

Regional optimization of biohydrogen production in rural areas: Opportunities for manure utilization through hierarchical clustering

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Abstract

There is a notable gap in research concerning the regional potential and spatial planning tools of biomass-based hydrogen production. This study addresses this gap by assessing the biohydrogen production potential from agricultural manure and applying location optimization modelling with hierarchical clustering, using South Ostrobothnia, Finland, as a case study. The analysis focuses on large and medium-sized farms to estimate the theoretical biomethane and biohydrogen yields.

According to results the total biomethane potential of the region is nearly 0.5 TWh annually, which theoretically corresponds to 8,000 tons of biomass-derived hydrogen per year. The ten most promising areas in the region for producing biohydrogen from manure were identified. The hierarchical clustering-based optimization method could be used as a decision-making tool in similar studies as well as for promoting biomethane and biohydrogen planning in other regions. The proposed method is useful in cases where the locations of the plants are not predetermined.

Keywords: GIS, hydrogen economy, regional development, renewable energy sources, farms, biomethane, manure

Tiivistelmä

Tällä hetkellä tutkimusta, joka tuottaisi aluesuunnittelun tueksi työkaluja biovedyn tuotannon suunnitteluun, on liian vähän. Tässä tutkimuksessa vastattiin tähän tarpeeseen kehittämällä hierarkinen klusterointimalli, jonka avulla arvioitiin maatalouden lannan alueellista biovedyn tuotantopotentiaalia Etelä-Pohjanmaalla. Analyysissa keskityttiin suuriin ja keskisuuriin maatiloihin, joiden tuottaman lannan ja sijainnin perusteella laskettiin alueen teoreettinen biometaani- ja biovetypotentiaali.

Tulokset osoittavat, että Etelä-Pohjanmaan vuotuinen biometaanipotentiaali on lähes 0,5 TWh, mikä vastaa teoriassa noin 8 000 tonnia biomassapohjaista vetyä vuodessa. Tutkimuksessa tunnistettiin kymmenen lupaavinta aluetta lannasta tuotettavan biovedyn tuotantoon. Alueet sijaitsivat Ilmajoella, Lapualla, Ylistarossa, Kurikassa, Seinäjoella ja Alavudella. Hierarkkiseen klusterointiin perustuva optimointimenetelmä tarjoaa käytännöllisen työkalun alueelliseen suunnitteluun ja päätöksentekoon, ja se soveltuu myös muiden uusiutuvien energiaratkaisujen sijaintien optimointiin. Menetelmä tukee hajautetun energiainfrastruktuurin kehittämistä ja vihreän siirtymän edistämistä maaseutualueilla.

Asiasanat: GIS, vetytalous, aluekehitys, uusiutuvat energialähteet, maatilat, biometaani, lanta

1 Introduction

The hydrogen economy presents a sustainable alternative to fossil fuel-based systems, as hydrogen has been identified as a crucial component of the green and sustainable energy transition e.g, (Falcone et al., 2021). Hydrogen can be utilized in several ways, including energy production and industrial processes such as fertilizer production, oil refining, and iron refining. Additionally, hydrogen can also be converted into

synthetic green electrofuels (IEA, 2019; IRENA, 2024; Seddon, 2022). Unlike most fuels, hydrogen combustion produces no greenhouse gases, emitting only water vapor. However, the impacts of hydrogen depend significantly on how it is produced.

Currently, nearly all hydrogen production relies on fossil resources like natural gas and coal. In 2022, total global hydrogen production amounted to 95 million tons (Mt), with low-carbon and renewable hydrogen production below 1 Mt (IEA, 2023a; IRENA, 2024). In Finland, the situation is very similar, as 99% of all dedicated hydrogen is produced either through steam reforming or partial oxidation of fossil fuels (Laurikko et al., 2020). With a total hydrogen production of 150,000 t/a (Laurikko et al., 2020) and median upstream emissions of 11.4 kg CO_2-eq./kg H_2 (IEA, 2023b), 1.7 million tons of CO_2-equivalent emissions are generated annually. The sustainability of hydrogen production could be significantly improved by using renewable energy sources such as wind and solar power. Green hydrogen has been identified as a promising solution for reducing greenhouse gas emissions and mitigating global warming (Singh et al., 2023; Wilkinson et al., 2023). This has encouraged many European countries to foster hydrogen economies in alignment with climate policy goals e.g. (European Commission, 2020).

One of the most promising technologies for producing green hydrogen is electrolysis, where electricity is used to extract hydrogen from water via water decomposition (Kumar & Lim, 2022). However, current technologies are energy-intensive and inefficient, with energy losses of up to 30–40% as heat (IEA, 2019; Kishk, 2022). Research is ongoing to develop more efficient electrolysis technologies (see, e.g., Kani et al., 2024). Other options are available for producing green hydrogen as well, including biological and chemical processes using biomass, which offer carbon-neutral pathways (Xu et al., 2022). Many hydrogen production methods are based on methane reforming. According to (Alves et al., 2013), conventional methane reforming processes for hydrogen include steam reforming (SR), partial oxidation reforming (POR), autothermal reforming (ATR), dry reforming (DR), and dry oxidation reforming (DOR). Among these, hydrogen from steam biomethane reforming and biomass gasification is ready for immediate market adoption, providing viable alternatives for hydrogen production (Buffi et al., 2022). These technologies also complement intermittent solar and wind-based hydrogen production by offering a stable supply of green hydrogen (Buffi et al., 2022)

Hajjaji et al. (2016) conducted a life cycle assessment study, recommending biogas as an eco-friendly source for green hydrogen production. The energy efficiency of steam reforming from biomass is higher and the water footprint is lower compared to electrolysis, for example, in producing ammonium from green hydrogen (Ghavam et al., 2021). In addition to methane reforming technologies, methane pyrolysis has received increasing attention. The most significant benefit of methane pyrolysis is that all carbon is captured in a solid form, and no carbon dioxide is produced (Mauthner & Malkamäki, 2022). Hence, biomethane pyrolysis can be considered a negative-emissions technology. However, in practical continuous or batch pyrolysis systems, complete conversion is unlikely to be achieved. In real processes, side reactions, incomplete conversion, and system-level energy inputs may lead to the formation of minor amounts of CO_2 or other carbon-containing gaseous by-products (see e.g., Rohani et al., 2025).

