Digitalization & Sustainable Logistics

Group Project

Windmill Potential in Switzerland: a Comprehensive Investigation and Analysis

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1 Executive summary

I. Background and purpose:

This executive summary details the findings of a comprehensive study intended to guide Swiss policymakers on determining optimal wind turbine locations in Switzerland, with a special emphasis on the canton of Vaud. The aim of the study is to facilitate the objectives of the Swiss Energy Strategy 2050 via minimum utilization of wind turbines to achieve the outlined energy production targets.

II. Methodology and parameters:

This study is an extension of previous research by the Swiss Federal Institute of Technology (ETH). It addresses the challenge of site optimization while considering several constraints. The study harnesses geospatial data, incorporating parameters such as the proximity of wind turbines to cities, national parks, UNESCO natural heritage sites, and other significant restrictions. Google's OR-Tools are used to optimize the placement of wind turbines while respecting the geospatial constraints.

III. National-level findings:

Our analysis on the national level projects that Switzerland will need approximately 150 functional wind turbines by 2035 to meet its wind energy production targets. These findings can be seen as a valuable addition to the ETH study's forecasts for 2050. In particular, both studies highlight a clustering of wind turbines in the upper plateau area.

IV. Cantonal-level implications - a focus on Vaud:

On a more localized level, the canton of Vaud is projected to require 10 wind turbines by 2035 to meet its electricity needs, commensurate with its GDP contribution. However, the clustering of turbines into wind farms is considered a more viable approach, culminating in the optimal functioning of two clusters comprising a total of 17 turbines. The study showcases the significant differences in optimal wind turbine locations in the canton of Vaud based on whether the problem is defined at the cantonal or at the national level.

V. Considerations and limitations:

We hereby emphasize that the study's results are grounded in a theoretical optimization problem, and may not fully encompass real-world complexities such as policy implications, economic factors, and social acceptance.

VI. Conclusion and policy recommendations:

Despite these limitations, the study offers meaningful guidance to policymakers and other stakeholders in their pursuit of a sustainable energy future. By demonstrating consistency with existing studies and ongoing projects, this study affirms its relevance and potential utility as a bridging agenda towards the practical implementation of the Swiss Energy Strategy 2050.

2 Introduction

The search of a future that is both desirable and sustainable has led to widespread consensus that our current mix of energy sources has to be revised. The current reliance on fossil fuels and non-renewable energy sources poses significant environmental challenges, including climate change, air pollution, and resource depletion. To address these pressing issues and secure a greener and more sustainable tomorrow, countries around the world are actively investing in the diversification of their energy mix.

This research paper focuses on Switzerland, a country renowned for its breathtaking landscapes and advanced infrastructure, which is currently at the forefront of the global movement towards a sustainable energy future. By examining Switzerland's current energy situation and its endeavors to embrace renewable energy sources, we can gain valuable insights into the strategies and policies necessary to achieve a sustainable and low-carbon energy future.

In the following sections, we will delve into the specific details of Switzerland's energy landscape, with a focus on wind power, a controversial but necessary energy source in the country [8]. More precisely, this research report will study the optimal locations for windmills, taking into account various constraints, including the energy requirements outlined in the Swiss Energy Strategy [1]. Furthermore, we will conduct a detailed case study of the canton of Vaud, providing valuable insights into the specific challenges and opportunities associated with wind power implementation in a specific region of Switzerland. By analyzing the potential for wind power in the canton of Vaud and studying the broader context of Switzerland's energy transition, this report aims to inform policymakers and stakeholders in their decision-making processes towards a sustainable energy future.

A significant study in this field was previously conducted by R. Spielhofer, J. Schwaab, and A. Grêt-Regamey of the Swiss Federal Institute of Technology in Zurich (ETH) [9]. Their work revolved around using optimization to determine the pareto-optimal locations of wind turbines in Switzerland to meet the country's wind energy production goals in 2050. In our study, we build on their groundwork by not only addressing the entire country but also conducting a more localized analysis on the canton of Vaud, our region of interest. Furthermore, we choose a shorter time horizon (2035), modify certain constraints, and test another objective function for our analysis. This detailed exploration of Switzerland's energy landscape and the in-depth study of the canton of Vaud provides a comprehensive understanding of the potential for wind power in the region. By using the same dataset as the ETH study, which was obtained from the Swiss Federal Office of Topography [16], we aim to ensure the relevance and consistency of our findings, while offering a novel viewpoint to aid in decision-making processes for a sustainable energy future.

Our study on wind power in Switzerland aligns with the United Nations' Sustainable Development Goals (SDGs) [18]. Specifically, it supports SDG 7 (Affordable and Clean Energy) by promoting renewable energy. The research also relates to SDG 9 (Industry, Innovation, and Infrastructure) through the innovative application of wind turbines, SDG 11 (Sustainable Cities and Communities) by fostering sustainable urban environments, and SDGs 12 (Responsible Consumption and Production) and 13 (Climate Action) by promoting sustain-

ability and reducing greenhouse gas emissions. Thus, our work contributes to these critical global objectives, facilitating the development of renewable energy.

3 The state of energy in Switzerland and the future of Swiss wind energy

In light of climate change and Switzerland's energy strategy, we need to decarbonize our energy mix. Moving away from fossil fuels while still meeting the country's demand will require the increase of low-carbon energy production, including wind energy. This section aims at providing an overview of Switzerland's current energy situation, its energy strategy, and the role of wind energy within this strategy. It will also discuss the current deployment of wind turbines and previous research that has been led to optimize the locations of future turbines.

3.1 Current energy situation in Switzerland

Switzerland's energy policy aims at ensuring a secure supply of energy to the country while reducing reliance on fossil fuels and diminishing dependence on foreign nations (reducing imports). Additionally, it aims to lower CO2 emissions and meet the climate objectives set forth by the Paris Agreement [14]. The Federal Council has developed the Energy Strategy 2050, which aims at continuing to provide secure and affordable energy to the country despite changing market conditions and reducing the nation's energy-related impact on the environment [1].

Switzerland's primary energy consumption was just under 300 TWh in 2021 [5], a trend that has been steadily declining over the past two decades despite a growing population (energy consumption per capita has decreased). According to the government [13], the mix is currently built as follows: oil (36.3%), nuclear (19.9%), hydropower (14%), followed by gas and other sources. Over the course of the past five years, Switzerland has been actively working towards reducing its carbon footprint and embracing renewable energy sources. Domestically, hydropower produces two thirds of the electricity, followed by nuclear (29%) and other sources, including renewables. The share of wind power is therefore currently low.

70% of the country's energy is imported, and the Swiss Energy Act (enforced in 2018) plans to phase out nuclear energy and increase the role of renewables [13]. Wind power will thus be necessary to reduce reliance on imports and to reach these energy mix goals, which is the main motivation for this paper.

3.2 The role of wind energy in Switzerland

Switzerland is gradually increasing its investment in renewable energy, including wind power. The country has set ambitious goals to achieve net-zero greenhouse gas emissions by 2050, which will require significant scaling up of renewable energy sources such as wind power. Currently, wind represents the smallest source of renewable energy for the country, although the energy strategy aims at increasing its output [15].

Concretely, Swiss wind turbines generate 0.3% of the country's electricity consumption per year. The Swiss Energy Strategy for 2050 sets out to increase the role of wind energy by making it responsible for around 7% of the electricity, implying a production of 4.3 TWh per year by 2050 [17]. Our paper aims at providing tangible recommendations of turbine

locations to policymakers in the canton of Vaud, so we choose to follow a shorter time horizon. The association Suisse Eole estimates that the energy production required by 2035 to match the energy strategy should be 1.2 TWh per year [11].

