sustainable and carbon-free. Nevertheless, even though the hydrogen CHP is the recommended application, it should also be noted that the local conditions of greenhouses still have to be taken into account. Geographical conditions of greenhouses could for instance vary and affect the feasibility of alternatives. Infrastructural conditions may also differ, e.g. greenhouses could have different types of heating installations and distribution networks. At last, while most horticulturists manage their energy provision individually, cooperative projects are also present. Including the latter can result in different findings regarding the feasibility of applications.

Moreover, it is debatable whether the four selected technological applications can be regarded as isolated implementation solutions since renewable energy technologies can often be complementary to each other. For instance, the residual heat could be utilised for heat pumps, hydrogen CHPs and boilers to improve efficiency. Similarly, heat pumps and boilers are often combined, forming hybrid heat pump installations. Assessing the feasibility of such hybrid combinations was beyond the scope of this analysis and we, therefore, recommend Solinoor to continue examining these possibilities. Furthermore, it should be noted that the analysed alternatives are not fully developed at the time of this research. As these alternatives develop, the performance of each alternative in the analysis could change. Further research when these technologies are more developed could provide new insights into how each technology performs.

Besides financial and technical criteria, socio-technological drivers and barriers to the green hydrogen production process have been identified as well. A major driver is that the green hydrogen production process receives support from various actors, including supply-side manufacturers, horticulturists, governments and politicians. Subsequently, societal goals and policy programs are presently aiming to stimulate the development and implementation of the green hydrogen production process. Moreover, its implementation and development are further stimulated due to the increasing natural gas and electricity prices.

However, several barriers to the green hydrogen production process have been identified as well. Besides insufficient practical knowledge, experimental projects and regulation, the implementation of the green hydrogen production process within the horticulture sector is questioned. It is currently uncertain whether its implementation within this sector is preferred. Moreover, other sustainable heating solutions for greenhouses, e.g. geothermal energy and the residual heat of (heavy) industries, are prioritised over the green hydrogen production process. Finally, the legitimacy of the green hydrogen production process is inhibited due to public safety concerns, the obligation for horticulturists to purchase additional CO_2 and a more desired demand for green electricity instead.

Solinoor should take these socio-technological drivers and barriers into account within their implementation strategies. For instance, drivers can be exploited to legitimise the implementation of the green hydrogen production process, while barriers can be anticipated. Solinoor should be aware that the horticulture sector is primarily regarded as a marginal off-taker of the green hydrogen production process. Its implementation within other sectors, especially the heavy industry and mobility, is currently more desired and legitimised. As the green hydrogen production process is perceived as an alternative or add-on within greenhouses, we recommend Solinoor to focus on these legitimised roles, while continuing with assessing its implementation opportunities and challenges within different sectors. To conclude, there can be various pathways that contribute to making sectors more sustainable and this study has provided valuable insights into the feasibility, opportunities and challenges of the green hydrogen production process within the horticulture sector.

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1. Client problem statement

Hydrogen produced from renewable energy sources, so-called *green hydrogen*, is one of the renewable energy solutions that is being explored to mitigate climate change. Striving for a sustainable energy system in 2050, the Dutch government endeavours for a more sustainable hydrogen production process and wants to stimulate the usage of green hydrogen as a fuel in various sectors (Rijksoverheid, 2022a). Solinoor is a company that is investigating the application of green hydrogen within various sectors, one of which is the horticulture sector. The Dutch horticulture sector has committed to reducing its CO_2 emissions to 2.2 Mton annually by 2030, saving approximately 3.5 Mton per year compared to the period of 2015-2017 (Klimaatakkoord, 2019). Moreover, the Dutch horticulture agenda expresses the aim to have a climate-neutral horticulture sector by 2040 (Greenports Nederland, 2019).

Currently, common greenhouse heating methods in the Netherlands are unsustainable natural gas boilers or combined heat and power (CHP) installations (Blom et al., 2021; DutchGreenhouses, n.d.; Royal Brinkman, 2018). Replacing these heating systems with a more sustainable solution would help the horticulture sector to reach its climate goals. Solinoor is one of the companies that currently explores these opportunities in the horticulture sector.

Solinoor provides innovative and sustainable energy solutions. It carries out various projects throughout the Netherlands, ranging from floating solar parks to industry-related solar arrays. As of April 2022, Solinoor is the exclusive partner of Essent regarding the production of green hydrogen (Essent, 2022)[1]. This partnership provides new opportunities for both companies. One of the major challenges for solar PV occurs when electricity is generated. Once electricity is generated it must be consumed immediately unless it can be stored in an energy carrier. This question about what to do with the electricity and how this electricity can be stored in an energy carrier is being explored by both companies. The energy carrier that Solinoor and Essent are exploring is green hydrogen. The application that Solinoor is particularly interested in, is how green hydrogen can be used in the horticulture sector. This application is interesting to them, since Essent has access to a large number of potential off-takers in this sector, creating a large potential client base.

As of now, both companies have a lack of understanding of how the green hydrogen production process can be applied within the horticulture sector. This report, therefore, aimed to explore various heating applications related to green hydrogen within the Dutch horticulture sector. This will allow Solinoor to provide a solution to the horticulturists to allow them to transition to sustainable green hydrogen. Moreover, this report aimed to evaluate the socio-technological drivers and barriers to the green hydrogen production process within the Dutch horticulture sector. This will provide Solinoor with insights into the current state of the green hydrogen production environment and will allow them to anticipate the barriers and drivers

[1] In this study, the *green hydrogen production process* is defined as the process from renewable energy generation to production and utilisation of green hydrogen.

affecting this market. To guide this report, the following research question has been formulated:

"How could the green hydrogen production process enable a more sustainable heating system for the horticulture sector?"

As illustrated in *Figure 1,* the production process of green hydrogen is characterised by three energy outputs: green electricity, residual heat and hydrogen. These energy outputs can be applied to the horticulture sector in different ways. Accordingly, four heating application alternatives for greenhouses have been identified. The first of these alternatives is the electric heat pump, which uses electricity to capture and generate at high efficiencies. The second alternative is directly utilising the residual heat from the electrolysis process to heat the greenhouses. The third alternative is the hydrogen-powered boiler, which burns hydrogen to produce heat for the greenhouses. The final alternative, the hydrogen Combined Heat and Power (CHP) system, combusts hydrogen in a turbine to generate both heat and electricity. A further elaboration on these alternatives can be found in *section 2.1 of the Annex*. This research only focuses on the alternatives individually, which means that combinations of alternatives are not taken into account. This is done to review the individual characteristics of each alternative, so it can be compared accurately. To compare these application alternatives and to provide Solinoor with tangible advice, this research is further divided into two sub-questions:

- *What is financially and technologically the most feasible alternative to implement the green hydrogen production process within the horticulture sector?*
- *How do socio-technological drivers and barriers affect the development and implementation of the green hydrogen production process?*

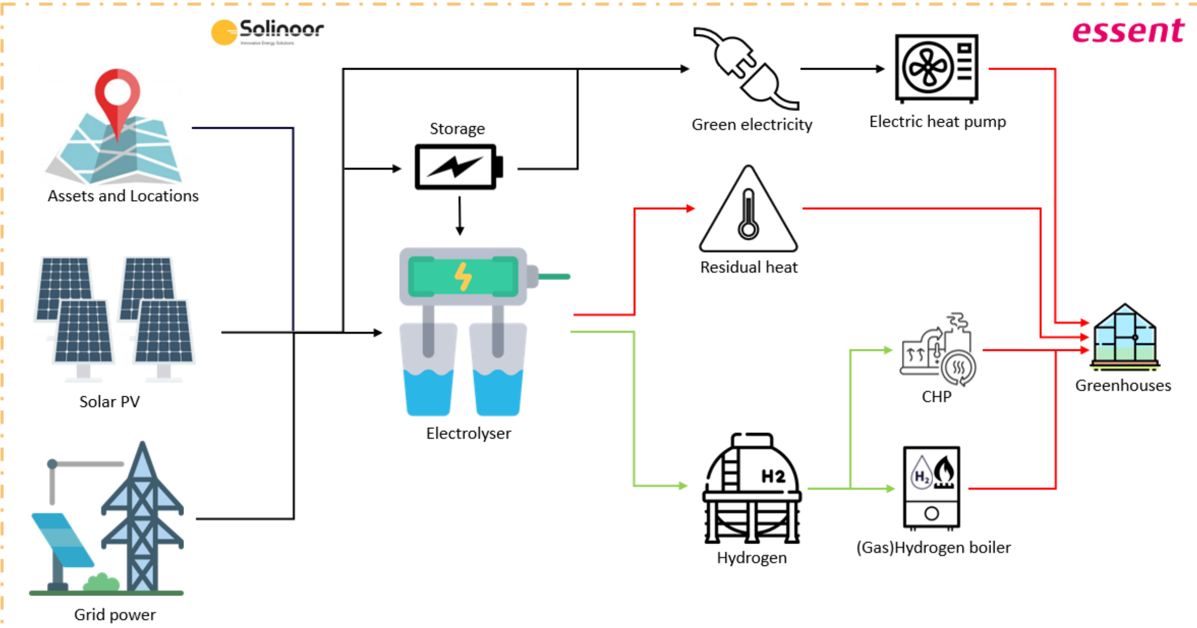

Figure 1. Overview of the three energy outputs of the green hydrogen production process.

2. Research approach

Two theoretical and analytical frameworks were used to address the research questions and are summarised below. A more extensive overview of these frameworks can be found in *section 3 of the Annex*.

2.1. Multi-Criteria Analysis

To assess the first sub-question regarding the feasibility of different heating alternatives in the horticulture sector, this research applies a Multi-Criteria Analysis (MCA). The MCA is conducted as this is an effective framework to compare alternatives on relevant criteria beyond mere financial criteria (Dodgson et al., 2009). By using the MCA approach, the different alternatives could be evaluated and ranked based on their financial and technological aspects. The process of conducting an MCA is summarised in *Table 1*.

Table 1. The three phases of conducting a Multi-Criteria Analysis.

1. Problem identification	**2. The Multi-Criteria Analysis**	**3. Robustness analysis**
Identify alternatives. Identify criteria. Gather data and assign scores to construct a performance matrix.	Standardise criteria. Assign weights. Conclude arrangement of the alternatives.	Sensitivity analysis to assess the robustness of the outcome. Formulate advice.

The different alternatives and criteria have already been identified during the design process of this study. As discussed in the previous section, four potential heating applications were found. Through literature evaluation and consultation with Solinoor, preliminary criteria were identified as well (see *Table 2*). The criteria are chosen for the following reasons;

Originally the NPV was chosen as MCA criterion, but due to the technological immaturity and recent developments of these heating solutions, the information to compute NPVs for the alternatives was inadequate. Therefore, only the investment costs are considered for this analysis. Implications of this are evaluated in *7. Discussion.*

Two types of efficiency; application and thermal, are included as criteria since energy losses are currently one of the largest drawbacks of the green hydrogen production process. These efficiencies have been analysed separately, to ensure a fair comparison between alternatives that produce more than just heat. The thermal efficiency on its own is still considered since the focus of this research is heating greenhouses. This allows the weight for thermal efficiency to be adjusted separately if the focus on heat should increase.

The third criterion is general applicability. This criterion indicates the extent to which the technological alternative can be applied within any greenhouses and is referred to as the scalability of the technology. Solinoor prefers a broadly applicable solution, as tailor-made solutions are seen as more time and cost-intensive. Furthermore, a technological alternative needs to be compatible with the existing infrastructure, this will be referred to as compatibility. The last identified criterion is technological maturity.

The 'technology maturity' criterion has been included during this study, as it became evident that the heating alternatives differ in development and deployment readiness, which affects decision making. The final step of phase 1 and the subsequent MCA phases will be discussed in *Section 3.2.1.* and *Section 4*.

A more comprehensive argumentation on the reason for these criteria to be included can be found in *Section 3 of the Annex*.

Table 2. Criteria overview.

Criteria	Description	Source
Financial aspects		
Investment costs	The initial investments per unit of heating power needed to acquire the alternatives.	SUP1, SUP2, SUP4, GOV2
Technological aspects		
Application efficiency	The ratio of the total produced power (heat and electricity) compared to the input power of the alternative.	(Abdalla et al., 2018; De Jonge, 2021; Glastuinbouw Nederland, 2022)
Thermal efficiency	The ratio of produced heat compared to the initial electrical power input.	(Abdalla et al., 2018; De Jonge, 2021; Glastuinbouw Nederland, 2022)
General applicability	The extent to which the alternative can be applied within any greenhouse.	(Rogers, 2003; Hydrogen Council, 2020; Unruh, 2000) & Solinoor
Compatibility	To what extent the alternative is compatible with the existing infrastructure or would require modifications.	(Groen Kennisnet, 2021; Van Der Veen & Kasmire, 2015) & Solinoor

2.2. Socio-technological analysis

In addition to the MCA that aims to answer the first sub-question of this research, the second sub-question is addressed by using the Technological Innovation System (TIS) framework of Hekkert et al. (2007). This framework can be used to evaluate the development and implementation of a technology by assessing seven key elements providing insights into the socio-technological system that the technology subsides in. The TIS theory suggests that the development and diffusion of a specific (novel) technology is not solely dependent on individual actors. Rather, it is characterised by the influence of four structural dimensions: *actors*, *institutions*, *interactions* and *infrastructure*. These structural dimensions form the building blocks of a TIS and are embedded in a set of seven *system functions* (*Table 3*) that represent the vital processes of innovation systems (Hekkert et al., 2007). By assessing the fulfilment of these seven functions, an overview of the strengths and weaknesses of a technology could be provided.

Table 3. The seven TIS functions as described by Hekkert et al. (2007).

TIS functions	**Description**
Entrepreneurial activities	Presence of active entrepreneurs, whether they are new entrants or incumbent firms.
Knowledge development	Technological learning, indicated by R&D projects & investments and patents.
Knowledge diffusion through networks	Exchange of information, indicated by networks & conferences and network size & intensity.
Guidance of the search	Clearly articulated and shared goals.
Market formation	Providing niche shielding and/or competitive advantages to promote development.
Resource mobilisation	Diffusion of financial capital to aid technology development.
Creation of legitimacy / Counteract resistance to change	Empower technologies by creating advocacy and legitimacy.

Furthermore, the configuration of the structural dimensions could affect the TIS performance positively and negatively (Suurs et al., 2010). The negative effect on TIS performance can be caused by absent or lacking structural dimensions and is often referred to as *systemic problems* or *barriers* (Markard & Truffer, 2008; Wieczorek & Hekkert, 2012). Contrarily, if the structural dimensions are highly present or of high quality, these can induce technology development and diffusion; these are referred to as *systemic drivers* (Darmani et al., 2014).