Currently, steam-methane reforming (SMR) is commonly used in the production of hydrogen from natural gas. Alternatively, biogas can be used in hydrogen production and refining hydrogen into chemical products or energy (e.g., for fuel cells (Ohkubo et al., 2010; Awe et al., 2017)), as the chemical content of natural gas is

similar to that of biomethane (Alves et al., 2013). Biogas itself is a source of methane, making it a potential source of green hydrogen. Anaerobic digestion is a biological process through which biomass is turned into biogas. While biogas consists of different gaseous compounds (mainly methane and carbon dioxide), it can be upgraded into almost pure methane. There is also significant unrealized potential to produce biogas from organic waste and agricultural manure (IEA, 2020). Consequently, biogas could be an important renewable energy resource for many countries. For example, Finland aims to increase biogas production from 1 TWh to 4 TWh by 2030 (Suomen Biokierto ja Biokaasu (SBB), n.d.).

Methane (CH_4) contains four hydrogen atoms per molecule, which means that one mole of methane can theoretically produce two moles of H_2. The theoretical hydrogen potential of biomass can be assessed by calculating its methane yield and the hydrogen content of the methane. However, in practice, hydrogen yield from methane is dependent on the technology used for hydrogen production, which determines the total hydrogen yield. For example, SMR involves two main reactions: the SMR reaction $CH_4 + H_2O$ (+ heat) → $CO + 3H_2$ and the water-gas shift reaction $CO + H_2O \rightarrow CO_2 + H_2$ (+ a small amount of heat) (e.g., Ade et al., 2022). This means that methane and water together produce four moles of H_2 in this process. In practice, in steam reforming, half of the hydrogen comes from the biomass and the other half from the water used in the process. Consequently, it is crucial to understand the amount of hydrogen originating from the biomass and other process elements, such as water, to determine the theoretical potential of the biomass itself. Furthermore, even in countries where water is generally not a critical resource (e.g., Finland), it is important to recognize the risks related to water availability (e.g., Ahopelto et al., 2019; Mehmeti et al., 2018).

In recent years, regional potential studies have been conducted to identify and understand biogas potential (e.g., Kulišić et al., 2015; Martinov et al., 2020; Scarlat et al., 2018; Venier & Yabar, 2017; Zareei, 2018). However, fewer studies have addressed the potential of biohydrogen produced using biomethane (Karimi et al., 2020; Tleubergenova et al., 2023), despite the high technical readiness level for producing hydrogen from biomethane (Buffi et al., 2022). This gap may partly stem from the fact that methane is already a valuable and economically profitable gas to produce and use. Larger commercial efforts to refine biomethane into hydrogen have been limited, as cheaper technical solutions for hydrogen production are available. Biohydrogen production from biogas must always be assessed on a case-by-case basis at both the process and system levels. According to Braga et al. (2013), steam reforming of biogas can represent an economically and environmentally attractive option with a payback period of 8 years. However, biohydrogen production from biogas is not sustainable or energetically viable in all cases, as life cycle assessment studies have reported even negative net energy balances (Cvetković et al., 2021).

To make biomethane-derived hydrogen profitable, further research is needed to explore how hydrogen can be refined into products with greater economic value than methane. As the hydrogen economy develops, biohydrogen resources might become increasingly appealing due to the growing demand for stable green hydrogen sources, which can complement electrolysis-based production that relies on unstable wind and solar energy. By 2030, the demand for green hydrogen is expected to grow significantly, with low-emission hydrogen production potentially reaching 16–24 Mt per year (IEA, 2022).

Currently, the hydrogen economy is not well understood by the wider public, and many business developers are seeking opportunities in this emerging sector. For example, an increasing number of hydrogen economy

roadmaps are being created (e.g., Hydrogen Cluster Finland, 2023). Consequently, it is important to identify opportunities of the hydrogen economy to support the evolution of the hydrogen business sector. Geographical Information Systems (GIS) present one solution for analyzing the regional distribution of various biomass sources (e.g., Höhn et al., 2014; Laasasenaho, 2019; Laasasenaho et al., 2019). Further, GIS-based optimality analyses can address location-allocation issues, helping to match biohydrogen resources with societal demands for the hydrogen economy. Consequently, tools for regional hydrogen economy planning are urgently needed, alongside comprehensive and industry-specific assessments to determine where biohydrogen economy investments should be made.

The objective of this study is to better identify tools and methods for assessing theoretical biohydrogen potential at the regional level by integrating GIS and manure potential analysis. The research aims to determine how biohydrogen resources are geographically distributed, enabling efficient and effective actions to support the development of the hydrogen economy at the regional level. By doing this, financial risks related to investments in the hydrogen economy can be discussed and avoided. At the same time, stable sources of green hydrogen can be identified to complement electrolysis-based hydrogen production. This study seeks to provide new insights into decision-making tools for planning biogas and biohydrogen production.

2 Materials and methods

2.1 The case study area, manure, and biogas potential assessment

This study analyzed the manure production in a Finnish case study area to determine its biogas and biohydrogen production potential. The region of South Ostrobothnia in western Finland was selected for this purpose (Figure 1). The area is predominantly rural with intensive agricultural activity and is a nationally significant region for the food industry. According to Natural Resources Institute Finland (Luke, n.d.), a total of 5,242 farms operated in the region in 2019. Since manure is the largest individual feedstock for biogas production in the area (e.g., Laasasenaho et al., 2019), only medium-sized and large animal farms were considered in the analysis. These farms were identified as hot spots of manure production (see Table 1). Data on the locations (ETRS89 TM35FIN coordinate system) and the number of animals on 821 farms were obtained from the farm database of Finnish Food Authority (2019). However, due to incomplete data on farm locations, 20 farms were excluded from the analysis, leaving 801 farms for the manure potential analysis. The theoretical manure production per animal was estimated using data provided by Finnish Food Authority (2023), as shown in Table 1.