3.3 Current wind energy production and turbine locations

As of 2021, Switzerland has 11 fully-operating wind farms with a total of 41 wind turbines. The installed capacity of these turbines is 87 MW, with an estimated annual production of 146 GWh [11]. Figure 1 below shows the distribution of wind energy production sites in Switzerland [12].

The largest wind park is on Mont Crosin in the Bernese Jura near St-Imier: this facility comprises 16 wind turbines with a total output of 37.2 MW. Other large facilities in operation are situated in the St. Gotthard Pass (canton of Ticino), in the canton of Jura, in the Rhône Valley (canton of Valais), and in central Switzerland (cantons of Luzern and Uri).

Moreover, several wind farm projects are projected to launch in the coming years. One project has been approved by the federal tribunal (Sainte-Croix in the canton of Vaud, 6 turbines for an expected 22 GWh / year production), while 5 projects are waiting for the construction permits to be approved (two in Vaud, one in Solothurn, one in Valais, one in Neuchâtel, for a combined projected generation of 162 GWh / year). The largest of these to-be-approved projects (EolJorat in Vaud) could be materialized in 2023-2025 [4].

One of the major obstacles in the development of wind farms in Switzerland is social opposition. Inhabitants in the close proximity of announced wind farm projects frequently manifest their opposition to them, for reasons such as damages to biodiversity, the perceived lack of immediate need, or the aesthetic damages to Swiss scenery. This is for instance the case for the "Eole-de-Ruz" project in the canton of Neuchâtel [8].

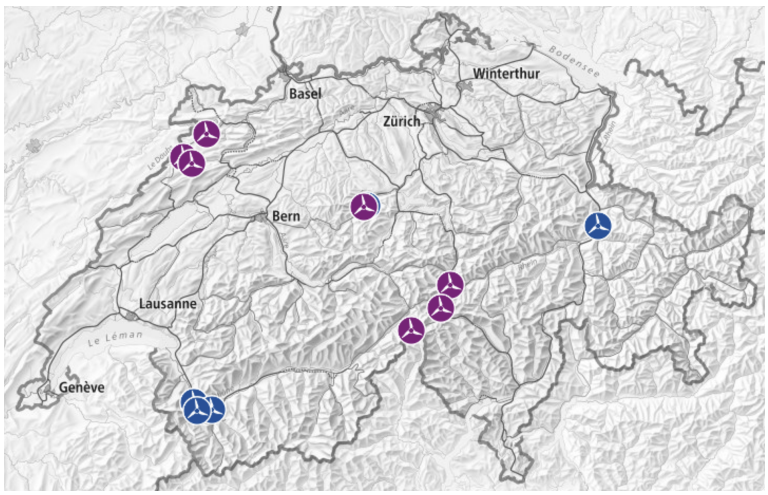

Figure 1: Current wind energy production sites in Switzerland. Purple dots are wind farms, blue dots are single turbines. Source: referenced in the text at the start of chapter 2.3.

3.4 Background

R. Spielhofer, J. Schwaab, and A. Grêt-Regamey of the Swiss Federal Institute of Technology in Zurich (ETH) wrote a paper in which they use optimization to determine the pareto-optimal locations of wind turbines in Switzerland to reach the country's wind production goals in 2050 [9]. They aimed at calculating the number of wind turbines needed to reach the 4.3 TWh yearly wind energy goal by 2050, and to find their ideal locations. Their goal was to minimize the number of turbines for the required production, by maximizing their effectiveness (placing them in windy areas where building them is feasible). They estimate that the country would require approx. 760 wind turbines, approximately located as shown on Figure 2 below, as presented in their follow-up article [2].

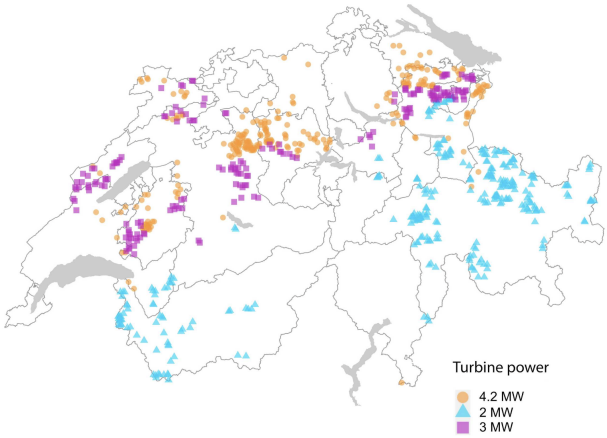

Figure 2: Results from the ETH paper: optimal distribution of wind power sites in 2050 based on the current wind energy concept. Orange circles: largest wind turbines on the Swiss Plateau. Purple squares: medium-sized turbines in the foothills of the Alps and in the Jura Mountains. Turquoise triangles: smaller turbines in the Alps. (Illustration: Reto Spielhofer / ETH Zurich). Source: referenced in the text above.

Building upon their work, we aim at solving a similar optimization problem with the following key differences:

1. With a strong belief in the need for immediate action rather than waiting until 2050, our objective is to identify the optimal distribution of wind power sites in 2035, for an annual energy generation of 1.2 TWh, as discussed in chapter 2.2.

2. We solve the optimization problem for Switzerland, and then conduct a more in-depth analysis for the canton of Vaud to inform policymakers at a cantonal level.

3. In the optimization problem, we play with a different set of constraints, and also change our objective function at the end of the analysis to maximize the energy density instead of minimizing the number of required turbines (see chapter 4.5).

4. In terms of reproducibility, we use the Google OR suite in the hopes that our code is easily reusable by other researchers for similar problems.

To conduct our analysis, we use the dataset that was used in Spielhofer et al.'s paper [6], which in turn was downloaded from the Swiss Federal Office of Topography [16].

4 Analysis for the country of Switzerland

4.1 Data overview

The dataset utilized in this study comprises 12,337 technically feasible location points across Switzerland for potential wind turbine construction. Each location point is represented by unique geographic coordinates, providing 12,337 distinct observations within the dataset. In addition to geographical coordinates, the dataset includes relevant information for each observation, such as the closest distance to housing zones, protected areas, and the identification of whether the location falls within a crop rotation area.

To begin our analysis at the national level, we use a map to visually represent those 12,337 technically feasible location points across Switzerland, enabling a comprehensive visualization of potential wind turbine sites throughout the country. The map is displayed in Figure 3 below.

Figure 3: Technically feasible location points

The geographical distribution revealed by this map demonstrates a logical pattern, with no wind turbine locations identified in the various lakes across Switzerland or in the high mountainous regions in Valais. Conversely, the Swiss plateau emerges as a favorable region for wind energy development, characterized by a substantial number of viable locations in comparison to the eastern part of the country. Consequently, this initial observation indicates that an optimal outcome would likely involve a significant number of wind turbine locations across the Swiss plateau.

Based on this foundation, we proceeded to examine the distinct attributes associated with

each of these locations. Firstly, we assessed the energy production potential of each observation, as depicted in Figure 4[1]. Furthermore, we conducted an analysis to determine if these locations fell within designated crop rotation areas, thereby considering the compatibility of wind turbine placement with agricultural practices.