Instead of assessing the seven TIS functions for the individual alternatives, this study examines systemic drivers and barriers by considering the entire green hydrogen production process as the focal technology. Subsequently, these barriers and drivers are related to the seven TIS functions to show how they are affecting the development and implementation of the green hydrogen production process, thus answering the second subquestion of this research. Accordingly, this is used to provide Solinoor with an overview of opportunities and challenges within a broader socio-technological context.

3. Method

To perform the MCA, this study used both quantitative and qualitative data. The socio-technological analysis has been conducted through an inductive, qualitative approach, as it aimed to examine perceived drivers and barriers related to the green hydrogen production process.

3.1. Data collection

The data used in this research originates from two different sources including, literature and interviews.

3.1.1. Literature

The first part of this research consisted of reviewing Dutch news articles and reports to provide initial contextual insights, select relevant respondents and support their claims. The search strings used to collect news articles were based on the three energy outputs of the green hydrogen production process: green electricity, hydrogen and residual heat. Since 'groene elektriciteit' was deemed too broad and would produce irrelevant results, this string was changed to 'warmtepomp' (the technology that runs on green electricity). An overview of the search strings, publication date and the number of articles are featured in *Table 4*.

Academic, consultancy and policy reports were assessed to provide insights into both the MCA criteria and the socio-technological drivers and barriers. Efforts were made to locate viable sources on Google Scholar and ScienceDirect with several, directed search strings until no novel findings were found, i.e. data saturation occurred.

Table 4. Data characteristics of the news articles.

Search string	Publication date	Source	Number of articles
"Glastuinbouw" and "waterstof"	01-01-2019 till 08-06-2022	Online newspapers	97
"Glastuinbouw" and "warmtepomp"	01-01-2019 till 08-06-2022	Online newspapers	56
"Glastuinbouw" and "restwarmte"	01-01-2019 till 08-06-2022	Online newspapers	121

3.1.2. Interviews

To achieve a multidisciplinary overview, eleven stakeholders along the value chain have been interviewed regarding the green hydrogen production process in the horticulture sector. In addition, one stakeholder participated through an email conversation in this research. This resulted in the following types of respondents participating in this study: a research institute, supply-side actors, an intermediary organisation and demand-side actor, and governmental actors. No interview could be conducted with individual horticulturists, yet as current respondents had prior experience working in and with the horticulture sector, the perceptions of horticulturists were still indirectly addressed during the interviews. An overview of the respondents is shown in *Table 5*. To ensure the interviews were consistent and covered all the relevant subjects, a semi-structured interview guide has been set up. This interview guide is included in *Appendix I – Interview guide*. The transcripts of the semi-structured interviews can be found in *the complementary transcript document*. To further increase the consistency of the interviews, at least two researchers were present during each interview.

Table 5. Respondents who participated in this research.

Respondent	**Company**	**Respondent type**
RES1	TNO	Research institute
SUP1	Adsensys	Supply-side (Hydrogen application)
SUP2	Reduses	Supply-side (Heat Pump)
SUP3	*Anonymous*	Supply-side (Heat exchangers)
SUP4	Pon Power	Supply-side (CHP) [Interview & email]
SUP5	2G	Supply-side (CHP) [Interview & email]
SUP6	Clean Power Hydrogen	Supply-side (Electrolyser)
SUP7	Bosch	Supply-side (Hydrogen Boiler) [Email]
INT1	BlueTerra	Intermediary organisation
DEM1	Lingezegen Energy	Demand-side (Collective)
GOV1	Municipality of Westland	Government
GOV2	RVO	Government
SOL1	Solinoor	Client

3.2. Data analysis

The literature and interviews have all been coded by at least two researchers. This has been combined with internal discussions in the research group to ensure coding is done accurately and to increase inter-coder reliability. The subsequent data analysis was conducted along with the two analytical steps – the MCA and the socio-technological analysis – which are elaborated below accordingly.

3.2.1. Multi-Criteria Analysis

Through theoretical coding, data on the criteria of the heating applications – retrieved from either the literature or interviews – were assigned to the MCA criterion it is related to. An overview of how the numerical values for the criteria are determined is shown in *Table 6*. A more elaborate description of how these values were determined is included in *Appendix II – MCA criteria*.

Table 6. Criteria overview and measurement.

Criteria	Description	Measurement level
Financial aspects		
Investment costs	The initial investments per unit of delivered heating power to acquire the applications.	Ratio (€) / kW_{out}
Technological aspects		
Application efficiency	The ratio of the total produced power (heat and electricity) compared to the input power of the application.	Ratio (P_{out} / $P_{in,\ application}$)
Thermal efficiency	The ratio of produced heat compared to the initial electrical power input.	Ratio (Q_{out} / $P_{in,\ initial}$)
General applicability	The extent to which the application can be applied within any greenhouse.	Ratio (No. of suitable cultivation types) *
Compatibility	To what extent the application is compatible with the existing infrastructure or would require modifications.	Ordinal (Modification extent) **
Technology maturity	The extent to which the application is developed and ready for the market.	Ordinal (Technology Readiness Level 1-9) ***

** Number of cultivation types in which the technology is suitable, ranging from 0-4. Cultivation types: heavily lighted-, moderately lighted-, unlighted-, and extensive cultivation (Vanthoor & de Zwart, 2017).*
*** 1 = Extensive collective modifications required; 2 = extensive individual modifications required; 3 = modular individual modifications required; 4 = no modifications required.*
**** Based on the 9 Technology Readiness Levels as described by Straub (2015), Appendix II – MCA criteria.*

As the measurements and units of these criteria are heterogeneous, standardised values are required to compare the alternatives. Out of several standardisation methods, interval standardisation would best fit the aim of this research. The advantage of interval standardisation over other standardisation methods is that it entails consistency within the assessment of each criterion and that it amplifies the differences between alternatives (Dodgson et al., 2009). Regarding the nature of the criteria, the investment cost criteria could be seen as a *cost* criterion and should strive for the lowest value. All other criteria could be seen as *benefit* criteria which prefer the highest value. Consequently, different standardisation formulas apply. *Formula [1]* depicts the interval standardisation formula for cost criteria:

$$[1]\ Standardised\ score = 1 - \frac{Criteria\ score - lowest\ score}{Highest\ score - lowest\ score}$$

For the benefit criteria, however, *Formula [2]* applies:

$$[2]\ Standardised\ score = \frac{Criteria\ score - lowest\ score}{Highest\ score - lowest\ score}$$

After calculating the standardised values for each criterion, weights have been assigned to each of the criteria (*Table 7*). In this way, more important criteria can have a larger influence on the final score than less important criteria. These weights have been determined through contact with the client (Email 4, SOL1). The assigned weight for efficiency is equally divided among application efficiency and thermal efficiency.

Table 7. Assigned weight per criterion in consultation with Solinoor (Email 4, SOL1).

Criteria	Weight (%)
Financial aspects	
Investment costs	25%
Technological aspects	
Application efficiency	7.5%
Thermal efficiency	7.5%
General applicability	20%
Compatibility	30%
Technology maturity	10%

After assigning the weights, the final scores for each technology have been computed. Accordingly, the arrangement of the alternatives is computed and the robustness of the outcome is tested in a sensitivity analysis. By changing standardisation methods and adjusting the weights, variations in MCA scores and outcomes were assessed. Consequently, the robustness of the outcome and the advice regarding the MCA encompasses less uncertainty. The results of the MCA and its robustness are discussed in *Section 4*.

3.2.2. Socio-technological analysis

Similar to the Multi-Criteria Analysis, data for the socio-technological analysis has also been analysed through theoretical coding. Yet instead of the selected MCA criteria, literature and interviews were now theoretically coded based on the seven TIS functions of Hekkert et al. (2007). When potential drivers and barriers of the green hydrogen production process were identified, these were allocated to the specific TIS function they were stimulating or inhibiting. Through axial coding within these TIS functions, similar codes were finally aggregated, providing an overview of systemic drivers and barriers that are affecting the development and implementation of the green hydrogen production process per TIS function. Technology- or application-specific drivers and barriers have not been included, as the socio-technological analysis is focused on the encompassing green hydrogen production process instead.

4. Multi-Criteria Analysis

This section entails the MCA to answer the first sub-question of this research. The MCA consists of four different application alternatives identified; an electrical heat pump, residual heat, hydrogen CHP and a hydrogen boiler. Given this analysis, the arrangement from best to worst alternative is computed. This section follows the three MCA phases as described in *Table 1*.

4.1. Evaluation of alternatives

In the first phase of the MCA, the financial and technical aspects of the alternatives are evaluated and scored. This way, the criteria scores are summarised in a performance matrix (*Table 8*).

Firstly, heat pumps and hydrogen CHPs scored similarly for investment costs. However, the hydrogen boiler has almost double the investment costs per kW compared to these technologies. As argued in *Appendix III – Multi-Criteria Analysis*, the investment costs of residual heat can be disregarded. Secondly, the application efficiency is relatively comparable to most technologies. The heat pump does have a higher score given its Seasonal Coefficient of Performance (SCOP). In the case of thermal efficiency, the hydrogen boiler does have a relatively high efficiency compared to the other alternatives. Regarding applicability, residual heat scores low compared to the other technologies as it could not provide sufficient heat solely. As for compatibility, heat pumps and hydrogen boilers would require more extensive infrastructural modifications and, therefore, score marginally lower than the other alternatives. Lastly, the technological maturity shows the readiness of the technologies of the heat pump and residual heat. Hydrogen CHPs are almost fully mature, however, hydrogen boilers are still underdeveloped. This scoring process for each alternative is further substantiated in *Appendix III – Multi-Criteria Analysis*.

Table 8. Performance matrix of the assigned criteria scores for each alternative.

Criteria/technology	Heat pump	Residual heat	Hydrogen CHP	Hydrogen Boiler
Investment costs (€/kW)	1250	0	1275	2400
Application efficiency (%)	315	95	80.5	91
Thermal efficiency (%)	315	32.5	27.3	63.7
Applicability*	4	2	4	4
Compatibility**	2	3	3	2
Technology maturity***	9	9	8	5

** Ranging from 0-4 suitable cultivation types. Cultivation types: heavily lighted-, moderately lighted-, unlighted-, and extensive cultivation (Vanthoor & de Zwart, 2017).*
*** 1 = extensive collective modifications required; 2 = extensive individual modifications required; 3 = modular individual modifications required; 4 = no modifications required.*
**** Based on the 9 Technological Readiness Levels (Straub, 2015), Appendix II – MCA criteria.*

4.2. Multi-Criteria Analysis

In the second phase of the MCA, the performance matrix (*Table 8*) is standardised and multiplied with the weights per criteria (*Table 7*). This has led to the following overview as shown in *Table 9* where the standardised weighted criteria scores are summarised. From the accumulated scores, it becomes evident that the hydrogen CHP is the best performing alternative for heating greenhouses, because of its high applicability and compatibility (0.69). Residual heat emerges as the second most feasible alternative, due to its relatively low investments costs and high compatibility (0.66). Heat pumps are ranked third (0.57), as they performs weaker in terms of applicability when compared to the other alternatives. At last, the hydrogen boiler should be considered as an alternative for heating greenhouses (0.21).

Table 9. MCA outcome and cumulative scores for each alternative.

Criteria/technology	Heat pump	Residual heat	Hydrogen CHP	Hydrogen boiler
Investment costs	0.12	0.25	0.12	0.00
Application efficiency	0.08	0.00	0.00	0.00
Thermal efficiency	0.08	0.00	0.00	0.01
Applicability	0.20	0.00	0.20	0.20
Compatibility	0.00	0.30	0.30	0.00
Technology maturity	0.10	0.10	0.08	0.00
Final score	**0.57**	**0.66**	**0.69**	**0.21**

4.3. Robustness analysis

In the third and last phase of the MCA, sensitivity analyses are conducted to assess the robustness of the outcome. Different scenarios are proposed that alter the weight distribution of the criteria and a different standardisation method is used.

4.3.1. Weight allocation

For the weight sensitivity analysis, four different scenarios are considered and listed below. According to these scenarios, the weights are altered per criteria (*Table 10*).

1. *Equal weights* – each criterion is valued as equally important. The 20% for efficiency is evenly subdivided among the two considered efficiency types.
2. *Infinite capital* – the importance of financial criteria is decreased to 5% and weight is equally distributed among the other criteria. This scenario illustrates the case of an abundance of subsidies or financial resources available.
3. *Maximise efficiency* – additional emphasis on reducing energy losses and most optimal energy usage. In this case, 5% of each other criteria is deducted and evenly spread among the efficiency criteria.

4. *Technologically most feasible* – technological specifications play a more vital role as this may ease and accelerate the implementation process if a more rapid sustainability transition is desired. Hence, applicability, compatibility and technological maturity are increased by 5%.

Table 10. Weight distribution in different scenarios.

Criteria	Original Weight	Weight uncertainty scenarios			
		Equal weights	*Infinite capital*	*Maximise efficiency*	*Technologically most feasible*
Investment costs	25%	20%	5%	20%	15%
Application efficiency	7.5%	10%	10%	17.5%	5%
Thermal efficiency	7.5%	10%	10%	17.5%	5%
Applicability	20%	20%	25%	15%	25%
Compatibility	30%	20%	35%	25%	35%
Technology maturity	10%	20%	15%	5%	15%

Given the scenarios, some deviations are noticeable regarding emerging dominant alternatives (*Figure 2*). In the *Equal weights* scenario, the heat pump (0.70) performs slightly better than the hydrogen CHP (0.64). Yet, both are feasible alternatives and score relatively high. Regarding the *Infinite capital* and *Technologically most feasible* scenarios, the hydrogen CHP is still preferred as it scores the highest with 0.74 and 0.78 respectively. The further increase of hydrogen CHPs in the *Technologically most feasible* scenario is because of the current natural gas CHP heating systems which could be retrofitted to become 100% hydrogen-compatible CHPs (SUP4; SUP5). Besides, in this scenario, the residual heat alternative (0.65) also performs marginally better than the heat pumps (0.57). As the weight of the efficiency criteria decreased, so did the score of heat pumps which possess a significant (thermal) efficiency advantage over the other alternatives due to the high (S)COP values. Because of the high efficiency, the heat pump is the best and preferred alternative in the *Maximise efficiency* scenario (0.65), followed by the hydrogen CHPs (0.53). The potential complementarity of the alternatives, however, is further substantiated in *7. Discussion*.