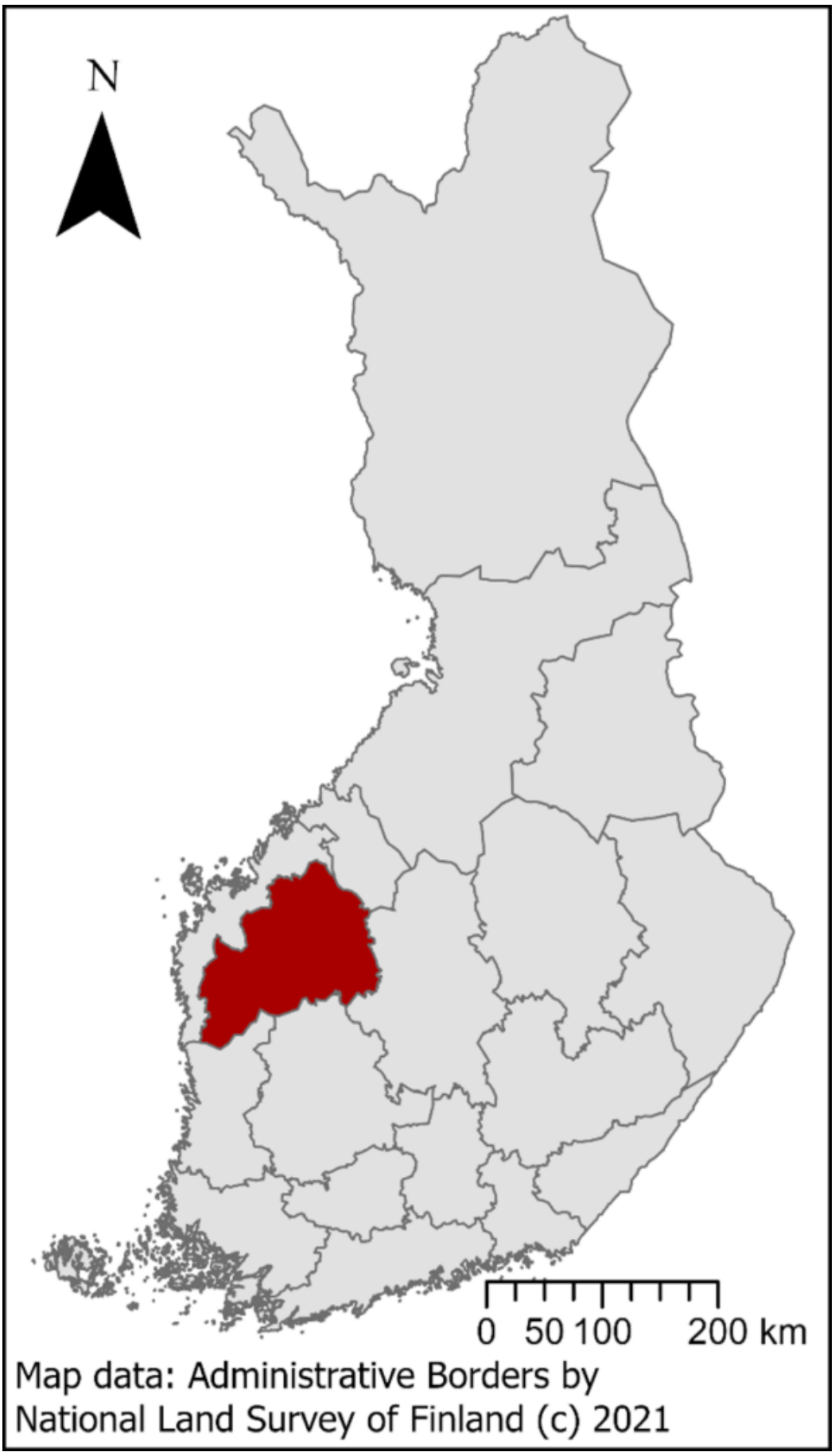


Figure 1. Location of the South Ostrobothnia region, selected as the study area, denoted in the red color in the map of Finland (Map of regional borders: National Land Survey of Finland).

Table 1. The animal species, the minimum number of animals on each farm, and the theoretical manure production per animal considered in this study.

Animal species	**Min. number of animals per farm included in this study**	**Theoretical manure production of one animal (m^3) annually (**Finnish Food Authority 2023)*****	**CH_4 potential, (m^3/ton of fresh matter)**
Calves	50	13.6	19 [1]
Pigs	500	5.67	10[2]
Horses	30	24	48[2]
Chickens	500	0.054	81[2]
Turkeys	500	0.1	81[2]

* As the ages of the animals were partially unknown, manure production was calculated as average manure production, including both adult and young animals.

[1] Laasasenaho, 2012

[2] Rasi et al., 2012

After estimating the amount of manure, methane and biohydrogen potentials were calculated. Theoretical methane potential for each farm was calculated using Equation 1, while biohydrogen potential was calculated using Equation 2 (see animal-dependent methane potentials in Table 1). The biohydrogen potential was calculated theoretically without factoring in separate hydrogen extraction technologies. The calculation was based on the molar mass of hydrogen (4 x 1.008 g/mol g/mol) in methane (16.04 g/mol) and a methane density of 0.657 kg/m^3 (25 °C, 1 atm).

Methane potential (m^3y^{-1}) *= The number of animals x manure production per species (t y^{-1}) x manure-based methane potential (m^3 per ton of fresh matter)* *(1)* ***Biohydrogen potential from manure (t y^{-1})*** *= methane potential (m^3y^{-1}) x 0.00016515 (theoretical hydrogen yield from 1 m^3 of methane in tons)* *(2)*

The regional methane and biohydrogen potentials were then estimated by aggregating data from the 801 farms.