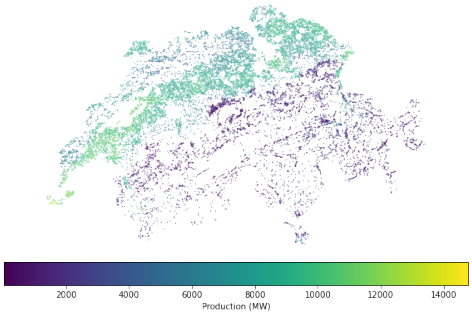

Figure 4: Wind Turbine Production [MW]

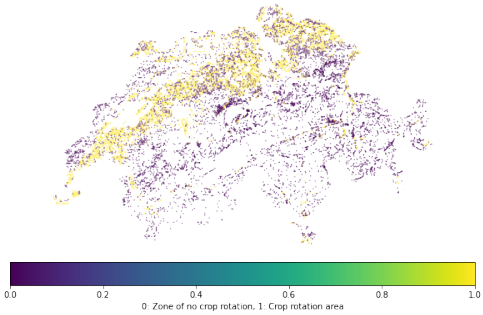

Figure 5: Crop rotation area

The analysis of the two maps reveals a notable finding: a significant portion of the areas exhibiting high energy potential coincides with regions designated as crop rotation areas. This initial observation will have important implications for the optimization process, as the inclusion of these areas as constraints will directly affect the optimal results. These results are consistent with Spielhofer, Schwaab, and Grêt-Regamey's (2022) findings, which suggest that incorporating crop rotation areas into wind power development could potentially result in a reduction of 300 turbines in their 2050 scenario.

4.2 Optimisation

In this chapter, we will begin by introducing our objective function and initial constraint for windmill optimization in the broader Switzerland. To enhance the realism of our model, we will progressively incorporate additional constraints that reflect real-world considerations. These additional constraints will enable a more practical approach to windmill placement across the country, aligning with the complexities and requirements of the Swiss context.

4.2.1 Overview

In the process of transitioning to more sustainable and renewable energy sources, the placement and number of wind turbines is a critical decision with both economic and environmental implications. Our primary goal is to meet the projected wind energy production in 2035, which is estimated to be 1.2 TWh per year, as outlined in the Swiss Energy Strategy 2050[11]. However, we aim to accomplish this objective while simultaneously minimizing the overall quantity of wind turbines deployed.

Firstly, it's important to minimize the number of wind turbines because each turbine represents not only a significant financial investment but also a physical intrusion into the

[1]These values are derived from a formula presented in [9], section 2.3.3.1.

landscape. Turbines can have visual and auditory impacts on the surrounding communities, and they can affect local wildlife, particularly bird and bat populations. By minimizing the number of turbines, we aim to reduce these potential negative impacts.

Secondly, the infrastructure required for wind turbines is considerable. Each turbine needs to be connected to the power grid, which may require building new transmission lines. Additionally, roads may need to be constructed or upgraded to allow for the transportation of turbine components and ongoing maintenance. By minimizing the number of turbines, we can reduce the extent of this necessary infrastructure and potentially lessen environmental disruption and costs.

Finally, the fewer turbines we use to meet the energy demand, the more efficient our solution. If we can meet our energy targets with fewer turbines, it means that we're making the most of the wind resources available, and our solution is economically and environmentally efficient.

Hence, the optimization problem that we are solving is not merely an academic exercise but a real-world problem with tangible implications for the economy, the environment, and society. It involves balancing the need for renewable energy with the desire to minimize the impact on the environment and communities. By formulating this as a binary integer programming problem, we can use powerful computational tools to find the optimal solution, informing policymakers in their decisions.

4.2.2 Problem formulation

The problem aims to minimize the number of wind turbines while ensuring a total power production of at least 1.2 TWh/y.

4.2.3 Decision variables

Let's denote the binary decision variables with the letter x. Each x_i represents whether a wind turbine is placed at location i or not. If a wind turbine is placed at location i, x_i will be 1; otherwise, it will be 0.

$x_i \in \{0, 1\}$ for each $i \in I$, where I is the set of all locations.

4.2.4 Objective function

The objective is to minimize the total number of wind turbines, which is equivalent to the sum of the decision variables x_i.

This can be mathematically represented as:

$$\text{Minimize:} \quad \sum_{i \in I} x_i$$

4.2.5 Initial constraint

The problem has a constraint on the total power production. The sum of the power production from all locations where wind turbines are placed should be at least 1.2 TWh/y.

Let p_i represent the power production in MW from location i.

This can be mathematically represented as:

$$\sum_{i \in I} x_i \cdot p_i \geq 1.2 \times 10^6$$

4.2.6 First results

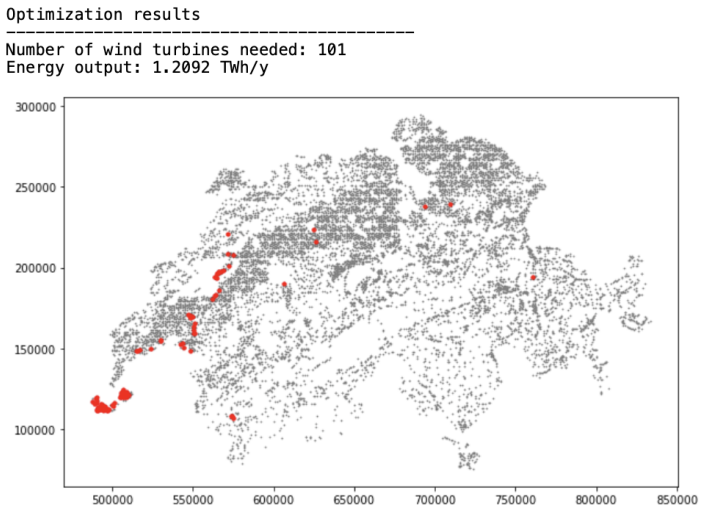

Figure 6: Optimization results with a single constraint

This figure shows that with one single constraint, namely the 1.2 TWh/y energy generation, 101 wind turbines would be necessary. In terms of optimal locations, we observe that they would almost exclusively be deployed in the Swiss plateau, which is in line with Figures 4 and 5, discussed in chapter 3.1. We observe a major cluster of wind turbines in and around the city of Geneva, several smaller clusters around the Lausanne region, and multiple turbines located around the Neuchâtel lake. We also see a few outliers in Valais, in Graubünden, to the south of Zurich, and in the cantons of Bern / Luzern. Since we have not applied any constraints yet, our model defines these locations as the most optimal. However, they may be situated in urban areas or crop rotation areas (agricultural land dedicated to crops), which would not be realistic, hence the need for further constraints.

4.3 Additional constraints

As previously mentioned, we will now augment our model by incorporating additional constraints to reflect real-life scenarios. In other words, we aim to create a more realistic representation of the factors that influence windmill placement and ensure that our optimization results align the best with practical considerations and potential real-world outcomes.

In addition to the previously introduced constraint regarding the energy output requirement, we have identified several other additional constraints, which are as follows:

Constraint 2: Distance to UNESCO heritage (cultural and natural) areas should be more or equal to 2000m (2km)

This constraint aims to safeguard the cultural and historical significance of UNESCO heritage areas by preventing the placement of wind turbines within a 2km radius of these sites.

Let $d_{UNE,i}$ represent the distance to the nearest UNESCO heritage area from location i, in meters. This can be mathematically represented as:

If $d_{UNE,i} < 2000$, then $x_i = 0$.

Constraint 3: Distance to Swiss national park or regional nature park should be more or equal to 2000m (2km)

This constraint aims to preserve national and regional parks by prohibiting the placement of wind turbines within a 2km radius of these areas.

Let $d_{PARC,i}$ represent the distance to the nearest national or regional park from location i, in meters. This can be mathematically represented as:

If $d_{PARC,i} < 2000$, then $x_i = 0$.