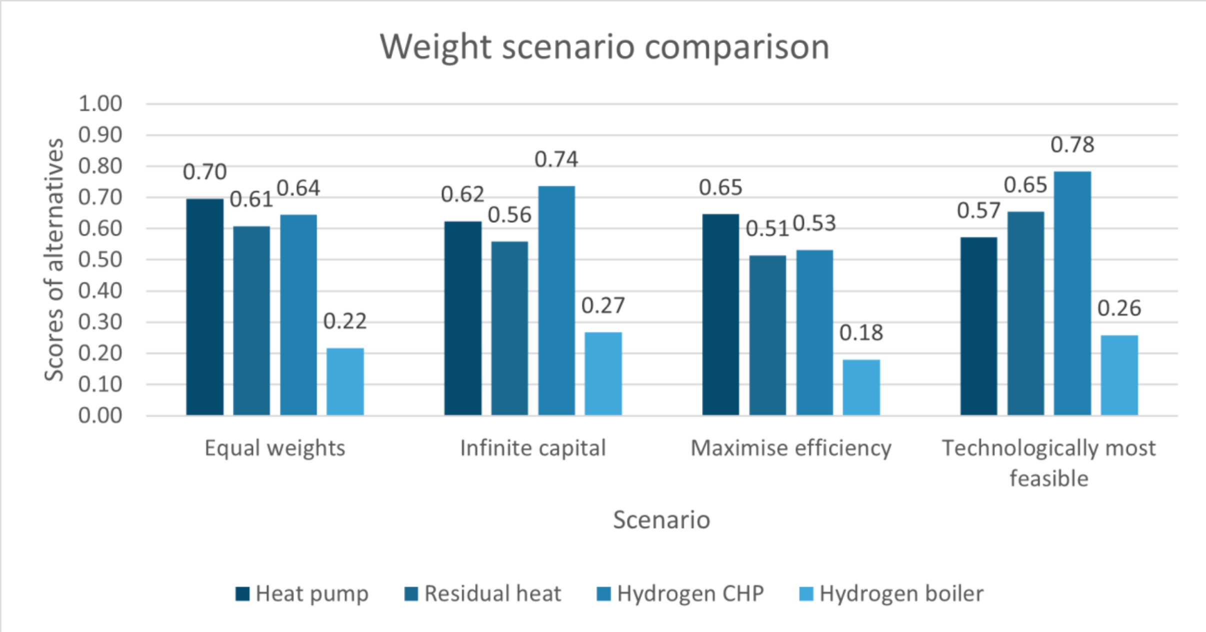

Figure 2. Robustness analysis overview of the different outcomes in different scenarios.

4.3.2. Standardisation method

For the standardisation sensitivity analysis, maximum- and goal- standardisation are possible alternatives (Sudhakaran et al., 2013). Maximum standardisation enables an absolute performance comparison of alternatives based on a specific reference point, something that is disregarded with the use of interval standardisation (Dodgson et al., 2009). With goal standardisation, however, goals and baseline values have to be set as specific targets (Sudhakaran et al., 2013). As this study is explorative and no targets are proposed, goal standardisation is not considered for the sensitivity analysis.

To convert the performance matrix (*Table 8*) to standardised values, the *Formula [3]* is used for standardising benefit criteria and *Formula [4]* is used for standardising cost criteria.

$$[3]\ Standardised\ score = \frac{Criteria\ score}{Highest\ score}$$

$$[4]\ Standardised\ score = \frac{1 - \ Criteria\ score}{Highest\ score}$$

With maximum standardisation, the new MCA scores were computed (*Figure 3*). Accordingly, the heat pump (0.77) performs somewhat better than the hydrogen CHP (0.73) when compared to the MCA with interval standardisation. For comparison with the interval standardisation MCA, the heat pump scored 0.57 whereas the hydrogen CHP scored 0.69. The residual heat now scores the highest (0.78) whereas the hydrogen boiler is still the least preferred alternative by scoring 0.49. Noticeably, the hydrogen boiler scored substantially better with maximum standardisation. A cause for this is that maximum standardisation mitigates the extreme values of the interval standardisation (e.g. 0 or maximum points).

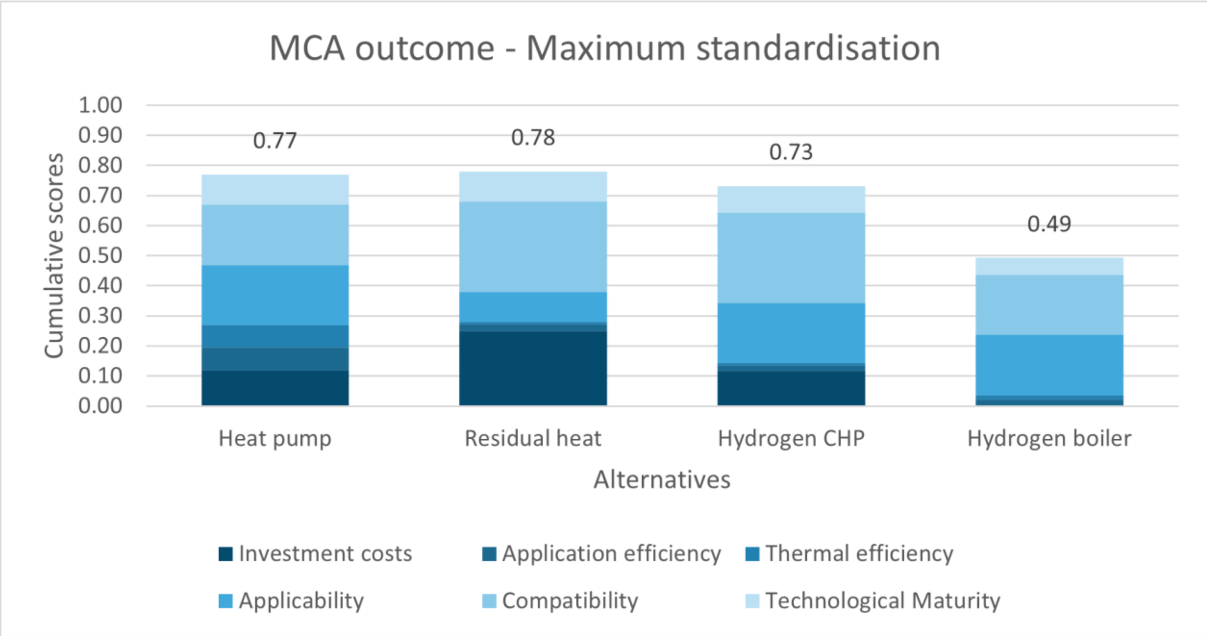

Figure 3. MCA outcome with the use of maximum standardisation of scores.

5. Systemic drivers and barriers analysis

This section describes the systemic drivers and barriers that have been found regarding the development and implementation of the green hydrogen production process in the horticulture sector. These drivers and barriers have been allocated to the corresponding system function they are affecting and are summarised in *Table 11.*

Table 11. Identified drivers and barriers per TIS function.

TIS function	Driver / Barrier	Description
F1. Entrepreneurial activities	Driver	Supply and demand-side actors are expressing their interests in the green hydrogen production process.
	Barrier	Entrepreneurs experiencing hindrances due to a lack of knowledge and practical expertise about the green hydrogen production process. Safety, financial and environmental regulations are insufficiently developed and create uncertainty for entrepreneurs.
F2. Knowledge development	Driver	-
	Barrier	Insufficient knowledge on how to implement the green hydrogen production process in greenhouses due to a lack of experimentation and pilot projects.
F3. Knowledge diffusion	Driver	-
	Barrier	Roughly 80% of the horticulturists manage their energy provision individually, hence collaborative projects and knowledge sharing is marginal.
F4. Guidance of the search	Driver	Articulation of a shared horticulture goal by the Dutch government and horticulturists; carbon-free sector by 2040.
	Barrier	Implementation of the green hydrogen production process in the horticulture sector, concerning other sectors, is questioned. Compared to alternative sustainable energy solutions for the horticulture sector, the green hydrogen production process is not perceived as a prioritised one.
F5. Market formation	Driver	Increasing natural gas and electricity prices, combined with flexibility from horticulturists, stimulate the demand

		for sustainable and potentially cheaper energy alternatives.
	Barrier	Lack of supply and the high price of green hydrogen inhibits the formation of a market surrounding the green hydrogen production process. Insufficient regulation (niche protection) to stimulate market formation.
F6. Resource mobilisation	Driver	Present and future policy programs providing financial resources.
	Barrier	Due to an inversely proportional coupling of sustainable subsidies and natural gas prices, the number of subsidies decreases with higher gas prices.
F7. Creation of legitimacy	Driver	The green hydrogen production process is receiving both governmental and political support. The green hydrogen production process is perceived as a desired alternative or add-on. Implementation of the green hydrogen production process could contribute to solving grid congestion.
	Barrier	Directly utilising electricity, instead of using it for the green hydrogen production process, is perceived as more efficient and socially desired. Implementation of the green hydrogen production process is accompanied by the obligation to purchase additional CO_2. Public safety concerns regarding the green hydrogen production process.

5.1. Entrepreneurial activities

Supply and demand-side actors expressing their interests in the green hydrogen production process is seen as a driver for entrepreneurial activities. Companies are collectively reserving a budget to develop and realise such projects, and due to an increasing demand entrepreneurial activities are becoming more appealing (SUP5).

The first barrier within this function relates to entrepreneurs experiencing hindrance due to a lack of knowledge and practical expertise about the green hydrogen production process (SUP2; SUP5). SUP5 is for instance not considering any hydrogen-related projects, as other projects are currently seen as more profitable and more suitable with their current expertise. Similarly, SUP2 argues the lack of knowledge and expertise inhibits the installation and wider societal implementation of heat pumps. SUP6 elaborated on a lack of knowledge regarding green hydrogen business models; their commercial and economic sides are currently unclear. *"Everyone knows about the hydrogen economy, but no one knows how to scale up the hydrogen economy"* (SUP6). Questions arise regarding where green hydrogen production processes should be located, who the off-takers should be and against what price. As a result, SUP6 argues entrepreneurial activities are lagging globally.

Another barrier impeding entrepreneurial activities relates to lacking regulations. As hydrogen is an explosive and flammable gas, safety regulations need to be established which involves municipalities and environmental services (SUP1). As the application of hydrogen is relatively new, these safety regulations but also tax and environmental regulations are not yet sufficiently developed. This gives rise to uncertainty which inhibits entrepreneurs from implementing the green hydrogen production process in their businesses (SUP5; Van Dijk, 2019; Van den Dikkenberg, 2020).

5.2. Knowledge development

The barrier identified within this function is characterised by a limited number of projects where the green hydrogen production process is implemented within greenhouses. Some studies have been conducted and subsidised pilot projects have been operational, providing valuable insights and knowledge (SUP2; SUP5). According to RES1 however, these are currently not sufficient to properly assess the opportunities of the green hydrogen production process in this sector. A lack of experimenting and pilot projects thus inhibits the creation of new knowledge (RES1).

5.3. Knowledge diffusion

As addressed in the MCA, most horticulturists – 80% according to SUP5 – are individually fulfilling their energy demands (DEM1; GOV1; GOV2; SUP5). Collective energy provision and projects for horticulture clusters are therefore an exception rather than the rule. The predominant individual energy provision and resulting lack of collective energy projects within the horticulture sector are thus inhibiting the diffusion of knowledge.

5.4. Guidance of the search

The Dutch government can be seen as a driver for articulating a shared goal and direction. For instance, a sustainable objective has been defined for and together with the horticulture sector; the sector should be carbon-free by 2040 (Rijksoverheid, 2022b).

However, it is questioned whether the horticulture sector should be one of the first sectors to implement the green hydrogen production process (Verheul, 2020; Westerveld, 2022). In a report of the Port of Rotterdam – showing the port's vision on the application of this process in the Netherlands – the horticulture sector is only regarded as a marginal off-taker (Port of Rotterdam, 2020). The implementation of the green hydrogen production process within other sectors, especially the heavy industry and mobility, is currently more desired and legitimised (RES1; SUP3; GOV1; GOV2). This is because (grey) hydrogen is already being used within the heavy industry and the extensive production of green electricity by the off-shore wind makes utilisation near coastal areas more attractive (RES1).

Furthermore, the perceived role of the green hydrogen production process within the horticulture sector, compared to sustainable and unsustainable alternatives, constitutes a major barrier found within this study. Both the literature review and interviews indicated that the green hydrogen production process is not regarded as a prioritised solution to reduce the CO_2 emissions of the Dutch horticulture sector. This process is generally perceived as a solution to cover only peak heat demand (RES1; INT1; GOV1; GOV2). GOV2 stated two options are recommended first to horticulturists who want to make their greenhouses more sustainable: geothermal energy and generic measures to reduce energy consumption. This research found that geothermal energy and residual heat are currently seen as the dominant sustainable heating processes for the horticulture sector (e.g., GOV2; Sleegers, 2019). In many locations, geothermal energy could cover the relatively large base load of heat demanded by horticulturists effectively and efficiently (RES1; GOV1; GOV2).

5.5. Market formation

The increasing price of natural gas, as well as electricity, has been identified as a driver stimulating the market formation of the green hydrogen production process. Due to these increasing prices, there is a growing interest and demand for sustainable and potentially cheaper alternatives (INT1; SUP2; Clifford, 2022; Keating, 2022; Komaiszko, 2022). As long as it is financially attractive, INT1 argues that the horticulture sector is quite flexible and supports a transition towards sustainable energy alternatives. This is also substantiated by the fact that both the Dutch government and the horticulturists aim for the horticulture sector to phase out natural gas and become carbon-free (GOV2; Rijksoverheid, 2022b).

Moving on, a major barrier affecting market formation is that there is currently not sufficient green hydrogen being produced and commercially available (SUP5; GOV2). Currently, physical infrastructure is lacking to facilitate the production and transport of hydrogen (RVO, 2021). Due to increasing electricity demand in some regions and grid congestion (electricity surpluses) in others, the grid capacity needs to get expanded first before green hydrogen can be produced (RES1; SUP2; Voermans, 2020). Corresponding to the natural law of economics, as a consequence of this rather scarce supply, the market price of green hydrogen is relatively high (SUP5; GOV1). While this lack of supply and high price inhibits the formation of a market surrounding the green hydrogen production process, an underlying cause is further explained in the *creation of legitimacy* function.