2.2 Hierarchical clustering

A previously developed self-programmed hierarchical clustering-based location optimization method,

programmed in the R Statistics program, was used in this study (see Laasasenaho et al., 2019). This method was chosen because of its ability to handle a large amount of data and its effectiveness in biogas plant planning and solving location-allocation problems. Unlike methods requiring predefined potential plant locations, this approach identifies concentrations or clusters formed by farms and optimizes biogas plant locations to minimize transport costs. The only information needed is geographic information about the locations of the farms, a road network, livestock methane potentials (manure amounts), and a maximum transportation distance for manure. The background of the analysis is explained in greater detail in Laasasenaho et al. (2019).

Farm location data were obtained from Finnish Food Authority (2019), and methane potentials were estimated according to Section 2.1. Maximum transportation distances of 2, 5, and 10 km were tested to identify solutions including a large proportion of the farms in the clusters while minimizing transportation distances. The aim was to determine whether enough farms were close enough to each other to achieve sufficient methane and hydrogen potential when using very short maximum distances, as this would minimize costs and emissions from the biomass transports. However, solutions with larger distances were also calculated since not all farmers may elect to participate in this kind of bioenergy production activity, which would result in slightly longer distances for biomass transportation. The solutions allowed end users to compare different scenarios and select economically feasible options.

The location allocation analysis was conducted using R software (v. 4.4.1) with add-on packages shp2graph (v. 1-0), igraph (v. 2.1.1), sf (v. 1.0-19), and sp (v. 2.1-4). The road network data were sourced from Digiroad 2020 (Finnish Transport Infrastructure Agency, 2020), removing only pedestrian walkways and bicycle routes. As some farms are close to the borders of the case study area, some roads outside of the region’s borders could be necessary to connect them. Therefore, Digiroad data were obtained from neighboring provinces as well to avoid any route optimization problems. The road network was imported into R using the sf package and converted via sp data structures into an igraph optimization network, which was then used to determine the shortest paths from all biomass source points to all other points in the road network. Then, clusters of biomass sources were formed with hierarchical clustering (following the approach explained in Figure 3 of Laasasenaho et al., 2019).

The analysis provided methane potential estimates for clusters, optimal locations for the centralized biohydrogen plants, and transport distances between farms and plants. The optimisation was done to minimise the total transportation effort (in ton km) between the biomass sources and the biogas plants. These distances allowed us to estimate annual transport costs by multiplying the number of loads by the length of the route in km and transport costs per km. In the calculation of loads we assumed that weight would be the limiting factor in transportation, which allowed converting the estimated mass into a number of loads for each route. Other factors, like possible shared use of transportation equipment, continuous loading of the biomass reactors, etc. were not taken into account. Based on the methane potentials of clusters, using maximum transportation distances of 2, 5, and 10 km, the top 10 potential locations for biogas plants were identified for each distance.

The data analysis is summarized in Figure 2. In the results and discussion section, we discuss how hierarchical clustering can be used to support the regional planning of biogas and biohydrogen plants and

identify significant potential hotspots for hydrogen-based business development.

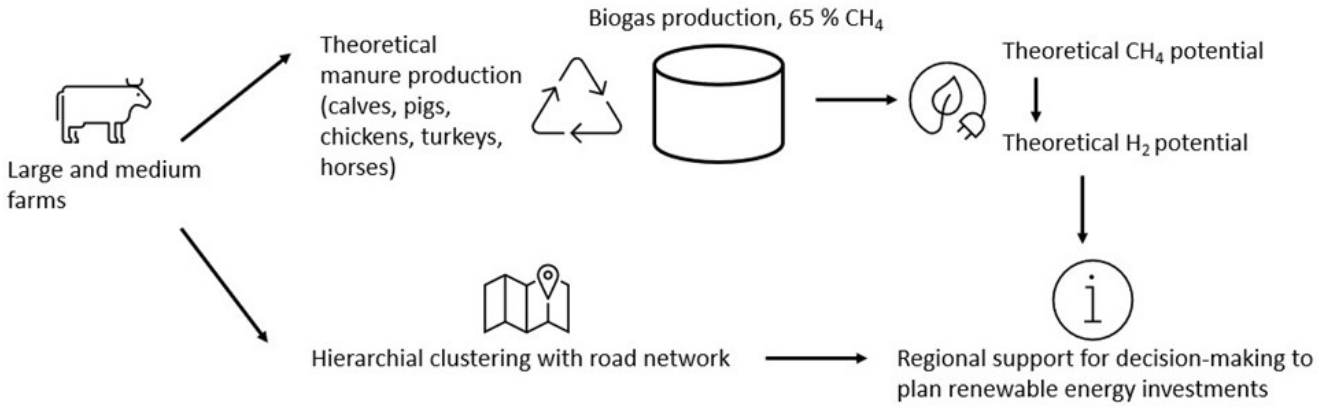


Figure 2. The figure illustrates the study analyses. Methane and biohydrogen potentials were estimated based on manure production by regional large and medium-sized farms in South Ostrobothnia, Finland.

3 Results and discussion

3.1 The amount of manure and regional biomethane and biohydrogen potentials

South Ostrobothnia is home to nearly 3 million domestic animals, generating a significant amount of manure annually on large and medium-sized farms (Table 2). Most of the animals in the region are chickens, numbering over 2.5 million. However, most of the manure originates from cattle and pig farms, with over 100,000 individuals of each species in the area. Farm sizes vary widely. For example, many cattle farms have less than 100 animals, but the largest farms have more than 1,000. This variation affects the feasibility of establishing biogas plants at different farms.

Annually, approximately 2.5 million cubic meters of manure are produced, representing a substantial biomass resource. This quantity of manure could theoretically fill an area measuring about 2.5 km x 1 km to a depth of 1 m every year.