Constraint 4: Distance to housing zone area should be more or equal to 1000m (1km)

This constraint is implemented to safeguard against the placement of wind turbines in close proximity to residential areas. It enforces a minimum distance requirement of 1km between any potential wind turbine location and nearby housing zone areas.

Let $d_{HZ,i}$ represent the distance to the nearest housing zone from location i, in meters. This can be mathematically represented as:

If $d_{HZ,i} < 2000$, then $x_i = 0$.

Constraint 5: Distance to transmission should be less or equal to 1500m (1.5km)

This additional constraint aims to ensure the proximity of wind turbines to transmission lines by limiting the selection to turbines located within a maximum distance of 1.5km. By imposing this constraint, we want to minimize transmission losses, but also reduce the need for extensive transmission line development.

Let $d_{PL,i}$ represent the distance to the nearest transmission line from location i, in meters. This can be mathematically represented as:

If $d_{PL,i} > 1500$, then $x_i = 0$.

Constraint 6: Avoid crop rotation area

This constraint is implemented to safeguard against the selection of wind turbine locations within areas designated for crop rotation. the primary objective is to prevent any potential disruptions to agricultural practices and ensure the preservation of fertile lands exclusively for crop cultivation.

Let f_i represent whether location i is a crop rotation area or not. This can be mathematically represented as:

If $f_i = 1$, then $x_i = 0$.

4.3.1 New results

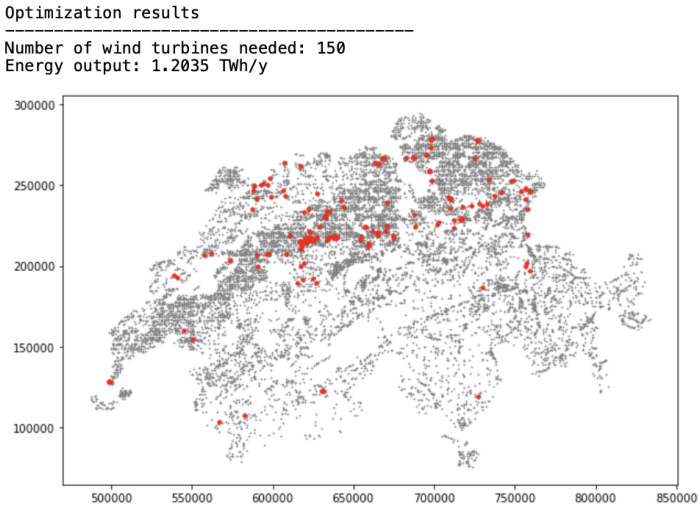

Figure 7: Optimization results with additional constraints

The map displayed above, which is the result of the optimization problem with the 5 constraints listed above, contrasts drastically with Figure 6, which shows the optimization without constraints. First, we now require 150 turbines to reach the desired energy generation, an increase of 49 compared to the unconstrained results. The locations of these turbines also differs significantly. While a major concentration in Geneva and Lausanne was recommended by the unconstrained optimization, we now have a much more widespread, less concentrated distribution. The turbines are still mostly situated in the Swiss plateau, but with a much higher percentage located in the central and northeastern parts of Switzerland. The cantons of Geneva and Vaud now only possess a handful of turbines, while the concentration has greatly increased in cantons such as Bern, Luzern, Zug, Zurich, and St. Gallen. The cantons of Graubünden, Ticino, and Valais also have a handful of turbines.

In this study, the introduction of new constraints allows for a fairer comparison of the obtained results with those from the ETH study. However, it is important to acknowledge several key differences between the two analyses at this stage. Spielhofer et al.'s paper [6] focused on assessing the number of wind turbines required in Switzerland by 2050, whereas our analysis pertains to the year 2035. Consequently, it is expected that our findings would indicate a lower number of turbines. Furthermore, our optimization process thus far has not incorporated any clustering methodology, resulting in a more dispersed distribution of wind turbines across Switzerland, in contrast to the approach adopted in the ETH study. These differences naturally yield distinct outcomes. Nonetheless, valuable insights can still be gleaned from Figure 2 and Figure 6, which depict the results of the ETH study and our analysis with the inclusion of new constraints, respectively.

When comparing the numerical outcomes, Spielhofer et al.'s study [6] proposes the construction of 760 wind turbines, while our optimal solution suggests a significantly lower number of

150. Despite the 15-year difference in timeframes, a common spatial pattern emerges when examining the turbine locations. Specifically, both studies reveal a concentration of wind turbines in the upper plateau region, spanning from Berne to Olten, Lucerne, and Zurich. In light of these findings, our results can serve as a foundational basis for observing the actual wind turbine distribution in 2050. It is conceivable that if we extend our analysis to a later period, such as between 2040 and 2045, we may observe an increased deployment of wind turbines in Valais and Grisons. This sequential approach aligns with the notion of initially establishing wind turbines in the plateau area, where the energy potential is most favorable, and subsequently expanding the deployment towards those regions.

In addition, the noticeable absence of wind turbines between Geneva and Lausanne, as well as in the northern part of Canton de Vaud, is an interesting observation shared by both analyses, with the ETH study even suggesting zero turbines in these areas. In this context, considering a scenario where a national collaborative strategy is established based on our 2035 analysis and Spielhofer et al.'s [6] projections for 2050, the Canton de Vaud would potentially be spared from extensive wind turbine construction within its territory. However, an important question arises: What if the Canton of Vaud is required to develop its own strategy for the 2050 Swiss Energy Strategy, without collaboration among cantons? How would this impact the number of wind turbines to be constructed? This crucial inquiry forms the basis for the subsequent chapter, where we delve into a comprehensive examination of wind turbine deployment specifically within the Canton de Vaud region.

5 Analysis for the canton of Vaud

5.1 Rationale for localized research

This chapter of the report focuses on the canton of Vaud within Switzerland to examine the implications of delegating the responsibility of implementing the Swiss Energy Strategy 2050 to individual cantons. By conducting a comprehensive study at the local level, this research aims to analyze the challenges and opportunities associated with windmill placement in this specific region. The canton of Vaud, as the fourth largest canton in Switzerland in terms of area, provides an ideal case study for investigating the specific dynamics of windmill placement within a defined geographical and socio-economic context. The research findings presented in this paper aim to directly inform the decision-making process of the cantonal parliament, aiding in the successful realization of the national energy plan and the delivery of clean energy solutions to its citizens.

Delegating the implementation of the Swiss Energy Strategy 2050 plan to individual cantons, such as the canton of Vaud, holds several potential rationales, which can be considered hypothetical assumptions for the purpose of this study. While national cooperation among cantons would be desirable, the delegation of responsibility to individual cantons may arise due to certain contextual factors and practical considerations.

- Regional autonomy and tailored solutions: Switzerland follows a federal structure, granting a certain level of autonomy to its cantons. Delegating the implementation of the national energy plan to individual cantons allows for the development of tailored solutions that align with the specific regional characteristics, resources, and needs of each canton. In addition, each canton can prioritize its renewable energy projects based on its available resources, such as wind potential, suitable sites for windmill installations, and existing energy infrastructure. This flexibility allows for optimal utilization of resources and reduces the risk of bottlenecks or delays that may occur in a centralized implementation approach.

- Local stakeholder engagement: Swiss cantons possess different community dynamics, regulatory frameworks, and political governments. Therefore, the ease in convincing inhabitants of windmill implementation might be very dependent of the canton studied in Switzerland. This is why the Swiss parliament would want to specifically delegate decisions to each canton to align with the local will of the inhabitants.