The final identified barrier inhibiting market formation is the unfinished regulation, as also discussed within the *entrepreneurial activities* function. However, unfinished tax regulations are not only affecting the activities of entrepreneurs, but also the formation of the market as a whole (SUP5; Van den Dikkenberg, 2020). Path-breaking innovations often require 'protected spaces' (niches) to compete with incumbent technologies, which can for instance be done by financial policy incentives (Smith & Raven, 2012; Boon et al., 2014). Since these regulations are currently not yet in place, the formation of a market around the green hydrogen production process is not yet sufficiently stimulated.

5.6. Resource mobilisation

The Dutch government currently has several policy programs that provide support, primarily financial, to sustainable manners of energy production. The SDE++ program is available for such sustainable energy production alternatives, where green hydrogen production processes can receive subsidies if they meet certain criteria. (Rijksoverheid, 2020; Staatscourant, 2022). In addition, from 2023 onwards, new financial incentives and fiscal policy measures will be in place to achieve the environmental and sectoral goal of becoming climate neutral in 2040. These include the lowering of ODE tariffs (tariffs on sustainable energy storage), increasing tariffs for natural gas and lowering them for electricity, and funds to scale up the development of energy carriers (Rijksoverheid, 2022b; Westerveld, 2021; Van der Lught, 2021). These present and future financial policy programs can thus be seen as a driver for resource mobilisation.

Nevertheless, there has also been a policy barrier identified which inhibits resource mobilisation. Currently, the amount of subsidies for sustainable projects is inversely proportional to the natural gas price, i.e. subsidies are decreasing when natural gas prices are increasing (Talsma, 2022; Verbiesen, 2022). The horticulture sector wants to decouple the subsidies from the gas prices, as otherwise sustainable projects cannot be realised financially, thus resulting in a termination of these projects (Van Dijk, 2022).

5.7. Creation of legitimacy

As priorly discussed, the Dutch government is aiming to phase out natural gas and the green hydrogen production process is therefore perceived as a desired, sustainable and on-demand energy solution in general (RES1; GOV2; SUP4; SUP6). Similarly, the Dutch political support for the green hydrogen production process is also rather positive. As of the present house of representatives, 104 seats represent parties with positive sentiment towards it, 15 are neutral, 17 are negative and 14 make no explicit statement about hydrogen potentials in their election programmes (Mietes, 2021; Penders, 2021). The governmental and political support for the green hydrogen production process can thus be seen as an institutional driver of its legitimacy.

Even though the green hydrogen production process might not be perceived as the primary energy solution for the horticulture sector, it is still regarded as the desired alternative. Geothermal energy and residual heat, for instance, cannot be applied everywhere (GOV2). In addition, the green hydrogen production process is still suitable to cover the peak heat demand and could thus also function as an add-on (RES1; GOV2).

Furthermore, the green hydrogen production process could play a crucial role in stabilising the energy grid. Currently, CHP installations are already functioning as net stabilisers (GOV2). Using the electricity surpluses that are causing grid congestion to produce hydrogen and reduce grid pressure, legitimises the implementation of the green hydrogen production process (GOV2; SUP3; Voorn, 2019).

Besides these drivers, several barriers affecting the societal legitimacy of the green hydrogen production process have been identified as well. The demand for (green) electricity keeps increasing and since energy losses are occurring when producing and using green hydrogen, the general legitimacy of the green hydrogen production process is for instance questioned. Directly utilising the electricity instead is seen as more efficient and socially desired (RES1; GOV2). A result of this barrier is the scarcity of the available green hydrogen and its resulting high price, as discussed in the *5.5 Market formation*.

Interestingly, the green hydrogen production process acting as a carbon-zero energy solution is another major barrier inhibiting its legitimacy among horticulturists. Besides heat and electricity, CO_2 is also one of the main resources demanded by the horticulture sector. When horticulturists would transition to the alternatives discussed in this report, an external supply of CO_2 would have to be supplied to the greenhouses (GOV1; DEM1). GOV1 and SUP2 elaborate on how current natural gas-based CHPs have a strong advantage; they deliver heat, electricity and CO_2, thus enabling individual horticulturists to independently manage their greenhouses and businesses. The obligation to purchase additional CO_2 by implementing the green hydrogen production process is inhibiting its legitimacy (GOV1; SUP4; Stallen, 2022; Van Dijk, 2022). Especially since the storage of CO_2 is subsidised, it is less profitable for industries for instance to supply the CO_2 to horticulturists (GOV1; SUP4; De Jonge, 2020; Van Winsen, 2021).

Another barrier affecting the legitimacy of the green hydrogen production process relates to safety. As priorly discussed, hydrogen is a flammable and explosive gas, which is why it needs to be handled carefully when produced, stored and used (SUP3). Safety concerns are primarily present among the general public (SUP3; SUP6). *"They* [the people] *think or have heard that hydrogen might have a safety issue but technically it has not and is already solved [...] So there are no real safety issues involved but it is more limited regarding the knowledge of the people that are using the technology." (SUP3).* Due to these public safety concerns, whether or not justified, the legitimacy of the green hydrogen production process is inhibited (SUP3; SUP6; GOV1).

6. Conclusion

As Solinoor has expertise in renewable energy production and partnered with Essent, which has access to the end-users, they could contribute to making the horticulture sector more sustainable by implementing green hydrogen. However, uncertainty emerged on what this new sustainable value chain would look like. Accordingly, the following research question was addressed during this study:

"How could the green hydrogen production process enable a more sustainable heating system for the horticulture sector?"

To answer this research question, this analysis was further divided into two subquestions:

- *What is financially and technologically the most feasible alternative to implement the green hydrogen production process within the horticulture sector?*
- *How do socio-technological drivers and barriers affect the development and implementation of the green hydrogen production process?*

With the use of two theoretical and analytical approaches, a Multi-Criteria Analysis (MCA) and a socio-technological Technological Innovation System (TIS) framework, these two sub-questions were answered respectively. Consequently, Solinoor could (1) learn which sustainable heating solution is the most feasible to implement within the horticulture sector, and (2) envision the potentials and hindrances present in this sustainability transition.

When conducting the MCA to address the first subquestion, it was found that hydrogen CHPs are the most feasible alternative for heating the greenhouses (0.69/1.00). The advantage of hydrogen CHPs is that they can be applied in each type of greenhouse and that the existing heating infrastructure of greenhouses – natural gas CHPs – could rather easily be converted into 100% hydrogen-compatible CHPs. From a financial perspective, however, the investment costs of hydrogen CHPs are not the cheapest (1275 €/kW) and are slightly more expensive than the heat pumps (1250 €/kW). Residual heat emerged as the second most feasible alternative, due to no additional investment costs and its high compatibility. In additional robustness analyses, electric heat pumps also scored rather high. Nevertheless, more extensive infrastructural modifications are required to implement heat pumps in greenhouses. Hydrogen boilers are deemed the least feasible application, as they are less maturely developed and the most expensive. Based on financial and technical criteria, hydrogen CHPs are thus seen as the most feasible heating solution for the horticulture sector.

Besides financial and technical criteria, socio-technological drivers and barriers to the green hydrogen production process have been identified, as these affect its development and implementation as well. These results contributed to answering the second sub-question of this research. A major driver is that the green hydrogen production process receives support from various actors, including supply-side manufacturers, horticulturists, governments and politicians. Subsequently, societal goals and policy programs are presently aiming to stimulate the development and implementation of the green hydrogen production process. Moreover, its implementation and development are further stimulated due to the increasing natural gas and electricity prices.

However, several barriers to the green hydrogen production process have been identified as well. Besides insufficient practical knowledge, experimental projects and regulation, the implementation of the green hydrogen production process within the horticulture sector is questioned. It is currently uncertain whether its implementation within this sector is preferred. Moreover, other sustainable heating solutions for greenhouses, e.g. geothermal energy and the residual heat of (heavy) industries, are prioritised over the green hydrogen production process. Finally, the legitimacy of the green hydrogen production process is inhibited due to public safety concerns, the obligation for horticulturists to purchase additional CO_2 and a more desired demand for green electricity instead.

7. Discussion

By combining an MCA with a socio-technological analysis, this study identified the most feasible application of the green hydrogen production process within the horticulture sector, while also indicating encompassing drivers and barriers affecting its development and implementation. Of the various green hydrogen production process applications, hydrogen CHPs are the most feasible to implement within the horticulture sector. This finding is providing Solinoor and Essent with a substantiated direction on how they can implement the green hydrogen production process within greenhouses, which would contribute to making the Dutch horticulture sector more sustainable and carbon-free.

By analysing the socio-technological drivers and barriers, the development and implementation of the green hydrogen production process were examined in a broader context. Solinoor and Essent can take these insights into account within their implementation strategies. Drivers can for instance be exploited to legitimise the implementation of the green hydrogen production process, while barriers can be anticipated upon or utilised in discussions with policy-makers. These barriers can for instance be leveraged to substantiate the need for pilot projects implementing the green hydrogen production process in the horticulture sector.

From an academic perspective, this study led to new insights regarding societal factors that stimulate or hamper the development and implementation of a sustainable energy solution. Several barriers have been identified, primarily present within the *entrepreneurial activities, guidance of the search, market formation* and *creation of legitimacy* system functions. Interestingly, these barriers were often caused by other weak system functions or in turn inhibited other functions' performance. For example, due to a limited number of entrepreneurial activities (F1), new knowledge is insufficiently developed and shared (F2/F3) which in turn creates uncertainty and restricts entrepreneurs (F1). These barriers thus create a vicious circle of weakened system functions. Moreover, as the usage of green hydrogen is less legitimised compared to green electricity (F7), market formation of the green hydrogen production process is inhibited (F5).

The causal interactions between system functions are referred to by scholars as motors of change, which was later also defined as *cumulative causation* (Hekkert et al., 2007; Suurs & Hekkert, 2009). As this study indicated the presence of cumulative causation between system functions, future research could further examine which motors or cumulative causation mechanisms are present in and affecting the green hydrogen production process TIS.

Despite the concrete findings of this study, there are still points for improvement. First of all, whilst this research started with the aspiration to implement a Net Present Value (NPV) criteria within the MCA, this turned out to be not feasible as some heating alternatives were not fully developed or data was not publically available. As an alternative, investment costs (€/kW) are considered. Accordingly, the financial assessment of this research might be limited and superficial as the NPV would have provided more significant insights into the profitability of investments (Juhász, 2011). Hence, follow-up research should evaluate how including an NPV affects the comparison and ranking of the greenhouse heating applications.

Although general applicability and compatibility were included in the MCA, it should be noted that local conditions of greenhouses have to be taken into account as these can affect the feasibility of implementing specific applications. Geographical conditions of greenhouses could for instance vary, which does not always allow for certain heating applications to be implemented. Infrastructural conditions may also differ, e.g. greenhouses could have different types of heating installations and distribution networks. At last, while most horticulturists manage their energy provision individually, cooperative projects are also present. Including the latter can result in different findings regarding the feasibility of applications.

Moving on, it is debatable whether the four selected technological applications can be regarded as isolated implementation solutions since renewable energy technologies can often be complementary to each other. Residual heat could for instance be utilised for heat pumps, hydrogen CHPs and boilers to improve efficiency. Similarly, heat pumps and boilers are often combined, forming a hybrid heat pump installation (Energy Saving Trust, n.d.). Assessing the feasibility of such technological combinations was beyond the scope of this analysis and provides a new avenue for future research.

Furthermore, it can be questioned to what extent the MCA would change if socio-technological aspects were included, instead of conducting two separate analyses. Whereas the scope of the MCA was on individual greenhouse heating applications, the socio-technological analysis emphasised the green hydrogen production process as a whole. Qualitatively, encompassing drivers and barriers of this process were identified, while drivers and barriers for specific heating applications were left unaddressed. Further research could include socio-technological aspects of specific applications and quantify these to perform a single, rigid analysis. Nevertheless, due to methodological and investigator triangulation, the findings of this study are still considered valid and reliable.

Another limitation of this research is that it solely focuses on the heat demand of the greenhouses. Whereas greenhouses do use a substantial amount of heat, they also require electricity for lighting and additional infused CO_2 for increasing crop yields, which is currently originating from their fossil-fuel-based heating installations. Consequently, this research tried to account for the electricity input by dividing efficiency into application efficiency and thermal efficiency. By doing so, alternatives such as the hydrogen CHPs that also produce electricity are assessed by their entire output to achieve a more equal comparison. As for the CO_2 input, no additional measure is included in the MCA. We argue that the CO_2 aspect is a socio-technological driver *and* barrier to the green hydrogen transition in horticulture. Whereas the societal pressure to reduce greenhouse gas emissions is driving this sustainability transition, the technological limitations of renewables that do not emit usable CO_2 form a barrier for horticulturists.

Finally, as this research primarily emphasised the implementation of the green hydrogen production process for heating greenhouses, the comparison with other sustainable avenues such as residual heat from (heavy) industries or biomass installations could be further explored. Although there can be various pathways to achieving a sustainable horticulture sector, this study has shown valuable insights into the feasibility and potential of green hydrogen in this sector.

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9. Appendices

9.1. Appendix I - Interview guide

[Introductie]

Welkom [respondent] en bedankt voor het mee willen werken aan ons interview voor vandaag. Laten wij onszelf maar even kort voorstellen. Wij zijn een groep van vijf Innovation Sciences masterstudenten aan de Universiteit Utrecht en momenteel zijn wij bezig met een consultancy opdracht. Voor deze opdracht werken wij een innovatie/duurzaamheid gerelateerd vraagstuk voor een bedrijf genaamd Solinoor. Bij dit bedrijf zijn ze gespecialiseerd in zonnepanelen en zonneparken aanleggen alleen nu hebben zij de vraag hoe ze vanuit de duurzame zonne-energie waterstof kunnen produceren op een efficiënte manier en hoe dit vervolgens gebruikt kan worden door eindgebruikers. In het specifiek kijken we bij dit onderzoek naar een van de grote energieverbruikers; de glastuinbouw. Bij dit onderzoek kijken wij naar verschillende technieken waarmee waterstof gebruikt kan worden in deze industrie, wat hier allemaal voor nodig is en wat voor problemen hierbij komen kijken.

[Consent]

- Vindt u het goed als dit interview wordt opgenomen zodat wij dit kunnen transcriberen en gebruiken in ons academische onderzoek? U kunt hierbij anoniem blijven als dit gewenst is. Bovendien kunnen we dit bijtijds naar u doorsturen zodat u eventuele correcties en misconcepties kunt aankaarten.
- Dit interview duurt ongeveer 30 minuten
- Mocht u vragen hebben gedurende het interview, onderbreek ons dan gerust. Aan het einde krijgt u van ons ook nog de alle tijd voor eventuele vragen.

[Openingsvragen]

Kunt u ons over uw functie binnen [bedrijf/organisatie] vertellen en op wat voor manier bent u betrokken met waterstof (binnen glastuinbouw)?