The manure in the region has the potential to produce over 480 GWh of biomethane annually, equivalent to almost 0.5 TWh (Table 2). The most significant methane potential comes from cattle manure. If this methane potential were converted to biohydrogen, it could theoretically yield almost 8,000 tons of hydrogen per year. This biohydrogen potential is based on the assumption that hydrogen is converted totally from methane. In practice, the hydrogen yield would be higher depending on the selected hydrogen production technology; however, this would need to be calculated separately.

The methane potential of the region accounts for about 10% of Finland’s national target of increasing biogas production by 4 TWh by 2030 (SBB, 2024). The theoretical biohydrogen production corresponds to a small percentage of Finland’s current total hydrogen production of 150,000 tons per year. Hydrogen production in

Finland is expected to double by 2030. Currently, 99% of dedicated hydrogen is produced through steam reforming or partial oxidation of fossil fuels, with less than 1% produced via water electrolysis (Laurikko et al., 2020). In this context, biohydrogen production from biomethane could help reduce reliance on fossil fuels for hydrogen production.

If energy plants with an output of at least 100 kW (biomethane potential of over 800 MWh/year) were established, up to 149 farm-scale biogas plants could be built in South Ostrobothnia. This includes 63 at cattle farms, 41 at pig farms, 40 at chicken farms, four at turkey farms, and one at a horse farm. Together, these 149 farms could produce approximately half of the total biomethane and hydrogen potential of the region.

Estimating the hydrogen potential of the study area is challenging due to the scarcity of studies examining theoretical hydrogen potential based on the chemical content of methane. However, using SMR technology, the hydrogen potential in the region could theoretically reach approximately 16,000 tons per year, corresponding to 11% of Finland's current hydrogen production (Laurikko et al., 2020).

Table 2. The manure, methane and biohydrogen potentials in large and medium-sized farms in South Ostrobothnia.

Animal species	Amount	Manure m^3 y^{-1}	Biomethane potential MWh y^{-1}	Hydrogen potential of biomethane t y^{-1}
Calves	103,432	1,406,675	267,268	4,414
Pigs	168,827	957,249	95,725	1,581
Horses	180	4,320	2,074	34
Chickens	2,541,748	137,254	111,176	1,836
Turkeys	80,914	8,091	6,554	108
Total	2,895,101	2,513,590	482,797	7,973

3.2 Biohydrogen production optimization

Hierarchical clustering analyses identified the most important locations for developing biohydrogen production in the region. Figure 3 depicts large and medium-sized farms in South Ostrobothnia, divided into clusters based on a maximum transport distance of 10 km. Large farms are particularly concentrated in the municipalities of Kurikka, Ilmajoki, Seinäjoki, and Lapua. Optimal locations for the biohydrogen production plants, minimizing transportation distances, were computed within each cluster based on the road network. A transportation distance of 2 km was identified as the most effective for prioritizing the largest farms in close proximity to one another.

The top ten clusters with a 2-km transportation distance are listed in Table 3 and the top ten clusters with a

10-km transportation distance illustrated in Figure 3. For example, the optimized location for cluster number 2 is shown in Figure 4 (with a 10-km transportation distance). Collectively, these clusters represent over 10% of the region's total biomethane and hydrogen potential. The top ten clusters with a 10-km transportation also represents 2.5% of the Finnish national target to increase biogas production to 4 TWh by 2030. The cluster with the highest biohydrogen potential (with a 2-km transportation distance) in the Alavus municipality is located near a large and busy road between Alavus and Lapua, which could facilitate the transportation of biomethane or hydrogen to users. The cluster is sufficient to meet the annual gross energy demand of more than 500 biogas vehicles (if the fuel consumption is 14 MWh/car a year).

If the transportation distance increases from 2 to 5 and 10 km, the potential of the top ten clusters would grow from 54.8 GWh to 69.9 GWh and 100.7 GWh, respectively. The clusters with 5- and 10-km transportation distances include some of the same farms as the clusters with a 2-km transportation distance. However, the number of farms increases with longer transportation distances, as they encompass more farms and thus a larger amount of manure. Figure 5 identifies the best areas for biomethane and hydrogen production.

The clusters in the Kurikka municipality are located near an existing wind energy production facility, where wind turbines are already operational and new ones are under construction (Finnish Wind Power Association, n.d.). Additionally, some of the region's first biogas plants have been constructed in Kurikka (Bioenergy Association of Finland, 2023). Investments in renewable energy present an opportunity for future hydrogen production. Electrolysis-based green hydrogen production from wind power may require stable green hydrogen sources, such as biogas. For example, steam biomethane reforming technology could be readily adopted in the area (e.g., Buffi et al., 2022).