It is worth noting that the delegation assumption to individual cantons made in this study is solely for the purpose of analysis. The effective implementation of the Swiss Energy Strategy 2050 may involve various considerations, and may even prioritize a more centralized or collaborative approach among the cantons. Nonetheless, by investigating the implications of localized implementation within the canton of Vaud, this research can offer valuable insights into the potential advantages, obstacles, and takeaways for other regions, thus contributing to a comprehensive understanding of renewable energy deployment within the Swiss context.

In summary, in this chapter, we begin by examining the current state of windmill installations in the canton and explore various variables accordingly. Building upon this understanding, we then present our two primary objectives. Firstly, we aim to assess the outcomes of windmill optimization at the cantonal level, using the same constraints employed in the

broader Swiss study. Secondly, we introduce a novel clustering methodology that emphasizes the formation of wind farms by grouping windmills together, departing from the conventional approach of considering individual placements in isolation. Furthermore, a new objective function is proposed, prioritizing the maximization of energy output while minimizing the visible area footprint. This objective function is motivated by the need to ensure the social acceptance of windmill installations by mitigating their visual impact on the local landscape. By addressing these objectives, this chapter provides a valuable windmill placement strategy that is both effective and socially acceptable for the canton of Vaud region.

5.2 Current situation in the canton of Vaud

In the canton of Vaud, there are currently no operational wind turbines. However, the association Suisse Eole has reported the existence of a planned wind farm project in the region. This project, known as the Sainte-Croix wind farm, aims to install six wind turbines with a total capacity of 13.8 MW and an estimated annual production of 22 GWh. The project was submitted for approval in 2010 and recently received validation for its building permit by the Federal Court in 2021.[11]

Furthermore, three additional wind farm projects in the canton of Vaud have reached significant milestones in their development. These projects have had their land use plans (LUPs) validated by the Federal Court and are currently progressing through the construction permit procedure. One of these projects is the Mollendruz wind farm, which is set to consist of twelve wind turbines with a total capacity of 50.4 MW and an estimated annual production of 112 GWh. The project was submitted for planning permission in 2015 and is currently undergoing development. It received validation by the Federal Court in 2022, and preparations for the building permit are underway.[11]

Another project, the EolJorat Sud wind farm, features eight wind turbines with a total capacity of 33.6 MW. It received validation by the Federal Court in 2022 and is currently in the process of obtaining a construction permit. Similarly, the Sur Grati wind farm, comprising six wind turbines with an installed capacity of 18 MW, obtained validation by the Federal Court in 2022 and is also in the process of obtaining a construction permit.

5.3 Optimisation

As previously mentioned, the analysis conducted on the canton of Vaud adheres to the same constraints as those established and developed at the national level. Therefore, to align with the Swiss energy strategy, it is necessary to adjust the energy requirements from wind turbines for the canton. To achieve this, the initial value of 1.2 TWh/year is proportionally reduced based on the percentage of the Swiss GDP assigned to the canton of Vaud. This approach is chosen due to the strong correlation between energy consumption and GDP [10], which provides a more meaningful representation than relying solely on population figures that may be influenced by the presence of cross-border workers in the canton. Given that the GDP of the canton of Vaud accounts for 8% of the overall Swiss GDP, this yields an initial constraint value of 0.096 TWh/y.

5.3.1 Decision variables

We refer to the constraints outlined in Section 3.2.3 of this report.

5.3.2 Constraints

We refer to the constraints outlined in Section 3.3 of this report.

5.3.3 Results

To begin, incorporating the five constraints into our model presents a challenge as it does not yield an optimal solution. This highlights the increased complexity of conducting a state-specific study for the canton de Vaud compared to the broader scope of Switzerland, where a larger number of potential locations are available. In order to generate any results, we are compelled to relax the distance to housing constraint to 650 meters. We have made this adjustment based on the belief that it represents a compromise where some degree of trade-off can be considered. Indeed, we find it infeasible to approach the UNESCO heritage sites any closer or to move further away from the transmission lines. With this modification, we present the initial optimization results at the cantonal level.

```
Optimization results
----------------------------------------
Number of wind turbines needed: 10
Energy output: 0.1 TWh/y
```

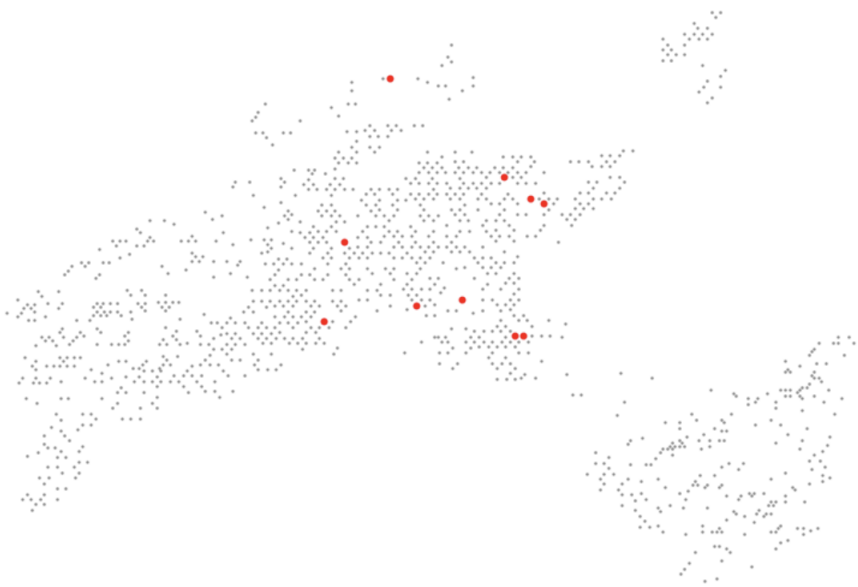

Figure 8: Optimization - canton of Vaud

The analysis of windmill optimization at the canton level reveals a diverse distribution of 10 locations across a large area of the central canton of Vaud. Interestingly, no wind turbines appear in the northwestern part of the canton, which has a low population density. Wind turbines are observed in various locations, including 5 in the southern region of the canton, close to the lake (near Morges, Renens, Prilly, and Cully). We then find 3 turbines

near Moudon, 1 near Cossonay in the central region, and 1 near Orbe to the north. This distribution showcases the presence of wind turbines in countryside areas and along the lake, reflecting their integration into the diverse landscapes of Vaud. Of particular interest is the identification of a turbine near Renens, close to EPFL. This finding suggests that, according to the optimization results, wind turbines would become an integral components of Vaud's landscape. As a consequence of this cantonal wind energy production target, the required number of wind turbines differs when considering Switzerland as a whole compared to focusing solely on the canton of Vaud.

During the establishment of these location points, various constraints were considered and manipulated to refine the results. Notably, the constraint regarding the avoidance of crop areas emerged as a highly influential factor in shaping the outcomes. This observation aligns with the findings of previous studies conducted at the national level, including the research conducted by ETH. The decision regarding whether to permit or restrict wind turbine development in crop areas holds significant implications for the future of Swiss wind energy, as well as for the specific context of the canton of Vaud examined in this chapter.

It is worth noting that the validity of this analysis depends on the implementation strategy that Switzerland chooses for wind turbines. The Swiss Energy Strategy [1] has been decided on at the federal level, but whether and the extent to which the federation delegates the implementation decisions to cantons, and the extent to which they coordinate their cantonal roadmaps among each other will be a key determinant of the amount of wind energy production that each canton will target. These decisions will also in turn influence the optimization of turbine locations.