Specifieke vragen per respondent-type

[Supplier]

Kunt u ons iets meer vertellen over [technologie]?
In hoeverre is [technologie] al operationeel (met 100% waterstof)?
Wat zijn de (investerings)kosten van [technologie]?
Hoe efficiënt zijn de installaties?
Is [technologie] toepasbaar voor het verwarmen van de glastuinbouw?
Waar zitten momenteel nog de uitdagingen voor [technologie]?
Hoe ziet u de kansen voor het gebruik van waterstof en [technologie]?

[Demand]

Hoe ziet de huidige verwarming infrastructuur eruit voor de glastuinbouw?
Zijn de tuinders met elkaar betrokken en is de verwarmings infrastructuur (collectief) gecoördineerd?
Hoe ziet het (energie)gebruik van de glastuinbouw eruit?

Waar zitten momenteel de knelpunten voor de verwarming van de glastuinbouw?
Naar wat voor duurzame verwarmingsmethoden wordt er al gekeken voor glastuinbouw?
Wat is hierin de rol van waterstof?
Voor glastuinbouw verwarming, waar ziet u momenteel problemen of kansen voor waterstof?

[Government]
Wat is de rol van [overheidsinstantie] voor het (duurzame) glastuinbouw beleid?
Naar wat voor alternatieven kijkt [overheidsinstantie]/glastuinbouw sector voor het verduurzamen?
Hoe is de huidige (verwarmings) infrastructuur voor de glastuinbouw georganiseerd? Is dit in collectief verband of voornamelijk individueel?
Waar zitten momenteel nog problemen voor de glastuinbouw die de transitie naar duurzaam moeilijk maken?
Hoe ziet u hierbij de rol van waterstof voor het verwarmen van de glastuinbouw?
Wat zijn de kansen en barrières voor waterstof?

[Intermediary]
Wat is de rol van [instantie] bij het verduurzamen van de glastuinbouw?
Hoe ziet momenteel de energie- en warmtevoorziening eruit bij de glastuinbouw?
Wat voor duurzame alternatieven worden er momenteel overwogen voor de glastuinbouw?
Wat is hierbij de rol van waterstof?
Welke kansen en barrières heeft het groene waterstof proces in het voorzien van de energie- en warmtevoorziening van de kassen?
Zijn de projecten in de glastuinbouw voornamelijk individueel of collectief?

[Research institute]
Wat is de rol van [instantie] bij het verduurzamen van de glastuinbouw?
Hoe ziet momenteel de energie- en warmtevoorziening eruit bij de glastuinbouw?
Wat voor duurzame alternatieven worden er momenteel overwogen voor de glastuinbouw?
Wat is hierbij de rol van waterstof?
Welke kansen en barrières heeft het groene waterstof proces in het voorzien van de energie- en warmtevoorziening van de kassen?

[Afsluiting]
Denkt u dat waterstof de toekomst is (voor de glastuinbouw)?
Heeft u nog vragen voor ons aan de hand van dit interview?
Mogen we u, indien nodig, nog een keer benaderen voor aanvullende vragen?
[*Optioneel*] Heeft u nog contacten die eventueel relevant zijn voor ons onderzoek?

9.2. Appendix II - MCA criteria

Investment costs

Originally the NPV was chosen as MCA criterion as this is a common and validated method to assess the profitability of the made investments (Juhász, 2011). Due to the technological immaturity and recent developments of these heating solutions, the information to compute NPVs for the alternatives was inadequate. Therefore, only the investment costs are considered for this analysis. Investment costs are expressed in euros (€) per kilowatt (kW) for a fair comparison between the four technologies. Each technology is available in different sizes, expressed in kilowatts, so size must be taken into account when comparing different technologies. This is done by dividing the kw through the investment costs resulting in €/kw. The investment costs only included the acquisition costs of the technology.

Application and thermal efficiency

A distinction is made between application efficiency and thermal efficiency. This study views application efficiency as the percentage of the power output compared to the power input of a specific application. Thermal efficiency is regarded as the percentage of the heat output compared to the power input across the entire green hydrogen production process. As the technological applications use different energy outputs, some additional processes (such as electrolysis) might occur with additional energy losses. In such calculations, the efficiency factors of these processes are thus included in the thermal efficiency as well.

The application and thermal efficiencies have been addressed separately, to ensure a fair comparison between heating alternatives that produce more usable energy than just heat, such as the hydrogen CHP. The thermal efficiency on its own is still considered, since the focus of this research is heating greenhouses.

General applicability

The general applicability will be evaluated based on the extent to which the alternatives are applicable in any greenhouse. Vanthoor & de Zwart (2017) distinguished four general types of cultivation with different heating requirements while examining sustainable heating solutions for greenhouses: heavily lighted-, moderately lighted-, not lighted-, and cooled cultivation. Based on this distinction, the number of cultivation types in which the alternatives can be applied will indicate the general applicability of these alternatives.

Compatibility

The compatibility will be evaluated based on the extent to which the alternatives are compatible with the existing heating infrastructure within the greenhouses. In their study, Blom and colleagues (2021) distinguish between individual and collective solutions to sustainably heat greenhouses. Taking this distinction into account, the following ordinal evaluation scale will be used: 1 = extensive collective modifications required; 2 = extensive individual modifications required; 3 = modular individual modifications required; 4 = no modifications required.

Technological maturity

Technological maturity is evaluated based on the Technology Readiness Level method, using a 9 point scale which is summarised in *Table 12* below. Each technological application is allocated to a corresponding TRL based on the article of Straub (2015).

Table 12. Technological Readiness Levels 1-9 based on Straub (2015).

TRL	Definition	Level description
1	Technology Research	Applied research and development gets envisioned in the form of paper studies into a technology's basic properties.
2	Technology concept	Practical applications get invented after the basic principles have been observed. Application is only speculative.
3	Proof-of-concept	Active R&D has been initiated in the form of analytical studies and lab experiments to validate that the technology is viable. Proof-of-concept gets made.
4	Technology Demonstration	Proof-of-concept gets tested in lab conditions. Results in a generic design demonstrating performance consistent with potential applications.
5	Conceptual Design and Prototype Demonstration	Conceptual design complete. Design is validated in a somewhat realistic, relevant environment.
6	Preliminary Design and Prototype Validation	Representative engineering model is created and gets demonstrated in a relevant environment.
7	Detailed Design and Assembly Level Build	Prototype should be near the scale of the finished technology and the demonstrations need to be in real environments.
8	Subsystem Build and Test	Product/technology has been proven to work under expected circumstances in relevant environments. The technology is now near completion.
9	System Operational	Product/technology gets applied in its final and is introduced into the market.

9.3. Appendix III - Multi-Criteria Analysis

9.3.1. Electric heat pump

Investment costs

According to a study by Pieper et al. (2018), several heat pump types are assessed and compared on various criteria, including the investment costs. For consistent heat production all year long, the groundwater heat pump type is taken as the reference technology (Chokchai et al., 2018; Self et al., 2013). For this research, the average investment costs of a 0.5-4MW heat pump is computed, leading to an overall investment cost of roughly *1.250 €/kW* (Pieper et al., 2018).

Application and thermal efficiency

The thermal efficiency of an electric heat pump, called the Coefficient Of Performance (COP), is influenced by the difference in the temperature of the input and output energy sources (NIBE, n.d.). A higher difference in temperature results in a lower COP (Klimaatexpert.com, n.d.; NIBE, n.d.). To take seasonal influences into account the Seasonal Coefficient of Performance (SCOP) has been established. Heat pumps typically run from 35 to 55 degrees Celsius (Milieu Centraal, n.d.). Therefore, two SCOPs are commonly stated: one for low temperature and one for medium-high temperature operation (see e.g., MasterTherm, n.d.; Anweiler & Masiukiewicz, 2018). Heat pumps used for greenhouse heating would need to run on the higher end of the temperature range (De Zwart, 2013), which is coupled with an average SCOP of *3.15* (*315%*) (Warmtepompvergelijker, 2020). As heat is the only energy output of electric heat pumps and the input power does not change compared to the thermal efficiency determination, the application efficiency of heat pumps also equals *3.15* (*315%*).

General applicability

Vanthoor & de Zwart (2017) state that electric heat pumps powered by green electricity that makes heat can be used for all four types of cultivation. The capacity of the heat pumps would however vary per cultivation type and size of the greenhouse. Therefore, this technology is awarded a score of *4; suitable for all four cultivation types.*

Compatibility

Heat pumps should operate continuously without too many fluctuations to function properly (SUP2). Vanthoor & de Zwart (2017) reinforce this statement and also partly address the compatibility of electric heat pumps. For three of the cultivation types, heat pumps would require an additional aquifer to store and withdraw heat from. Accordingly, the daily variations in energy from solar PV and the energy demand of greenhouses are not ideal for heat pumps, leading to lower compatibility of this technology for greenhouses. Heat pumps are thus not fully compatible with the current greenhouse infrastructure. As it requires several adjustments, this alternative is assigned a score of *2; extensive individual modifications required.*

Technological maturity

Extracting geothermal heat via heat pumps is one of the most promising technologies for heating greenhouses in the Netherlands (CE Delft, 2021; Scheepers et al., 2021; Vanthoor & de Zwart, 2017; RES1; INT1; GOV2). As this technology is readily available and a feasible solution for heating greenhouses, heat pumps are seen as a mature technology. Therefore, this alternative scored a *9 on the TRL scale*.

9.3.2. Residual heat

Investment costs

As the residual heat directly originates from the electrolyser, it could be argued that the costs of electrolysers are used for this criterion. However, since the heat is created as a side-product during the electrolysis process it can be regarded as a residual, yet useful output. This way, no additional costs have to be made to residual supply the heat, as the electrolyser is inherent to the green hydrogen production process. Moreover, electrolyser costs are not included within other alternatives either. In conclusion, the investment costs of residual heat are *0 €/kW.* Nevertheless, it is still important to keep into account that the distance between the electrolyser and the greenhouses needs to be relatively short to avoid additional transportation costs.

Application and thermal efficiency

During the electrolysis process, current PEM electrolysers on average convert ~70% of the energy input into green hydrogen (Scheepers et al., 2020; Tjarks et al., 2018; RES1; SUP3). The remaining ~30-35% of energy will be turned into residual heat with a temperature between 50-90 degrees Celsius (Ahmadi et al., 2013; RES1; SUP3; SUP6). Therefore, a thermal efficiency average of *32.5%* is taken for reference in this MCA. As there are marginal heat losses of the electrolyser (roughly between 3-7%) that are dissipated into the environment and are difficult to recover (SUP3), the application efficiency of the electrolysis process that produces hydrogen and heat as usable outputs is averaged at *95%*. Besides, heat transportation losses are neglected as these losses are stated to be marginal due to state-of-the-art heat distribution technology (SUP3).

General applicability

Besides extracting heat from external heat sources with heat pumps, the residual heat of electrolysis or fossil-fuel-burning processes could be utilised for heating the horticulture sector (Vanthoor & de Zwart, 2017; Vourdoubas, 2019). Vanthoor & de Zwart (2017) argue that residual heat can be used for all four types of cultivation as well. However, for the moderately lighted and unlighted cultivation types, it would require a large residual heat capacity (Vanthoor & de Zwart, 2017; Vourdoubas, 2019). As it is unfeasible to supply with merely the residual heat of an electrolyser, additional technologies such as boilers or heat pumps are required to supply the heat (Vanthoor & de Zwart, 2017; SUP3). Therefore, the residual heat is not a stand-alone solution for providing sufficient heat for all cultivation types and especially lacks for two cultivation types. Therefore, the general applicability of residual heat is awarded a score of *2.*

Compatibility

Although residual heat can be utilised to some extent in greenhouses, its (connection) capacity would vary depending on the type of cultivation. Heavily lighted and cold extensive cultivation requires a small capacity, while moderately lighted and unlighted cultivation needs a bigger connection capacity (Vanthoor & de Zwart, 2017). Vanthoor & de Zwart (2017) also state that the greenhouses which are currently utilising residual heat, often originating from the industry, are part of a cluster with a heating network. Nevertheless, collective energy provision for horticulture clusters is an exception rather than the rule. Most horticulturists – 80% according to SUP5 – are individually fulfilling their energy demands (DEM1; GOV1; GOV2; SUP5). Focusing on this majority and assuming that these horticulturists utilise the residual heat from their green hydrogen production, it is argued that this residual heat utilisation can relatively easily be implemented (SUP3, SUP6).[2] The compatibility of residual heat utilisation, therefore, gets a score of *3; modular individual modifications required*.

Technological maturity
In an empirical study, the waste heat that is produced from a PEM fuel cell could effectively be used for heating greenhouses (Ceylan & Devrim, 2021). The heat that is irradiated from electrolysers could effectively be captured and transported with well-developed state-of-the-art technology to be reused in other industrial purposes, including the horticulture sector for heating the greenhouses (SUP3; SUP6). Therefore, as the technology is available and applicable for heating greenhouses, this is assigned a *9 on the TRL scale*.

9.3.3. Hydrogen CHP

Investment costs
According to SUP5 (Email 3), hydrogen CHPs would cost roughly *1.430 €/kW*. In addition, SUP4 mentioned that the investment costs for a hydrogen CHP pilot project are estimated at *1.120 €/kW*, yet this might change throughout this pilot (Email 2, SUP4). Given these numbers, the average investment cost for a hydrogen CHP is used in this research and calculated to be *1.275 €/kW*.

Application and thermal efficiency
The total system efficiency of CHP systems – including both electricity and heat production – varies between 60-80% (EPA, n.d.). Yet, modern hydrogen cogeneration gas turbines are stated to reach up to 85% of overall system efficiency (Siemens, 2020). According to SUP4, this percentage of efficiency is divided among electricity production and heat generation. In a supplied document, the electric efficiency of CHP installations is stated to be 41.5%, and the thermal efficiency 39%, leading to an application efficiency of *80.5%* that will be used in this study (Email 2, SUP4). Regarding thermal efficiency, however, the CHP installation is situated after the electrolyser which runs at approximately 70% efficiency. Therefore, the thermal efficiency of the CHP is multiplied by the electrolyser efficiency, leading to an overall thermal efficiency of *27.3%*.

[2] The scenario in which the horticulturists transition to a more collective energy provision, requires extensive collective modifications for new heating networks, is also not considered.