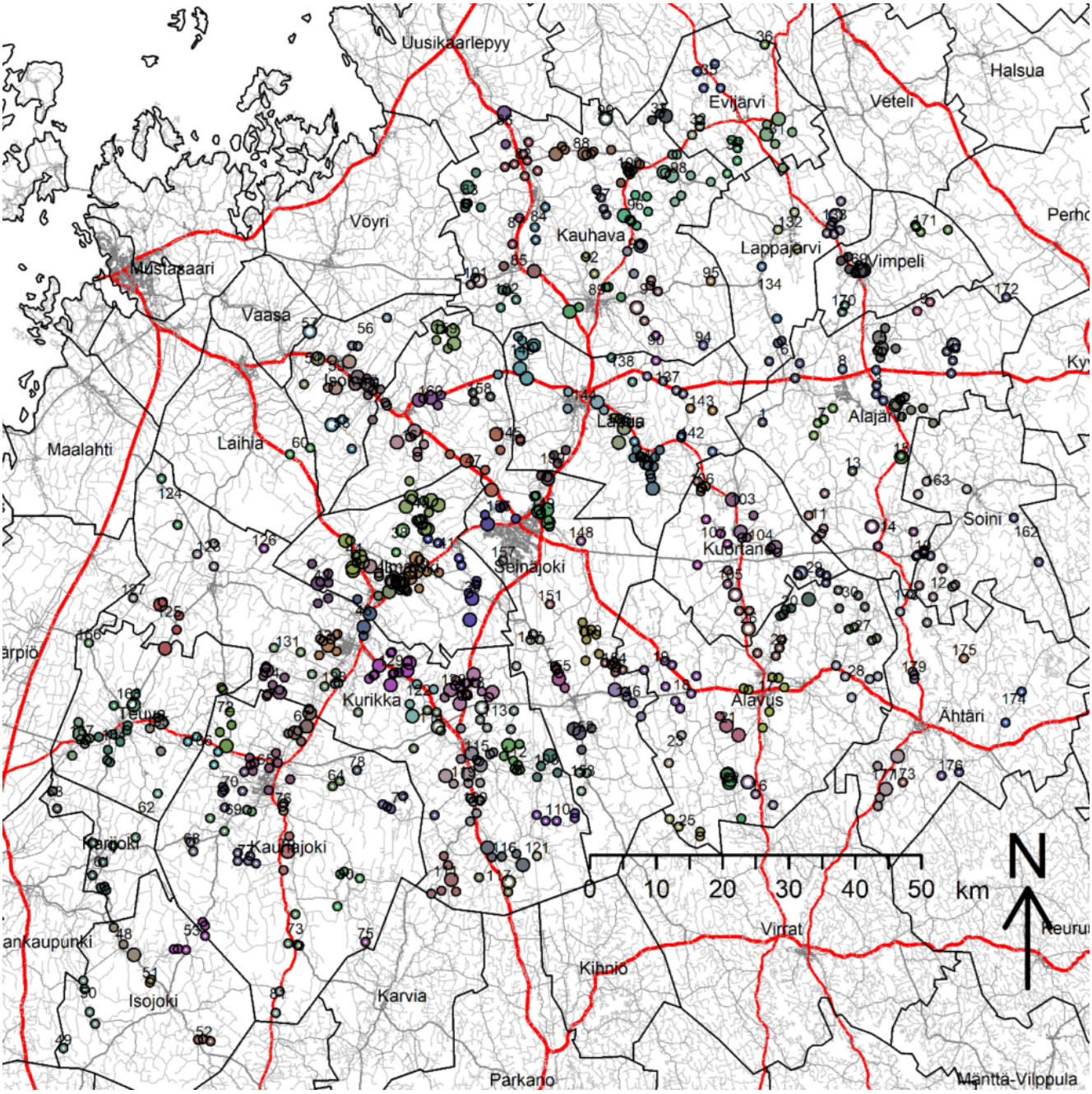


Figure 3. Locations of large and medium-sized farms in the study area, divided into 179 clusters (numbered) based on a 10-km transportation distance. The map also highlights 149 potential farm-scale biogas plants (larger circles, > 100 kW) and potential centralized biogas plant clusters (colored, > 300 kW) for biohydrogen production. Both lower-quality roads (gray) and higher-quality roads (red) were included in the analysis (Map Includes Digiroad data from Finnish Transport Infrastructure Agency (n.d., CC 4.0)

Table 3. The top 10 clusters with the largest biomethane and hydrogen potential in the study area using a 2-km transportation distance. The same locations are marked with red circles in Figure 5. The method allows single-site candidates if the farm is not located close to other farms (less than 2-km transportation distance).

Location	Biomethane potential (MWh/y)	Biohydrogen potential (t/y)	Number of farms

Alavus, Sulkavankylä	7,117	118	4
Ilmajoki, Torala	6,332	105	1
Lapua, Nevala	6,083	100	2
Ylistaro, Louhikonmäentie	5,751	95	1
Ilmajoki, Harjumäentie	5,612	93	1
Kurikka, Riihiluomanpään	5,178	86	1
Tammelanloukko	4,769	79	2
Ilmajoki, Idänpuolentie	4,681	77	5
Kurikka, Jyräntie	4,658	77	1
Ijäksentie	4,626	67	1
Total	54,807	897	19