However, from an efficiency standpoint, it is essential to question the rationale behind constructing installations that are geographically distant from one another. Is such a dispersed configuration truly advantageous in terms of overall output and resource utilization? For instance, this dispersed configuration often necessitates extensive infrastructure development, including the construction of access roads and the readaptation of transmission lines. These activities can have localized environmental consequences, which, in turn, may lead to secondary effects and heightened pressure on the local flora and fauna. To address these concerns, the concept of clustering has been incorporated into the optimization process. Clustering involves grouping wind turbines together to form wind farms, deviating from the traditional approach of considering individual placements in isolation.

5.4 Clusters

The incorporation of clustering into the windmill optimization process offers several advantages. Firstly, it facilitates operational efficiency by enabling the sharing of resources and capitalizing on economies of scale (e.g., shared infrastructure, same access roads, cost savings, etc.). In addition, the implementation of strategic clustering addresses a significant concern associated with the visual impact of windmills. By concentrating the placement of wind turbines in specific locations rather than dispersing them widely throughout the canton, the visual intrusion of these structures on the landscape can be minimized. By doing so, this strategy can actively address the visual concerns voiced by the community recently regarding the presence of wind turbines [7] and therefore promotes a higher degree

of acceptance.

The upcoming sub-chapter will focus on optimizing windmill placement using a cluster-based approach, deviating from the previously used methodology that considers uniquely individual point locations.

5.4.1 Optimisation

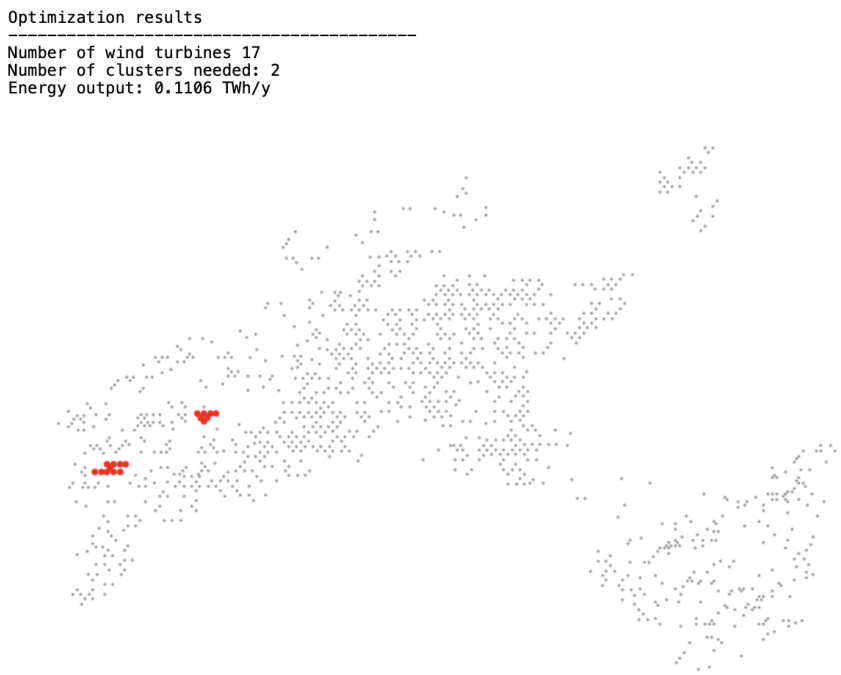

Figure 9: Optimization results wih additional constraints

In order to facilitate the formation of wind turbine clusters, the DBSCAN algorithm was employed, which effectively identifies closely grouped points in the feature space. For a more detailed description of the cluster formation process, we refer the reader to the code deposited on GitHub. In general terms, DBSCAN uncover clusters that yield to two constraint 1) Maximum distance between two wind turbines (800m), and 2) Minimum number of wind turbines in each cluster (3). As depicted in Figure 9, the optimization results indicate that only 17 wind turbines, concentrated within 2 clusters, are required to achieve the objective of 0.096 TW/y. These clusters are exclusively situated within the "Jura vaudois".

However, we want to stress that achieving these results required relaxing certain constraints that were originally included in the model. Indeed, in order to obtain resonant clustering outcomes (i.e., not exceeding 6 clusters across the canton), the distance constraint related to national parks had to be reduced to zero, while the distance constraint associated with transmission lines had to be significantly increased.

From our perspective, two insights can be drawn from this result:

- Firstly, in contrast to the individual-based approach discussed in Section 4.3.3, the implementation of a cluster-based wind farm placement strategy introduces significant

environmental and societal costs, as characterized by the relaxation of constraints. This strategy leads to wind farms encroaching national and regional parks, and becoming proximate to residential zones.

- Secondly, it is noteworthy that the identified clusters are in close proximity to ongoing wind farm projects. For instance, the Mollendruz Park, currently undergoing the building permit authorization process and set to accommodate 12 wind turbines, aligns with one of our identified clusters. A visual representation of wind projects, including those in progress, under construction, and operational, can be found in the appendix of this report.

The final observation is deemed satisfactory, indicating a degree of alignment between existing wind projects and the findings derived from our academic study. However, driven by our curiosity, we embarked on a new avenue of investigation: what if we were to redefine our objective function, which was initially focused on minimizing the number of wind turbines built?

5.5 New objective function: Energy output per visible area

In this chapter, we introduce a novel objective function that deviates from the previous focus on minimizing the number of wind turbines built. Our new objective seeks to optimize the individual location of wind turbines, opposed to section 4.4, which focused optimizing clustered windmills. Now, our new objective is to maximize the energy output per visible area. This adjustment was motivated by the understanding that individuals may prefer a scenario where five wind turbines are discreetly concealed behind a forest rather than having a single turbine prominently located in Bussigny for example. Consequently, we have replaced our previous objective function with the goal of optimizing the energy output while considering the unique visibility characteristics at each potential wind turbine location. To achieve this, we utilize a variable within our dataset that quantifies the visibility of a wind turbine at a given location. By integrating this variable with the potential energy output at each point, we are able to formulate our new objective function. Overall, the aim of this approach is to find a balance between efficient energy production while addressing concerns related to the visual impact of wind turbines. But maximizing energy density comes at the cost of the number of turbines. So we need to find a way to balance these two traits.

5.5.1 Problem formulation

The objective is to minimize the number of wind turbines and maximize the energy density per visible area (*ENER_DENS*), which measures a location's energy density divided by a measure of how visible a turbine would be in that spot. We introduce a trade-off which indicates the extent to which we prioritize maximizing the energy density per visible area versus minimizing the number of turbines. A higher trade-off means a higher weight given to maximizing energy density per visible area. If d_i represents the energy density per visible area at location i, and λ $[0, 1]$ represents the trade-off weight, this can be mathematically represented as:

$$\text{Maximize:} \quad \sum_{i \in I} (\lambda \cdot d_i - (1 - \lambda) \cdot 1) \cdot x_i$$

In our case, we can set λ to different values to display the trade-off between the two objectives. For the code below, we have chosen the following:

$$\lambda \in \{0.5, 0.75, 0.9, 1\}$$

The objective function also captures a plausible extension through the last 1-digit, which represent the cost of building wind turbine at location i. We have kept that variable to 1, indicating that we treat all plausible locations the same. For additional clarity and mathematical examples regarding the new objective function, we direct readers to the appendix section of this paper.

The constraints used are the same as the ones used in section 4.3.3.