General applicability

Natural gas CHPs are currently used for lighting and heating greenhouses (RES1; SUP2; DEM1). Instead of fueling CHPs with natural gas, hydrogen CHPs are produced which could be fueled with hydrogen (SUP4; SUP5). The technological principles of this technology stay the same (SUP4). Accordingly, since this technology uses the same principles the general applicability is scored with a *4* and is suitable for all cultivation types.

Compatibility

Companies such as PonPower and 2G are working on converting existing CHPs into 100% Hydrogen CHPs. This will create a sustainable process that will only change components of the CHP systems in place and maintain the existing infrastructure. CHPs can be adapted with conversion kits during regularly scheduled motor revisions (SUP4; SUP5) and hydrogen could be transported through the existing natural gas infrastructure (Deloitte, 2021). Currently, with this CHP technology, hydrogen can be mixed with natural gas with up to 30% hydrogen. This can be directly applied within certain sectors (Firstgas, 2021). Therefore, is this technology awarded with a *3* as it only needs modular individual modifications.

Technological maturity

Hydrogen gas turbines, which can be implemented in CHPs, are currently in development and still not broadly available in the market. (Kim, 2019, SUP4, SUP5). The main difficulties that arise with the transition towards 100% hydrogen turbines are the different burning characters well-developed flame temperature and burning velocity (Kim et al., 2020). 2G is currently the only manufacturer on the market already selling 100% hydrogen CHPs (SUP5). Competitors, like Caterpillar, aim to release their first hydrogen CHPs at the end of 2022 (SUP4), with full-scale prototypes of this technology already running.. This means that despite the difficulties, the technology is almost ready for a general entry into the market. Accordingly, this technology is in the *8th* TRL.

9.3.4. Hydrogen Boiler

Investment costs

According to Röben et al. (2022), the acquisition costs of a hydrogen boiler is roughly €11.000 with an output of 4.56 kW, therefore, the costs would entail *€2.400/kW.* In addition, The Engineer (2021), a UK magazine, claims that the investment costs of a hydrogen boiler will become equal to a boiler of natural gas. However, as will be explained in the paragraph on technological maturity the hydrogen boilers are still in the development phase. This means that the investment costs of a boiler are still uncertain, but are expected to become cheaper.

Application and thermal efficiency

Currently, hydrogen-ready boilers are certified to run at an ERP efficiency of 91%. Full hydrogen boilers are expected to maintain their energy efficiency (Gołdasz et al., 2022; Email 1, SUP7). This *91%* application efficiency of the hydrogen boiler, combined with the 70% efficiency of the electrolysers, leads to a thermal efficiency of *63.7%.*

General applicability
The article of Vanthoor & de Zwart (2017) also addressed the bio-oil stoked boiler. These boilers make use of bio-oil (green electricity) that can be used for all four types of cultivation. As the hydrogen boiler works similar to the bio-oil stoked boiler and current system (natural gas boilers), all four types of cultivation can be grown with this new type of technology. Therefore, this alternative is awarded a *4*.

Compatibility
Existing (natural gas) boilers in greenhouses should be able to handle a mix of natural gas and hydrogen up to ~20% according to the email correspondence with SUP7. Yet, this technology is not suitable for converting boilers into 100% hydrogen boilers. However, newer hydrogen-ready boilers can run hydrogen blends and can be converted to run on 100% hydrogen (Email 1, SUP7). In addition to this, hydrogen boilers do not require extensive infrastructure modifications, whilst the current infrastructure can be used (i.e. existing water pipelines, etc.) Therefore, as this technology would require extensive modifications, this alternative is awarded a *2; extensive individual modifications required*.

Technological maturity
Hydrogen boilers are still in the development phase where initial pilot projects are deployed to test the feasibility of hydrogen blending with natural gas (Gersen et al., 2020). However, 100% hydrogen boilers are not on the market yet and are not expected to be available before 2024 (Email 1, SUP7). Currently, multiple companies are working on prototypes that are running and being improved but are in early stages. Therefore the hydrogen boiler technology has been classified in the *5th TRL*.

10. Annex - Research design

11. Introduction

To achieve the energy goals to mitigate climate change, stakeholders from all layers of society are encouraging the usage of sustainable energy alternatives. Besides stimulating solar and wind energy, fitting the current electrification trend, alternative renewable solutions are also being explored. Hydrogen produced from renewable energy sources, so-called 'green' hydrogen, is one of these. Currently, 8% of the total CO_2 emissions in the Netherlands originate from the production of fossil fuel-based 'grey' hydrogen (Rijksoverheid, 2022a). Striving for a sustainable energy system in 2050, the Dutch government endeavours for a more sustainable hydrogen production process and wants to stimulate the usage of green hydrogen as a fuel in various sectors (Rijksoverheid, 2022a).

Achieving this goal requires the help of private-sector firms. One of such is Solinoor, which examines and pursues sustainable energy solutions. Currently, Solinoor is investigating the application of green hydrogen within various sectors, one of which is the horticulture sector. The Dutch horticulture sector has committed to reducing its CO_2 emissions to 2.2 Mton annually by 2030, saving approximately 3.5 Mton per year compared to the period of 2015-2017 (Klimaatakkoord, 2019). Moreover, the dutch horticulture agenda expresses the aim to have a climate-neutral horticulture sector by 2040 (Greenports Nederland, 2019). To reach these goals, the sector needs to save energy, reduce waste and find an alternative heat source for its greenhouses. Green hydrogen, or its related energy outputs, could contribute to achieving these goals by making the heating process more sustainable since it does not emit CO_2 when produced and burnt. In a mathematical study by Anifantis et al. (2018), a green hydrogen-powered heat pump for greenhouses is examined, showing that uncertainty remains on the feasibility of larger-scale application in terms of energy efficiency and economic viability. Accordingly, there is a lack of understanding of how the entire green hydrogen production process can be applied within the horticulture sector in the Netherlands. Currently, common greenhouse heating methods are natural gas boilers or combined heat and power (CHP) installations as part of a central heating system (Blom et al., 2021; DutchGreenhouses, n.d.; Royal Brinkman, 2018).

Therefore, this report aims to explore various heating applications related to green hydrogen within the horticulture sector. Moreover, this report aims to evaluate the current state, barriers and drivers of green hydrogen application alternatives within the Dutch horticulture sector. Thereby, assessing the feasibility of the green hydrogen production process for providing greenhouses with a more sustainable heating system. To guide this report, the following research question has been formulated:

"How could the green hydrogen production process enable a more sustainable heating system for the horticulture sector?"

This research question is further delineated into two sub-questions. The first sub-question will address the characteristics of the alternatives from a financial and technological standpoint. The second question will elaborate upon a systemic approach to how these alternatives fit within a broader socio-technological context. This is done, on the one hand, to provide Solinoor with clear, practical and directional insights. On the other hand, socio-technological context can help to explain other relevant factors that otherwise would be overlooked. The role of the government and potential rules and regulations as one of the examples. For the contextual analysis, the Technological Innovation Systems approach of Hekkert et al. (2007) will be operationalised by identifying the system barriers and drivers through the framework of Wieczorek & Hekkert (2012). Combining these approaches creates overlap regarding technological aspects. However, both methods are deemed necessary since these frameworks provide relevant insights based on the nature of the outcomes described above. Based on these frameworks, the following sub-questions have been drafted.

- *What is financially and technologically the most feasible option to implement the green hydrogen production process within the horticulture sector?*
- *How do socio-technological drivers and barriers affect the development and implementation of the green hydrogen production process?*

By answering these questions, this report aims to identify existing uncertainties and barriers regarding green hydrogen application. Moreover, it will indicate the drivers and practical applicability of integrating the green hydrogen production process within the Dutch horticulture sector. As the horticulture sector is currently energy-intensive and unsustainable through emitting a substantial amount of greenhouse gases (Persiani et al., 2019; Zhang et al., 2020), this study could highlight the potential and feasibility of making a transition toward a more sustainable approach.

In *section 2*, a more detailed description of the case, the hydrogen production process, and alternatives will be given. Thereafter, the theoretical approach will be elaborated upon in *section 3* which entails the criteria that will be used to compare the alternatives, followed by the description of the Technological Innovation System framework as described by Hekkert et al. (2007) for the contextual analysis. At last, *section 4* includes the methodology, describing the research strategy and data gathering approach.

12. Green hydrogen production process

To fully assess the opportunities and barriers of green hydrogen, its production process will first be elaborated on. Hydrogen (H_2) is an energy carrier and, as it is not a naturally occurring resource, always has to be produced first. The energy needed to produce the hydrogen could come from different energy sources, resulting in different types, or 'colours', of hydrogen.

In the Netherlands, 80% of the produced hydrogen (8 billion m^3) is produced by burning natural gas and is thus classified as grey (Milieu Centraal, n.d.-a).[3] Although this is currently the cheapest production method, the production of grey hydrogen results in CO_2 emissions. Green hydrogen, in contrast, is produced from renewable energy sources without emitting CO_2. As the production costs of green hydrogen are higher than those of grey hydrogen, the actual amount of green hydrogen produced in the Netherlands is negligible (Milieu Centraal, n.d.-a). Nevertheless, many actors within the Netherlands are experimenting with large-scale green hydrogen production (TNO, n.d.).

Within the production process of green hydrogen, two generic phases can be distinguished (TNO, n.d.). The first phase is the *generation of renewable energy* by wind energy or solar PV. This energy can then be used in the second phase, which is the actual *production of green hydrogen*. Green hydrogen can be produced through various biomass processes or by splitting water through chemical processes (Kumar & Himabindu, 2019). This research will only consider electrolysis, one of the latter processes, as this will be in line with Solinoor and other stakeholders' hydrogen production processes (TNO, n.d.). Green hydrogen is generally produced with one of two viable water electrolysis methods: the alkaline process and the proton exchange membrane (PEM) process (Dincer, 2012).[4] These chemical processes are discussed in greater detail in *Appendix I.I*, but it is noteworthy to mention that the PEM method especially produces significant residual heat.

12.1. Energy outputs & technological alternatives

As previously elaborated, the production process of green hydrogen is characterised by three energy outputs: *green electricity*, *residual heat* and *hydrogen*. The primary energy demand of the horticulture sector can be expressed in terms of heat and electricity (Blom et al., 2021; USDA, 2016; Vanthoor & de Zwart, 2017). In this subsection, the energy outputs of the green hydrogen production process will be related to single technologies which could supply the heat demanded by the horticulture sector. Technologies that can combine one of the three energy outputs with another energy source (i.e. hybrid technologies, such as a boiler using both hydrogen and natural gas), will only be included if they are also able to fully run on one of the three, climate neutral, energy outputs.

[3] The residual 20% of the hydrogen is produced as a by-product of the chemical industry (Milieu Centraal, n.d.-a)

[4] Other, less common, electrolysis methods are solid oxide electrolysis and microbial electrolysis (Kumar & Himabindu, 2019; Burton et al., 2021).

Greenhouses could use the electricity initially generated from solar PV and wind turbines for the electrolysis process. Here, part of this green energy will instead be allocated to the horticulture sector which could then be used to heat its greenhouses. This could be done using an *electric heat pump* as a central heating system (Vanthoor & de Zwart, 2017).

Due to a lack of electrolysis efficiency – the process reaches a peak efficiency of 60 to 80 percent (Burton et al., 2021; Kumar and Himabindu, 2019) – residual heat is being emitted to the environment when hydrogen is produced and is thus seen as lost (Buttler & Spliethoff, 2018). However, if the greenhouses are located near the green hydrogen production facility, efforts could be made to utilise the residual heat within the horticulture sector (Greenport West-Holland, 2020; Rijksoverheid, 2022b; Voogd et al., 2021). To be utilised in this manner, the residual heat of the electrolysers needs to be captured, transformed into hot water and transferred via a heating network first (Expertise Centrum Warmte, 2022). The residual heat could subsequently be used to heat the greenhouses.

Finally, the desired output of the green hydrogen production process, i.e. green hydrogen, could also be applied within the horticulture sector (Rijksoverheid, Vosmer, n.d.). Similar to a conventional natural gas boiler, a *hydrogen boiler* could burn the produced green hydrogen to heat greenhouses (Gigler & Weeda, 2018). Another solution could be a *hydrogen CHP* system producing both heat and electricity. Currently, the horticulture sector is assessing whether the current gas-powered CHPs could be transformed into hydrogen-powered ones (Hiddink, 2022). For the hydrogen to be applied in these cases, it needs to be transported and potentially stored on location.

To summarise, several technologies have been identified which could utilise the energy outputs of the green hydrogen production process for greenhouse heating, as is illustrated in *Figure 1*. To compare these technological options, criteria need to be established. The next section will delineate these heterogeneous criteria based on the theoretical framework of this research.

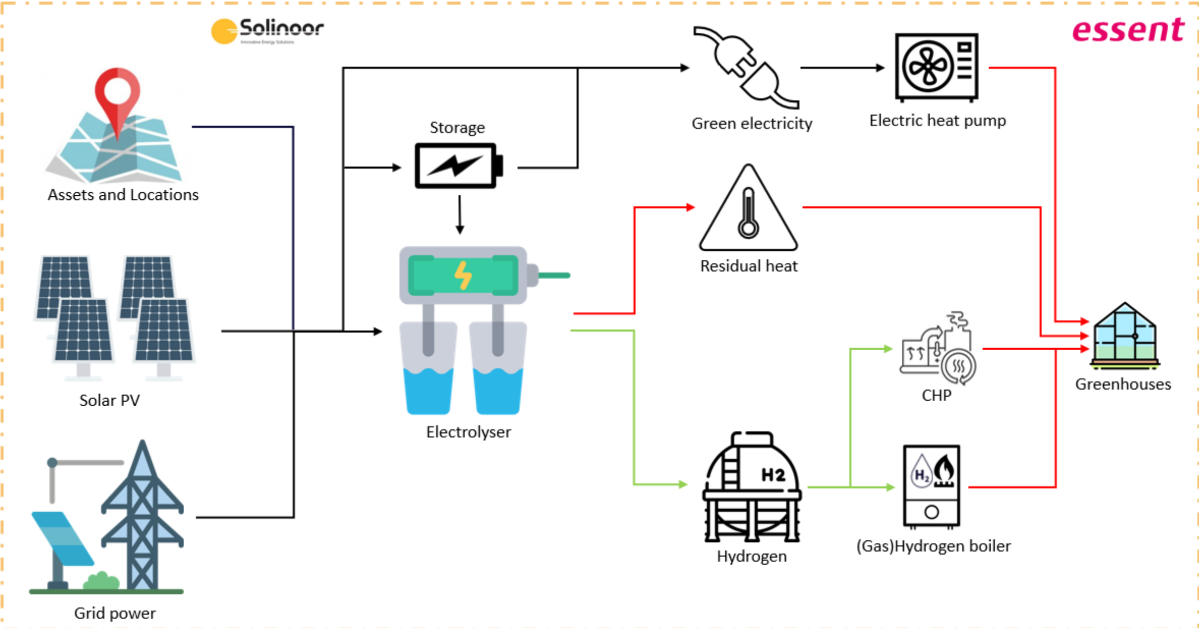

Figure 1. An overview of the three energy outputs from Solinoor's green hydrogen production process.