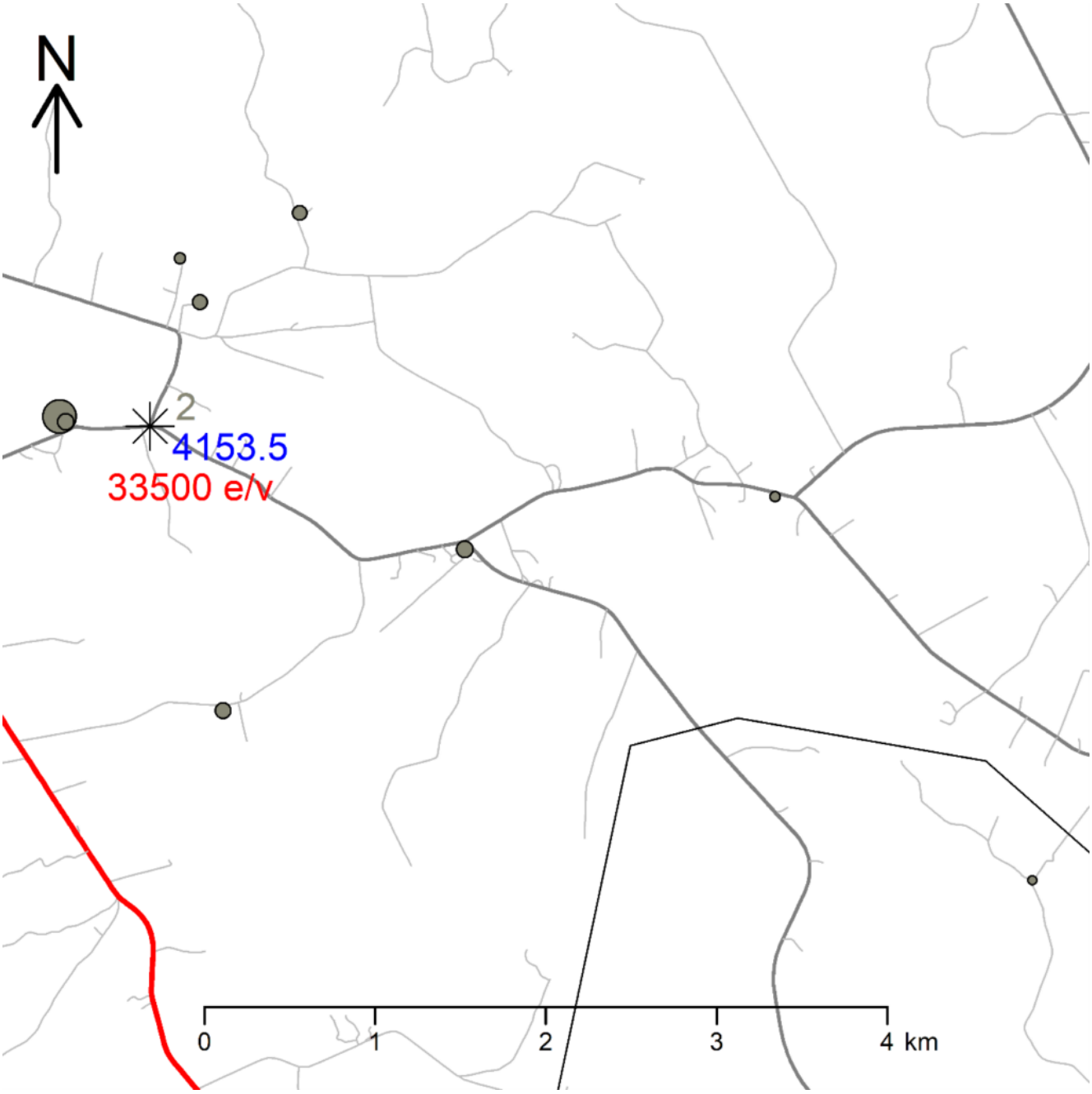


Figure 4. Cluster number 2 (with a 10-km transportation distance), showing an of biomethane or hydrogen production in the study area. This cluster illustrates the advantages of a hierarchical clustering method in situations where close farms are relatively similar in size and where manure quantities from individual farms dominate less transport optimization. The asterisk marks the location of the biogas plant with a minimized transportation distance. The blue number represents the biomethane potential (MWh/y), and the red number denotes the yearly manure logistics transportation cost (€/y) (Map Includes Digiroad data from Finnish Transport Infrastructure Agency (2020, CC 4.0).

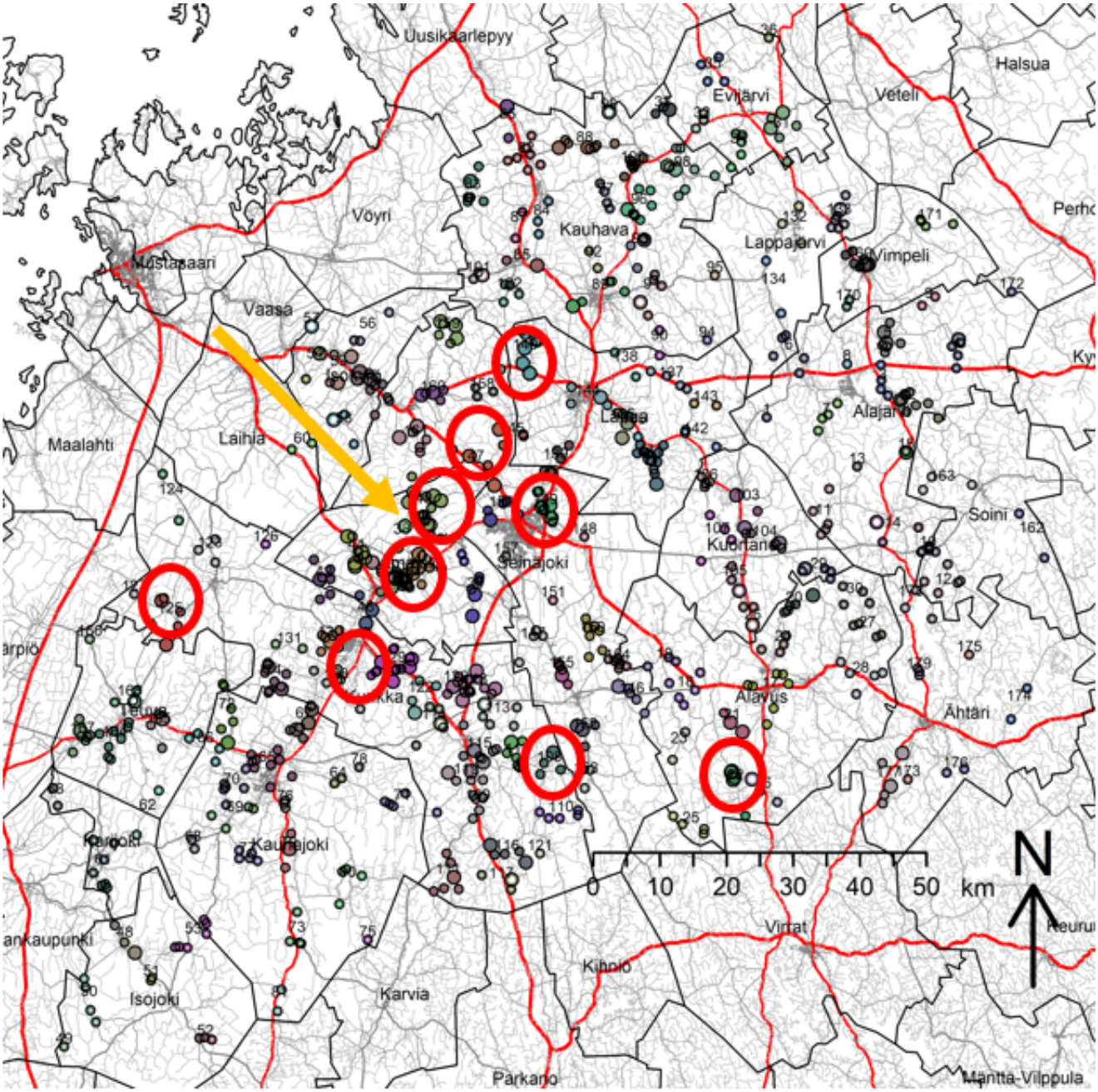


Figure 5. The best areas for biomethane and hydrogen production in the study area (red circles). The head of the yellow arrow indicates the optimal locations for biohydrogen production, encompassing several large and medium-sized farms (Map Includes Digiroad data from Finnish Transport Infrastructure Agency (2020, CC 4.0).