5.5.2 Results

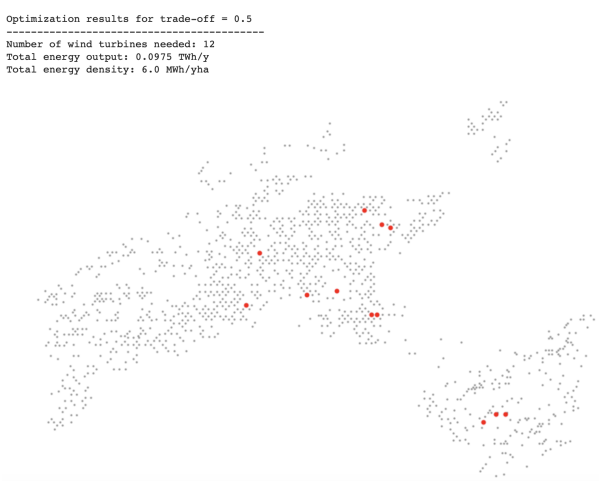

Figure 10: Trade-off with $\lambda = 0.5$

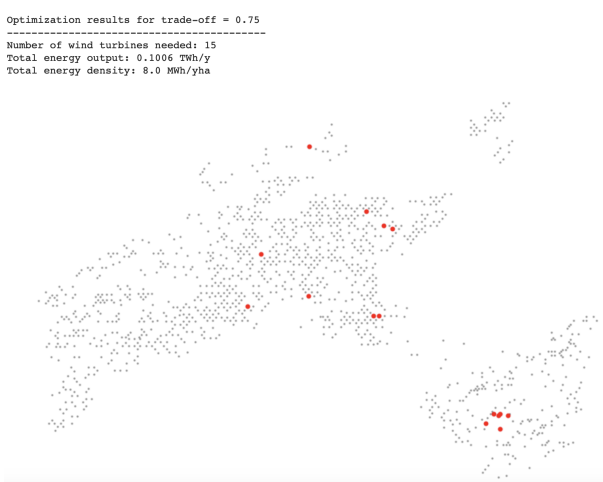

Figure 11: Trade-off with $\lambda = 0.75$

Figure 12: Trade-off with $\lambda = 0.9$

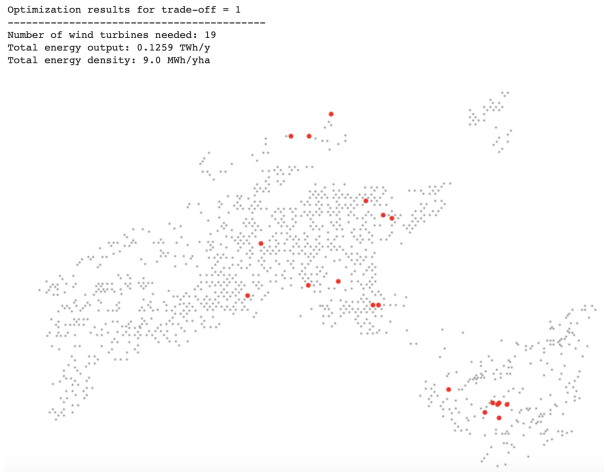

Figure 13: Trade-off with $\lambda = 1$

As a reminder, the trade-off figure serves as an indicator of the relative importance placed on maximizing energy density versus the number of wind turbines constructed. A higher trade-off value signify a greater emphasis on energy density, while a trade-off at zero simply implies minimizing the number of wind turbines.

Based on the analysis of the four maps presented above, several notable findings emerge. First, when considering a trade-off of 0.5, the windmill placement results indicate a need for the construction of 12 turbines, which is slightly higher compared to the previous results discussed in Section 4.3.3, which called for 10 turbines. However, the chosen locations, particularly those in close proximity to the canton of Valais, may exhibit a favorable trade-off between visibility and energy production. Compared to the previously identified sites, these selected locations are expected to offer reduced visibility while maintaining a high level of energy output. Notably, the analysis reveals the emergence of new wind farms in the countryside of the canton, near Fribourg, and in the Gros de Vaud region, areas characterized by relatively sparse population density (i.e., probably less visibility).

Furthermore, a notable trade-off emerges between minimizing the visual presence of wind turbines for the general population and the corresponding construction cost. As the trade-off parameter increases, indicating a greater emphasis on visual impact mitigation, the number of required turbines also escalates. This pattern is clearly depicted in figure 4, where the proposed wind farm entails the construction of 19 turbines, leading to an energy density of 9.0 MWh/yha. In contrast, Figure 10 achieves a lower density of 6.0 while employing a smaller number of turbines.

The trade-off approach enabled us to find a sweet spot, balancing two very important characteristics of wind turbine placements. We discussed other plausible techniques, involving additional constraints such as desired energy roof (maximal tolerated energy output) and floor (minimal tolerated energy output), but found that our new objective function gave us the best means to fine-tune our optimization towards the most desirable outcome.

6 Limitations and avenues for extension

The findings of this study open up avenues for potential extensions and further research in the field of wind turbine placement optimization. One potential extension could involve exploring additional constraints that consider the environmental impact of wind farm installations, such as proximity to protected species habitats or sensitive ecosystems. In fact, engaging in discussions with experts, such as a law PhD student from the University of Lausanne who conducted a master's thesis on the legal aspects surrounding wind turbine construction, revealed that many legal challenges arise due to proposed windmill sites being situated in close proximity to areas inhabited by protected species. This knowledge underscores the importance of considering very specific environmental concerns in the decision-making process, as it significantly affects the feasibility and successful implementation of wind energy projects in the real life. Furthermore, incorporating socioeconomic factors, such as proximity to industrial centers, could provide a more comprehensive understanding of the trade-offs involved in wind turbine placement. In summary, by progressively incorporating a broader range of constraints or modifying the objective function, this investigation has the potential for extensive expansion.

Similarly, while we primarily aimed at minimizing the number of required turbines in our study, we did not incorporate thorough construction, installation, and maintenance costs in our optimization problem (here, by costs, we mean both financial and environmental costs). Besides the costs of the turbines themselves, multiple other cost categories must be considered, such as the costs of conducting social acceptance or information campaigns, or the costs of making the roads to the construction sites viable for transport (in practice, it is complicated to bring huge turbine components up countryside roads). Overall, many aspects of the economic, social, political, environmental, and technical spheres are necessary to obtain a complete picture of such projects.

One potential and "low-hanging-fruit" extension that might be worth investigating is a scenario analysis whereby we treat the country's wind energy production target as a decision variable. The goal of the Swiss confederation is for wind to produce 7% of the country's total electricity consumption by 2050. However, it would be relevant to conduct a sensitivity analysis to study how the number of required wind turbines changes to reach different targets. What happens if Switzerland wants to produce 50% of electricity with wind? Investigating this would help clarify the limits of wind as an energy source for the country (assuming the same wind turbine technology and constraints). This analysis becomes even more relevant in a future scenario where our dependence on conventional and fossil-fuel based energy sources is significantly diminished, and there is a greater urgency to transition to renewable energy, particularly by the year 2035

Moreover, this research can be extended beyond the canton of Vaud to other regions, countries, or even continents. For instance, conducting a similar study in countries like China or India, which face significant challenges in implementing renewable energy sources, could offer valuable insights into the optimal placement of wind turbines in polluted areas. However, we want to acknowledge that accessing reliable data in such contexts may pose challenges, considering the scale and complexity of the regions. This presents a contrasting situation to the experience gained in the present study, where data availability and quality were highly

favorable.

Overall, expanding this research to new geographical contexts and considering additional objective functions and constraints would contribute to the advancement of sustainable wind energy deployment, providing valuable guidance for policymakers, energy planners, and stakeholders involved in the development of renewable energy projects.