13. Theoretical framework

The theory that will be used for this research can be divided into two parts. In the first part, a comparative analysis will be conducted on different alternatives to analyse how these relate to each other. In consultation with Solinoor, financial and various technological criteria were identified. The criteria are further substantiated through preliminary desk study research. These criteria are summarised in *Table 1* and will be further elaborated upon in *Section 3.1*. However, the formulation and evaluation of criteria is an iterative process, meaning that additional criteria could be included later on in this research when deemed relevant by involved stakeholders.

Table 1. Criteria overview.

Criteria	Description
Financial aspects	
Net Present Value (NPV)	Calculating the value of the made investment over time, indicating the financial profitability.
Technological aspects	
Energy efficiency	The percentage of useful end-usage energy when compared with the initial generated (solar) energy.
General applicability	The extent to which the technology is suitable in other and smaller/larger greenhouses.
Compatibility	To what extent the solution is compatible with the existing infrastructure or would require modifications.

In the second part of the analysis, social-technical criteria will be emphasised using the Technological Innovation System (TIS) approach of Hekkert et al. (2007). The TIS approach provides a guideline to include all relevant systemic factors that play a role in technological development. To assess the drivers and barriers that the systemic components entail, Wieczorek & Hekkert (2012) serves as a tangible framework. This approach is described in *Section 3.2* and helps to further assess the socio-technical context of the alternatives.

As briefly mentioned earlier, the two theoretical approaches partly overlap by both assessing the socio-technical aspects, yet the combination of both frameworks is deemed viable as it could provide interesting insights from different perspectives. Whereas evaluating the financial and technological aspects would result in a quantifiable outcome for tangible management advice, the TIS analysis can provide Solinoor with qualitative information on the systemic drivers and barriers of technologies that could be considered.

13.1. Financial aspects

Assessing the financial feasibility is a commonly included approach when exploring or comparing energy technologies. This has also been the case in reports which explore heating technologies for the horticulture sector, e.g. Vanthoor & de Zwart (2017) or Blom et al. (2021). Because of this, and as the financial feasibility of technologies would influence the business cases for both Solinoor and horticulturists, this report will address the financial feasibility of technologies as well.

13.1.1. Net Present Value (NPV)

The Net Present Value (NPV) is one of the most used financial comparison methods to indicate the profitability of the made investments (Juhász, 2011). It does this by looking at the initial investment value and the discounted annual cash flow. In this calculation, the temporal value of money is considered, which translates future cash flows into the present value of that money. Furthermore, it provides concrete numbers on the initial investments and the expected returns of the project (Gallo, 2014). This makes the NPV a suitable criterion for the financial feasibility of the technological alternatives.

13.2. Technological aspects

Similar to exploratory reports assessing greenhouse heating technologies for instance in energetic or infrastructural terms (e.g., Peeters & Hoek, 2017; Vanthoor & de Zwart, 2017), this report will include such technologically-related aspects as well. These technological aspects, or criteria, have been formulated in coordination with Solinoor and are substantiated below. Although being considered relevant by Solinoor and literature, below technological aspects compose an indicative, non-exhaustive list. As this research will be conducted iteratively, additional technological aspects can be included later on.

13.2.1. Energy efficiency

Besides reducing energy losses to make green hydrogen economically more viable, another key objective is encouraging sustainability. Yet, energy losses are currently seen as one of the application drawbacks of the green hydrogen production process (Abdalla et al., 2018). In an interview with Glastuinbouw Nederland – an overarching organisation representing 70% of the total greenhouse horticulture acreage in the Netherlands – the feasibility of the hydrogen production process in terms of efficiency is questioned and deemed as important within the horticulture sector as well (De Jonge, 2021; Glastuinbouw Nederland, 2022). This makes it relevant for the energy efficiency of the technological alternatives to be considered during the comparison.

13.2.2. General applicability

With general applicability, we refer to the degree to which the technological alternatives can be applied within any greenhouse. Solinoor prefers a scalable 'copy-paste' solution, as tailor-made solutions are seen as more time and cost-intensive. Moreover, a scalable and standardised solution is expected to result in a higher adoption rate. This is according to Rogers (2003), who argues that the complexity of an innovation inhibits its diffusion. A higher adoption rate of sustainable technologies can, in turn, lead to a reduced impact on the climate. From a sector perspective, scalable hydrogen applications are desired as they drive general cost reductions in the hydrogen value chain (Hydrogen Council, 2020). This is according to the concept of economies of scale; an increase in production leads to a decrease in costs per unit (Unruh, 2000).

13.2.3. Compatibility

The extent to which the technological alternatives are compatible with existing infrastructure is also seen as relevant. Besides Solinoor expressing the need for a compatible application, the horticulture sector also deems it as important. A news article by Groen Kennisnet – a knowledge platform for the Dutch agriculture, food and green sector – indeed shows that high infrastructural modifications and investments inhibit the implementation of green hydrogen applications by horticulturists (Groen Kennisnet, 2021). Moreover, it is argued that some situations, e.g. where hydrogen is supplied through a pipeline, require collective effort and infrastructural modifications of horticulturists. Following Rogers (2003), an innovation that is compatible with for instance preceding infrastructure is more rapidly adopted.

13.2.4. Technological maturity

Technological maturity is a key indicator to assess a technology's capabilities. By assessing the maturity of the technology it is possible to determine whether a technology has developed sufficiently to be applied to the case. Technologies that are currently still underdeveloped might not fit certain projects yet or there might still be uncertainty regarding the technology's yields. The horticulture sector might have a demand for certain certified or tested competencies that some technologies might not be able to deliver. The maturity of the technology can be determined based on various methods. One of the most useful methods consists of the TRL, or technology readiness levels. This method has been drafted by Straub (2015) and describes the key characteristics of the development of a technology, and based on that development, it is assigned a level on the TRL scale. The TRL scale is a 9 level scale that shows in which stage of readiness a technology is, and whether a technology is mature enough to be deployed for different projects. Level 1 on the TRL scale would indicate a very novel technology that is not ready yet for wide application, whereas level 9 would indicate a very mature technology that is sufficiently developed for widespread usage. These Technology Readiness Levels will be further elaborated on in the methods section.

13.3. Social-technical aspects (TIS)

In addition to the financial and technological aspects, the technological alternatives will also be evaluated on socio-technical criteria. The Technological Innovation System (TIS) approach by Hekkert et al. (2007) is chosen as the overarching framework for these socio-technical criteria. The TIS framework suggests that the development and diffusion of a specific (novel) technology is not dependent on individual actors. Rather, it is characterised by the influence of four structural dimensions: *actors*, *institutions*, *interactions* and *infrastructure*. Here, actors are the relevant social groups, such as society, companies and the government. Institutions consist of both hard and soft institutions; rules and regulations & habits and routines respectively. Interactions are delineated in two levels: the level of networks and the level of individual contacts. Lastly, infrastructure comprises physical, knowledge and financial infrastructure.

To assess the performance of TISs, seven system functions are proposed (*Table 2*) and represent the most vital processes for the functioning of innovation systems (Hekkert et al., 2007). By using the system functions analysis approach, the performance of innovation systems is more easily comparable, allows a more systematic approach for analysing technological development, and provides a clear set of targets to address (Hekkert et al., 2007). The functions are further elaborated in *Appendix I.I*.

Table 2. The seven TIS functions as described by Hekkert et al. (2007).

TIS functions	Description
Entrepreneurial activities	Presence of active entrepreneurs, whether they are new entrants or incumbent firms.
Knowledge development	Technological learning, indicated by R&D projects & investments and patents.
Knowledge diffusion through networks	Exchange of information, indicated by networks & conferences and network size & intensity.
Guidance of the search	Clearly articulated and shared goals.
Market formation	Providing niche shielding and/or competitive advantages to promote development.
Resource mobilisation	Diffusion of both financial and human capital to aid technology development.
Creation of legitimacy / Counteract resistance to change	Empower technologies by creating advocacy and legitimacy.

13.3.1. Applying the framework

To conduct a TIS analysis for a technology, the approach could be divided into five stages according to Wieczorek & Hekkert (2012), namely, (1) mapping structural dimensions, (2) coupled functional-structural analysis, (3) identifying systemic problems, (4) goals of systemic instruments and (5) design of systemic instruments. However, these last two phases are less relevant for this research as the TIS analysis is not intended to provide Solinoor with policy measures, but to provide them with insights about the socio-technical context. Accordingly, only the first three stages will be used for this analysis.

The first stage of a TIS analysis consists of mapping the four structural dimensions. This process entails gathering data to identify: the core actors, at what level interactions take place, what kind of (in)formal rules, norms and values are present, and assessing the level of physical, knowledge and financial infrastructure.

Hereafter, in the second stage, the structural-functional analysis leads to an evaluation of the four structural dimensions of the TIS. By using a set of diagnostic questions (*Appendix I.II*), the presence and quality of the structural dimensions could be indicated on a Likert scale ranging from 0 (completely absent) to 5 (very strong performance) (Wieczorek & Hekkert, 2012). Yet, as the TIS analysis for Solinoor is not specifically aimed at assessing TIS quality but more to serve as a socio-technical context description, this quantitative grading system is left out of this research.

In the third stage of a TIS analysis, the findings of the structural-functional analysis can be used to identify deficiencies in structural dimensions, thereby highlighting the factors that hinder the functioning of a TIS. Wieczorek & Hekkert (2012) refer to these restricting factors as *systemic problems*. Being aware of these systemic problems is both relevant for public and private actors, as this could guide them in stimulating the further development and diffusion of technologies. By assessing the systemic problems, barriers that the technological alternatives encounter can be emphasised. An overview of identifying systemic problems is summarised in *Table 3*.

Contrarily to systemic problems, Darmani et al. (2014) addressed to what extent *systemic drivers*, i.e. factors that particularly stimulate TIS development, could be identified. Besides some minor additions and alterations, this study largely reflects the systemic dimensions as mentioned by Hekkert et al. (2007). Therefore, this study will address the systemic drivers by means of the high presence and quality of the structural dimensions. Accordingly, socio-technical barriers and drivers of the alternatives will be analysed using the first three stages of a TIS approach, which is discussed and operationalised within the next section.

Table 3. A systemic problems identification framework based on Wieczorek and Hekkert (2012).

Structural dimension	Systemic problem	Type of systemic problem
Actors	Actors problems	Presence
		Capabilities
Interactions	Interaction problems	Presence
		Capacity
Institutions	Institutional problems	Presence

		Intensity
Infrastructure	Infrastructural problems	Presence
		Quality

14. Methods

The methods used to analyse the drivers and barriers of the green hydrogen production process in the horticulture sector will be applied iteratively. Preliminary data on the financial, technological and socio-technological aspects of the different alternatives will be collected through desk research and by conducting semi-structured interviews with relevant stakeholders. Hereafter, this data will be synthesised in; an MCA that leads to a quantitative score for the alternatives based on financial and technological criteria; as well as a qualitative TIS overview that encompasses the socio-technical drivers and barriers. Accordingly, the results will be presented in a comprehensible manner to advise which technological alternative or application Solinoor should promote and pursue in the horticulture sector. Although the alternatives could be complementary to each other, for a distinct comparison they will be analysed as separate and single solutions.

14.1. Operationalisation

14.1.1. Financial and technological aspects: Multi-Criteria Analysis

To compare the financial and technological aspects of alternatives quantitatively, a Multi-Criteria Analysis (MCA) will be used. An MCA is an analytical approach that allows for a comparison of alternatives based on a diverse set of criteria beyond mere financial aspects (Dodgson et al., 2009). This is therefore seen as a suitable approach to compare the financial and technological aspects of greenhouse heating technologies. An MCA consists of three phases, which are summarised in *Table 4*. Note that the previous two sections respectively elaborated on the alternatives and criteria. Yet as this research is conducted iteratively, new insights could be included during the analysis. How the financial and technological MCA criteria will be measured is elaborated below and summarised in *Table 7*.

Table 4. The three phases of conducting a Multi-Criteria Analysis.

1. Problem identification	2. The Multi-Criteria Analysis	3. Robustness analysis
Identify alternatives Identify criteria Gather data and assign scores to construct a performance matrix	Standardise criteria Assign weights Conclude arrangement of the alternatives	Sensitivity analysis to assess the robustness of the outcome Formulate advice

Net Present Value

To compute the NPV per alternative (*Formula 1*), data on the NPV variables (*Table 5)* will be individually collected. The *initial investment* will be expressed in euros per delivered power, which is a standard approach when evaluating energy technologies (EIA, 2022). The annual *cash flow* can be divided into two separate parts: revenue and operational costs. By applying technological alternatives, horticulturists might save costs compared to their current, unsustainable heating applications. These saved costs could thus be seen as revenue and will be expressed in the number of euros saved compared to the present situation. Operational costs could be further scrutinised, similar to a study by Almansoori & Shah (2009) which examines the hydrogen supply chain for vehicle use in Great Britain. Operational costs will cover fuel costs, maintenance costs and other operating costs if present. The *time in years* will be based on the maximum payback time desired by horticulturists. Finally, the *discount rate* will be set at 4%, which is typical for long term structural investments (European Commission, 2015).

$$[1]\ Net\ Present\ Value = I + \sum_{t=x}^{t} \frac{CFt}{(1+r)^t}$$

Table 5. NPV variables.

Variable	
Initial investment (I)	Initially invested euros per MW heat
Cash Flow (CF)	
▪ *Revenue*	Annual euros earned / saved per MW heat
▪ *Operational costs*	Annual fuel, maintenance and other operating costs per MW heat
Time in years (t)	Maximum desired payback time
Discount rate (r)	4%

Energy efficiency

The energy efficiency of technological alternatives will be expressed as a percentage of the total produced heat compared to the total produced energy of solar PV. Here the alternatives' efficiency factors will be multiplied by the initial solar PV output (= 1). As the technological alternatives use different energy outputs, some additional technologies such as electrolysers or heat exchangers might be required to turn the solar energy into the other desired energy outputs. In such calculations, the efficiency factors of these technologies are included as well. The efficiency factors will be based on the common efficiency of the technologies currently on the market and will be collected via publicly available (company) documents and websites.