3.3 General discussion

Hierarchical clustering location optimization is a useful tool for assessing biohydrogen potential on a regional scale. It identifies the most important farms within short transportation distances for biomethane and biohydrogen production. Such clustering analyses are also effective in identifying potential strategic partnerships between agribusinesses (Obal et al., 2023). This tool supports regional-scale planning and decision-making regarding hydrogen investments by highlighting the best geographic locations and optimal sizing of bioenergy plants in rural environments. Consequently, it can be used in the initials stages of

decision-making to identify cost-effective regions for biohydrogen production, and the information can be integrated with data on other green hydrogen projects to support further development.

However, the accuracy of the results depends on several factors, such as the accuracy of the coordinates, road network quality, and animal data. For instance, if farm operations cease or livestock numbers change, the optimization must be updated. In addition, several sources of uncertainty remain between the methane and hydrogen yields estimated by the method and those realized in practice. Actual methane yields may be constrained by factors such as collection efficiency, biological processes, storage-related losses, logistical losses, and the participation rate of farms. These uncertainties should be considered when interpreting the results, as they may lead to significant errors in estimated methane and hydrogen gas yields.

Anyhow, this self-programmed location optimization tool can help farmers better understand their role in the regional context of biogas and biohydrogen production. One significant benefit is that each farm can be grouped into a cluster with reasonable logistics. In the case study area, over 1,000 maps were generated to illustrate these farms and their division into clusters, helping to evaluate each farm's role in the regional context. However, it must be remembered that farmers always make the final decision about whether to invest in biogas and hydrogen technology. Thus, the clustering results represent technically optimal solutions rather than socio-economically proven concepts. The economic feasibility of the investment must be calculated separately in each case. When assessing economic feasibility, a system-level perspective must always be adopted, as the economic viability and energy balance of biohydrogen produced from biogas are case-specific (see, e.g., Braga et al., 2013; Cvetković et al., 2021). Different hydrogen production technologies also differ substantially from one another. For example, in steam methane reforming, a significant share of the produced hydrogen originates from water via the water–gas shift reaction rather than from the biomass itself. This distinction is important to acknowledge when comparing biohydrogen production with electrolysis-based hydrogen production. For farms, it is essential to assess whether biogas should be upgraded to biomethane or further converted from biomethane to biohydrogen. While large-scale biomethane production is already economically viable under current market conditions, a systematic comparison of the profitability of biomethane and biohydrogen production remains necessary. In any case, on-farm biohydrogen production would require additional capital and operational expenditures beyond those associated with the biogas plant itself, including the costs of the hydrogen production technology, such as steam methane reforming (SMR). It is also crucial to evaluate whether biohydrogen produced under such conditions could be competitive with hydrogen derived from natural gas. For instance, Arachchi (2024) reports levelised life-cycle costs of 3.69 € kg^{-1} H_2 for hydrogen produced from natural gas and 4.75 € kg^{-1} H_2 for hydrogen produced via thermal decomposition of methane (TDM).

In addition, transforming methane in hydrogen may be an unnecessary cost for farmers because CH_4 can be used as a fuel using existing infrastructure. A practical alternative involves supplying existing biogas plants with biomass from nearby farms identified in this study. However, biohydrogen resources may appeal to hydrogen producers due to the growing demand for stable green hydrogen sources to complement electrolysis, which is dependent on unstable wind and solar power.

Although biomass conversion into hydrogen is more environmentally friendly than hydrogen production from fossil fuels (Singh et al., 2023), it faces two major challenges: poor hydrogen yield and high production costs

(Pal et al., 2022). According to Alves et al. (2013), methane reforming processes for hydrogen also face technical challenges, such as coke formation on the catalyst surface, reduced hydrogen production and potentially discouraging investment in hydrogen-production technologies. However, biohydrogen production through SMR generates biogenic CO_2 emissions, which could be mitigated through Bioenergy with Carbon Capture and Storage (BECCS) technologies, offering a potentially carbon-negative solution for climate action in theory (e.g. Babin et al., 2021). Nevertheless, the BECCS technology and investments are still partly in pilot phase. The costs are also uncertain, and it is highly dependent on investment costs of the technology (IEA, 2026).

4 Conclusions

This study assessed hydrogen production potential and optimization based on agricultural manure in South Ostrobothnia, Finland. A hierarchical clustering method developed by our research group identified biogas potential and further biomethane-based hydrogen refining opportunities. The results show that South Ostrobothnia, an important livestock region has significant methane potential from manure (more than 10% of the manure of Finnish agricultural and horticultural companies), when considering large and medium-sized livestock farms. The potential theoretical hydrogen yield from biomethane is almost 8,000 t per year, with cattle manure being the primary contributor.

The results varied based on the selected boundary distance (2, 5, 10 km), but certain municipalities – Ilmajoki, Lapua, Ylistaro, Kurikka, Seinäjoki, and Alavus – consistently emerged as manure-rich areas for biohydrogen refining. Of these, the clusters in Lapua, Ylistaro, Seinäjoki, and Ilmajoki also benefit from high-quality road networks. The 10 largest farms could contribute 1.4–2.5% toward Finland's goal of increasing biogas production to 4 TWh by 2030. Kurikka offers particularly favorable conditions for hydrogen production from biomethane due to its high significant wind energy and biogas production investments. In conclusion, the hierarchical clustering method developed by our research group provides a practical tool for identifying and optimizing biogas and hydrogen production at the regional level.

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