7 Conclusion

The objective of this study was to inform Swiss policymakers in the decisions they will have to take regarding the locations of wind turbines, in order to reach the goals laid out in the Swiss Energy Strategy [1]. This initiative targets a wind energy production of 4.3TWh in 2050 in the country. Building upon research conducted by researchers at ETH [9] which estimates the optimal locations of wind turbines in 2050, we attempt to determine the optimal locations of wind turbines in 2035 in Switzerland (amounting to a goal of 1.2TWh) and in the canton of Vaud, to inform stakeholders at a more local level. This is translated into an optimization problem in which the objective is to minimize the number of turbines required to reach a given energy production target, given a set of constraints. In our study, we then explore a clustering strategy for turbines in the canton of Vaud, and later try another objective function to maximize the energy density per visible area.

As a disclaimer, we want to emphasize that we discussed the results of a theoretical optimization problem. The reality includes a vast array of multi-dimensional issues, including policy, economics, social acceptance, multi-actor collaboration, etc. Some very efficient turbine locations might never be used, and some less-than-ideal areas might one day contain large wind farms.

Our results at the national level indicate that Switzerland would need to have 150 wind turbines operating in 2035 in order to meet its wind energy production targets (Figure 7). This number decreases to 101 if we discard all constraints (Figure 6). At the cantonal level, Vaud would need to operate 10 wind turbines in 2035 to generate the required electricity in proportion to its GDP contribution (Figure 8). If we however choose to cluster turbines into farms, which may easier to digest for the local population, the canton would optimally have 2 clusters operating with a total of 17 turbines. Finally, when we use the maximization of the energy density per visible area combined with the minimization of wind turbines as our objective function, we get different results depending on the trade-off λ. A higher trade-off, implying a larger weight given to the maximization of energy density per visible area, leads to a larger number of wind turbines needed in the canton (12 for $\lambda = 0.5$, 19 for $\lambda = 1$, see Figures 10 to 13).

These results exhibit similarities with the study conducted by ETH as well as with the locations of upcoming wind energy projects. Specifically, our nationwide analysis for the year 2035 reveals a common pattern with the ETH study, particularly in terms of observations made on the plateau region. This alignment suggests that our analysis can be regarded as an intermediate agenda for the successful implementation of the Swiss Energy Strategy 2050 plan. Moreover, our study at the canton level in Vaud demonstrates the ideal presence of clusters near the Jura region, aligning with areas currently undergoing wind turbine constructions and development. These findings indicate a degree of consistency and agreement between our analysis and existing studies and projects in progress.

This analysis also highlights a significant discrepancy in the construction of wind turbines at the cantonal level, depending on whether the optimization is conducted collaboratively at the national level or individually at the cantonal level. Our findings, along with those of the ETH study, indicate that the Canton of Vaud and Geneva would be relatively unaffected by wind turbine construction under a national optimization scenario. In contrast, the cantons

of Bern and Lucerne would experience the greatest impact. This outcome carries significant social implications, as the acceptance of wind farm construction may vary among Swiss cantons.

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8 Appendix

Appendix 1: Wind turbines current situation in Switzerland

Results from the Suisse Eole website which allows to identify the location of existing wind farms in Switzerland as well as current and future projects with an interactive map.

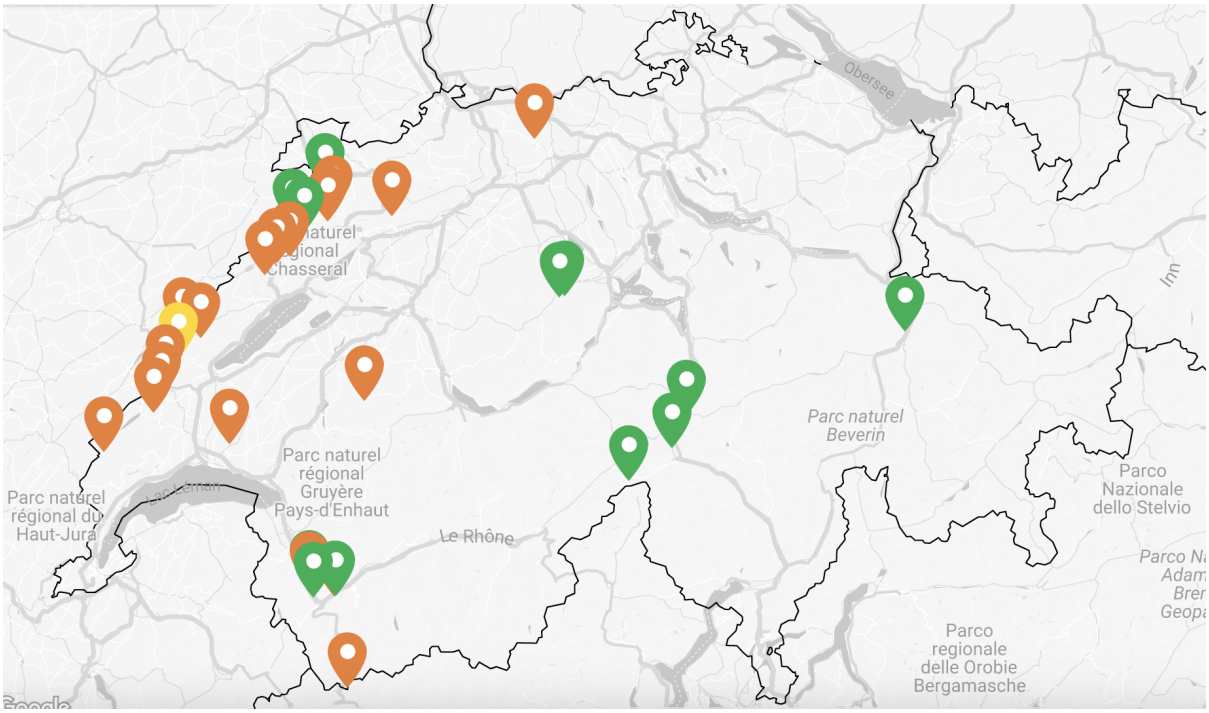

Figure 14: Green locations: wind farm in operation. Yellow locations: wind farm under construction. Orange locations: wind farm in procedure. Source: Suisse Eole [3]

Appendix 2: Clarification of the new objective function

$$\text{Maximize:} \quad \sum_{i \in I} (\lambda \cdot d_i - (1 - \lambda) \cdot 1) \cdot x_i$$

To further explain our objective, we can use two different cases ($\lambda = 0$ and $\lambda = 1$) to show what happens to our objective function.

$$\lambda = 0$$

$$Maximize: \sum_{i \in I} (0 \cdot d_i - (1 - 0) \cdot 1) \cdot x_i$$

$$Maximize: \sum_{i \in I} (0 \cdot d_i - (1) \cdot 1) \cdot x_i$$

$$Maximize : \sum_{i \in I} (-1) \cdot x_i$$

$$Maximize : \sum_{i \in I} -x_i$$

As we are trying to maximize a negative number, this means that we are trying to minimize the number of wind turbines. This is the same as the objective function in the previous section.

$$\lambda = 1$$

$$Maximize : \sum_{i \in I} (1 \cdot d_i - (1 - 1) \cdot 1) \cdot x_i$$

$$Maximize : \sum_{i \in I} (1 \cdot d_i - (0) \cdot 1) \cdot x_i$$

$$Maximize : \sum_{i \in I} (d_i) \cdot x_i$$

Now, we see that the objective function is trying to maximize the energy density. With no constraints, this will basically open all the wind turbines in the canton of Vaud.

In conclusion, a higher lambda (λ) will put greater emphasis on energy density, while a lower lambda (λ) will put greater emphasis on minimizing the number of wind turbines.