General applicability

The general applicability will be evaluated based on the extent to which the alternatives are applicable in any greenhouse. Vanthoor & de Zwart (2017) distinguished four general types of cultivation with different heating requirements while examining sustainable heating solutions for greenhouses: heavily lighted-, moderately lighted-, not lighted-, and cooled cultivation. The applicability of alternatives for each cultivation type could be determined by discussing technological specifications of the alternatives with horticulturists, intermediary organisations, and research institutes as further specified in *Section 4.2.2.* Based on this distinction, the number of cultivation types in which the alternatives can be applied will indicate the general applicability of these alternatives.

Compatibility

The compatibility will be evaluated based on the extent to which the alternatives are compatible with the existing heating infrastructure within the greenhouses. In their study, Blom and colleagues (2021) distinguish between individual and collective solutions to sustainably heat greenhouses. Taking this distinction into account, the following ordinal evaluation scale will be used: *1 = extensive collective modifications required; 2 = extensive individual modifications required; 3 = modular individual modifications required; 4 = no modifications required.*

Technological maturity

Maturity is measured based on the technology readiness level on a 9 point scale. The level is awarded based on the corresponding level based on the article of Straub (2015) and summarised in table 6 below.

Table 6: Technology Readiness levels 1-9 based on Straub (2015).

TRL	Definition	Level description
1	Technology Research	Applied research and development gets envisioned in the form of paper studies into a technology's basic properties.
2	Technology concept	Practical applications get invented after the basic principles have been observed. Application is only speculative.
3	Proof-of-concept	Active R&D has been initiated in the form of analytical studies and lab experiments to validate that the technology is viable. Proof-of-concept gets made.
4	Technology Demonstration	Proof-of-concept gets tested in lab conditions. Results in a generic design demonstrating performance consistent with potential applications.
5	Conceptual Design and Prototype Demonstration	Conceptual design complete. Design is validated in a somewhat realistic, relevant environment.
6	Preliminary Design and Prototype Validation	Representative engineering model is created and gets demonstrated in a relevant environment.
7	Detailed Design and Assembly Level Build	Prototype should be near the scale of the finished technology and the demonstrations need to be in real environments.
8	Subsystem Build and Test	Product/technology has been proven to work under expected circumstances in relevant environments. The technology is now near completion.

9	System Operational	Product/technology gets applied in its final and is introduced into the market.

Table 7. Criteria measurement overview.

Criteria	Cost/Benefit	Measurement level (unit)
Financial criteria		
Net Present Value	Benefit	Ratio (€)
Technological criteria		
Energy efficiency	Benefit	Ratio (% of E_{out} / E_{in})
General applicability	Benefit	Ratio (No. of suitable cultivation types) *
Compatibility	Benefit	Ordinal (Modification extent) **
Technological maturity	Benefit	TRL level (1-9)

**Ranging from 0-4*

*** 1 = extensive collective modifications required; 2 = extensive individual modifications required; 3 = modular individual modifications required; 4 = no modifications required.*

14.1.2. Socio-technical aspects: structural-functional approach

The assessment of the structural-functional analysis is constructed based on the theory of Wieczorek and Hekkert (2012). Within this methodology, the TIS functions are evaluated based on potential systemic problems. However, the first step of this process relates to the mapping of the structural dimensions, i.e. the actors, interactions, institutions and infrastructure of the system. Deficiencies in these structural dimensions highlight the underlying systemic problems. Since the root of most problems regarding the functions often originates from only certain features of the function, a further delineation is made based on the type of systemic problem. Based on these types of systemic problems, accurate opportunities and barriers can be described.

The initial mapping of the structural dimensions will be achieved by desk research. This way, key components of the system can be mapped efficiently from a broad range of sources, as mentioned in section 4.2.1. Further validation and elaboration of the dynamics between and within the structural dimensions will be provided by conducting interviews. These interviews will also be used to identify the barriers and drivers present in the system. Wieczorek and Hekkert (2012) set up a set of diagnostic questions that help identify barriers within the system. These questions are aimed at assessing the presence and quality of each system function, and answering them will show what are strong and weak elements of the system. The questions can also show which functions in the system are highly present and of high quality, which could help identify the drivers present in the system (Darmani et al., 2014).

14.2. Data collection

14.2.1. Desk research

For gathering sufficient and appropriate data for the MCA criteria and identifying the presence and quality of the structural TIS dimensions, multiple search engines such as Google Scholar, Scopus, Web of Science, and NexisUni will be used. These search engines will be used to look for recent publications (after 2018) on the available and state of the art technologies for hydrogen production and electric/hydrogen heating systems. Moreover, (annual) reports and documents of stakeholders that employ or have expertise in these fields will be assessed and approached for more detailed and specific information about the characteristics of the machinery. This includes analysing academic and grey literature, reports, policy briefs, news publications and other relevant sources.

14.2.2. Interviews

To achieve a multidisciplinary overview, different types of stakeholders along the value chain will be interviewed regarding hydrogen application in the horticulture sector. An overview of the targeted respondents is shown in *Table 8*. For the layout of these semi-structured interviews, interview guides will be composed and included in the Appendices wherein the MCA criteria, structural TIS dimensions, and the role of the respondents will be considered.

Table 8. Interview respondents.

Type of actor	Respondents
Supply-side	Producers and technicians of electrolysers, heat pumps, heat exchangers, hydrogen boilers and Combined Heat and Power (CHP) installations
Demand-side	Horticulturists
Intermediary organisations	Glastuinbouw Nederland, LTO Noord, ZLTO, LLTB
Research institutes	ECN, FME, TNO
Government	Ministry of Climate, Environment and Nature, Municipal and/or regional government actors

Ethics

Before the interviews, the respondents will be notified about the purpose of the interviews and that these will be recorded and transcribed for academic research. Moreover, respondents have the opportunity to stop participating in this research, revise and address misconceptions of the transcribed interviews, and have the possibility to be mentioned anonymously if preferred.

14.3. Data analysis

14.3.1. Multi-Criteria Analysis

After data has been collected, a performance matrix that encompasses the values and scores of the alternatives for each criterion will be composed. As the measurements and units of these criteria are heterogeneous, standardised values are required to compare the alternatives. Out of several standardisation methods, interval standardisation would best fit the aim of this research. The advantage of interval standardisation is that it entails consistency within the assessment of each criterion and that it amplifies the differences between alternatives (Dodgson et al., 2009). As all criteria could be seen as *benefit* criteria (*Table 7*), the following formula (*Formula 2*) for acquiring the standardised values could be used:

$$[2]\ Standardised\ score = \frac{Criteria\ score - lowest\ score}{Highest\ score - lowest\ score}$$

Besides standardising the scores, assigning weights to the criteria is required to emphasise the importance of each criterion, where the ones with higher weights are more important. To weigh the criteria, relevant decision-makers in this process will be consulted as well as deriving the importance from literature research. The decision-maker in many cases will be Solinoor (shareholders and employees), horticulturists (greenhouse owners), and Essent, i.e. the actors that have the desire to employ green hydrogen in horticulture. Eventually, with the standardised scores and weights per criteria, these could be combined to form finalised scores for each criterion that arranges the alternatives from worst to best performing alternative.

14.3.2. System barrier & driver analysis

As previously mentioned, the diagnostic questions of Wieczorek & Hekkert (2012) will be used to guide the interviews. Accordingly, the interviews can be analysed using theoretical coding to identify potential barriers and drivers using the structural dimensions as elaborated in *section 3.3.1.* Finally, the result will be an overview of both system barriers and system drivers within the context of the horticulture sector.

14.4. Reliability and validity

Regarding the reliability of this research, the criteria and framework used for this research are substantiated by peer-reviewed academic literature. For example, the TIS framework is academically and a well-recognised theoretical framework to assess technological development, thereby making this a suited approach to assure measurement validity and increasing internal validity when indicating causal relationships in the data analysis (Bryman, 2016).

Moreover, to improve internal validity, interviews will be conducted by multiple interviewers, prepared with a semi-structured interview guide and practised beforehand, and transcribed soon after the interviews are finished. The coding manual will be conducted collectively when all group members are present and will be revised during the coding process. The conflicts in coding will be discussed after the coding process has taken place when all group members are present until there is a mutual agreement.

As for validity in general of the MCA outcome and accompanying advice, a sensitivity analysis will be conducted in the last phase to illustrate the robustness of the analysis. An example of this sensitivity analysis entails changing the standardisation method from *interval standardisation* to, for example, *maximum standardisation* which is slightly different but also applicable for this research. Moreover, altering the assigned weights to each criterion could affect the outcome. By assessing such adjustments in the MCA, it could be determined to what extent this affects the eventual outcome of the analysis. To address the external validity of this research, the technologically specific criteria are assessed on a generic technological level which would make it easier to generalise and extrapolate to other greenhouses in other contexts as well.

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15.1. Appendix I.I - Electrolysis processes

Generally, there are two methods to produce hydrogen from electricity, i.e. electrolysis: the alkaline process and the proton exchange membrane (PEM) process. The former works based on a cell containing two solutions: an alkaline and electrolyte solution. A diaphragm separates the two compartments and solutions. At the cathode, water is converted into H^+ and OH^-. At the anode the OH^- is converted to oxygen and water, based on the following reactions:

$2\ H_2O + 2\ e^- \rightarrow H_2 + 2\ OH^-$

$2\ OH^- \rightarrow ½\ O_2 + H_2O + 2\ e^-$

Later, gas receivers collect the formed hydrogen and oxygen gases (Santos et al., 2013).

The second method (proton exchange membrane process) works by supplying water to the anode where it is decomposed into oxygen, electrons and protons respectively. The protons travel through the proton conductive membrane to the cathode. The electrons leave the cell through an external circuit. This circuit provides the cell potential for the reaction. At the cathode, the protons and electrons combine to produce hydrogen gas (Marshall et al., 2007). All of this is summarised in the following reactions:

$2\ H_2O \rightarrow 4\ H^+ + O_2 + 4\ e^-$

$4\ H^+ + 4\ e^- \rightarrow 2\ H_2$

Table 8. Overview of electrolysis methods based on Dincer (2012).

Electrolysis process	Electrolyte	Ions transport	Anode reaction	Cathode reaction	Current density, A/cm^2	Efficiency, %
Alkaline	KOH 25-30% wt or NaOH, NaCl	Hydroxyl OH^-	$4\ OH^- \rightarrow O_2 + 2H_2O + 2\ e^-$	$2\ H_2O + 2\ e^- \rightarrow H_2 + 2\ OH^-$	0.1-0.4	50-60
PEM	Polymer (NAFION)	Protons H^+	$2\ H_2O \rightarrow 4\ H^+ + O_2 + 4\ e^-$	$4\ H^+ + 4\ e^- \rightarrow 2\ H_2$	>1.6	50-75

15.2. Appendix I.II - TIS Functions

Below an extensive description of the different TIS functions of Hekkert et al. (2007) can be found.

The first system function is *Entrepreneurial activities*. Entrepreneurs are necessary for a system to turn new knowledge, networks and markets into concrete actions. They can either be new entrants entering a new market or incumbents diversifying their portfolios. This function is aimed at the presence of active entrepreneurs in a technological innovation system.

The *Knowledge development* function entails the mechanisms of learning and the development of new knowledge. R&D and knowledge development are essential in a system for innovation to take place. This function can be analysed by looking at R&D projects, patents and investments in R&D.

The third system function is *Knowledge diffusion* through networks. Networks are essential in exchanging information. Exchanging information can help bridge actors and bring forth new ideas, making it an important factor in an innovation system. It can be analysed by looking at the presence of networks and conferences.

The fourth function, *Guidance of the search*, focuses on having clearly articulated and shared goals. When the search is properly guided, knowledge development, or other functions, will have a certain direction and can be done much more efficiently. A clear example of this function is the long-term goal setting done by governments to reach a certain share of renewable energy in the future. Such a goal can guide actors in the system and make them move in a certain direction.

The fifth function is *Market formation*. This function looks at the market available for this technology and the developments in this market. New technologies often start as inferior options and they struggle to compete with embedded technologies. The market formation looks at the level of niche shielding provided to the new technology and which regulations are in place to help the niche develop and grow its market.

Resources mobilisation concerns both financial and human capital and how easy they are to acquire. Allocating sufficient resources is essential for the development of a technology and to make knowledge development possible. This function is best analysed through interviews, identifying whether the access to resources is problematic or not.

The final function is the *Creation of legitimacy* or *Counteracting the resistance to change*. The looks at the rise and growth of interest groups and their lobby actions to strengthen the niche and weaken the regime. These groups also work on making the niche technology more legitimate, making sure it is more easily accepted into the regime.

15.3. Appendix I.III - Diagnostic questions for a structural-functional analysis

Table 9. Set of diagnostic questions by Wieczorek & Hekkert (2012).

System function	Diagnostic questions
F1. Entrepreneurial activities	Are there enough entrepreneurs? What is the quality of entrepreneurship? What types of businesses are involved? What are the products? To what extent do entrepreneurs experiment? What variety of technological options are available? Are any entrepreneurs leaving the system? Are there new entrepreneurs?
F2. Knowledge development	What is the knowledge base in terms of quality and quantity? Is the knowledge basic or applied? Are there many projects, research, patents and articles? Is there a leading international position, trigger programmes, and many cited patents? Which actors are particularly active? Who finances the knowledge development? Does the technology receive attention in national research and technology programs? Are there enough knowledge users?
F3. Knowledge diffusion	Are there strong partnerships? Between whom? Is the knowledge development demand-driven? Is there space for knowledge dissemination? Is there strong competition? Does the knowledge correspond with the needs of the innovation system? Have any licences been issued?
F4. Guidance of the search	Is there a clearly articulated and shared goal for the system? Is it generic or specific? Is it supported by specific programs, policies, who are the system's frontrunners? Is the objective inducing government activities? What are the technological expectations (negative/positive)?

	Does the articulated vision fit in the existing legislation?
F5. Market formation	What does the market look like? What is its size (niche/developed)? Who are the users (current and potential)? Who takes the lead (public/private parties)? Are there institutional incentives/barriers to market formation? Must a new market be created or an existing one be opened up?
F6. Resource mobilisation	Are there sufficient financial resources for system development? Do they correspond with the system's needs? What are they mainly used for (research/application/pilot projects etc.)? Is there sufficient risk capital? Is there adequate public funding? Can companies easily access the resources?
F7. Creation of legitimacy / Counteract resistance to change	Is investment in the technology seen as a legitimate decision? Is there much resistance to change? Where is resistance coming from? How does this resistance manifest itself? What is the lobbying power of the actors in the system? Is coalition forming occurring?