Lay Summary

Hybrid Renewable Energy Potential for the Built Environment using Big Data: Forecasting and Uncertainty Estimation (HyEnergy).

Project team
Prof. Dr Jean-Louis Scartezzini; Dr Roberto Castello, Dr Alina Walch (EPFL/LESO-PB)
Em. Prof. Dr Mikhaïl Kanevski, Dr Federico Amato, Dr Fabian Guignard (UNIL/IDYST)
Dr Nahid Mohajeri (UCL/Bartlett School)

Contact address

Prof. Dr Jean-Louis Scartezzini
Laboratoire d'Energie Solaire et Physique du Bâtiment (LESO-PB)
École Polytechnique Fédérale de Lausanne (EPFL)
Station 18
CH-1015 Lausanne
+ 41 21 693 5549
jean-louis.scartezzini@epfl.ch

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1. Background

Buildings represent one of the largest shares of the energy demand in Switzerland: they account for more than 40% of the overall energy demand and more than 30% of the electricity demand. To reduce energy consumption as well as greenhouse gas emissions, buildings need to become much more energy-efficient and to rely primarily on renewable energy resources. Accordingly, estimating the renewable energy potential for the built environment is an important issue in Switzerland, particularly for municipalities, building owners and public utilities. Such estimates provide very useful information regarding renewable energy generation as well as their potential for satisfying the energy demand in the built environment.

Hybrid renewable energy systems combine solar, wind power and shallow geothermal energy. In the building sector, such systems substantially reduce the size of the energy systems compared to standalone installations, the required energy storage capacity, and the overall operating costs. In view of the Energy Transition 2050, it is important to assess the potential of combined renewable energy resources in the built environment to support stakeholders' decisions and policies for the corresponding sector in Switzerland.

2. Goals of the project

This HyEnergy project aims to estimate a hybrid renewable energy potential (HyREP) for the built environment at national scale, with application to Switzerland. The HyREP describes the spatial and temporal patterns of several renewable energy (RE) resources for electricity and heat generation. They may be combined with other non-renewable energy sources to assess complementarities between them and their potential for satisfying the energy demand in the built environment. The renewable energy resources addressed in this work are wind power, solar photovoltaic (PV) electricity and shallow geothermal heat. These are three renewable energy resources with ambitious expansion goals for the Energy Transition 2050 in Switzerland.

The focus of the project lies in the estimation over space and time of the technical potential of RE sources at large scale. The technical potential is defined as the maximum energy (electricity or heat) which can be generated using a specific RE technology. Its estimation accounts for physical, geographical, and technical constraints, which are addressed separately for all three forms of energy (wind, solar and shallow geothermal). The results form regional and national databases of RE potential, which can be used to study hybrid systems from neighbourhood to country scale based on data that are homogeneous across Switzerland.

3. Methods

The HyREP assessment was obtained by combining Big Data mining techniques, advanced statistical methods, including Machine Learning (ML), state-of-the-art analytical and geospatial models for RE estimations. The datasets hence contain a high level of detail on the natural resources, the built environment and the RE technologies. The work carried out as part of this project addresses: (i) the initial work on modelling of complex environmental data over space and time, (ii) the estimation of wind speed and wind power potential in Switzerland, (iii) the estimation of solar PV electricity and (iv) shallow geothermal heat potentials from ground-source heat pumps at regional and national scale for Switzerland.

Spatio-temporal analysis of complex environmental data

Environmental data are the primary input towards a reliable estimate of the power which can be extracted from renewable energy sources. They are usually characterized by simultaneous spatial and temporal correlations. Often these data are not homogeneously collected over the territory and thus capturing these correlations is essential to perform interpolation tasks. At the time of the project start, no ML-based methodology had been proposed to solve the spatio-temporal interpolation of spatially irregular ground measurements for complex environmental data. To address this gap, we have proposed an advanced framework to reconstruct spatio-temporal data fields on regular grids using spatially irregularly distributed time series. Another important aspect of this part of the project is related to the quantification of uncertainty on the results. We developed estimates of variance and confidence intervals for Extreme Learning Machine Ensembles (ELM-E), an aggregation of a particular type of neural network which has been widely used for the modelling and interpolation of environmental data in this project. Finally, to better understand the level of information contained in complex spatio-temporal data and to discover hidden patterns, we investigated the use of Information Theory to assess the complexity of distributional properties of temporal, spatial and spatio-temporal datasets.

Wind energy potential

Wind energy complements hydroelectric energy and solar energy as the third source for renewably generated electricity in the Swiss Energy Transition 2050. Wind energy, from large turbines, is increasing worldwide and currently provides for 20 % of the worldwide renewable electricity generation. In Switzerland, wind energy is also on the rise, with 37 wind energy plants and an installed capacity of 75 MW, which produced 145 GWh of electricity in 2019. In the Swiss Energy Transition 2050, wind energy is expected to yield an electricity production of 4 TWh by 2050. Reaching this target requires accurate studies to optimize the future location of energy plants, by considering precise estimates of power production and, at the same time, considering the conflicts between the installation of energy facilities, nature, and environmental protection policies.

Existing studies have attempted to model the wind speed in Switzerland at monthly frequencies only, without quoting uncertainties on the predicted values or attempting their propagation to the wind power generation potential. In this project, wind power potential at hourly frequency has been derived. The developed spatio-temporal methodology has been used to quantify the wind power potential in Switzerland, considering the complex topography that makes the modelling of such a stochastic phenomenon extremely challenging. First, ten years of wind speed measurements collected at an hourly frequency on a sample of 208 monitoring stations from the Swiss Federal Office of Meteorology (MeteoSuisse) have been interpolated, allowing the estimation of wind speed and its uncertainty at unsampled locations. Later, the modelled spatio-temporal wind field has been used to estimate wind power potential, considering the technical characteristics of horizontal-axis wind turbines as well as national regulatory planning limitations for the installation of power plants. These limitations include restrictions for noise abatement as well as natural, ecological, and cultural heritage protection plans, as provided by the Swiss national wind atlas.

Rooftop photovoltaic solar potential

Right after hydroelectric power, solar energy is the main source of renewable energy in Switzerland. In particular, the deployment of rooftop-mounted solar PV panels has attracted increasing attention in recent years. In the Swiss Energy Transition 2050, PV generation aims to reach an ambitious goal of 34 TWh, which will require the large-scale deployment of PV panels. A quantitative assessment of the potential electricity generation from rooftop-mounted PV is key to formulate effective incentive policies for their integration in the built environment. This requires accurate input data at high resolution to catch the variation of the potential in space and time. So far, no methodology has estimated the large-scale PV potential at hourly temporal resolution at building scale, while also addressing the propagation of uncertainties arising from the data noise and the modelling process. Reasons for the lack of national-scale studies at such resolutions are the computational challenges associated with the processing of the required input datasets, the handling of missing data and the lack of data for the entire region of study. The proposed method adapts best existing practices for a data-driven estimation of each parameter that impacts RPV potential. This includes (i) the spatio-temporal variation of the horizontal solar radiation, (ii) the effects of surrounding trees and buildings on roof shading and the sky view factor, (iii) the impact of roof geometry and superstructures on the available area for installing PV panels, and (iv) the temperature-dependence of the PV module efficiency.

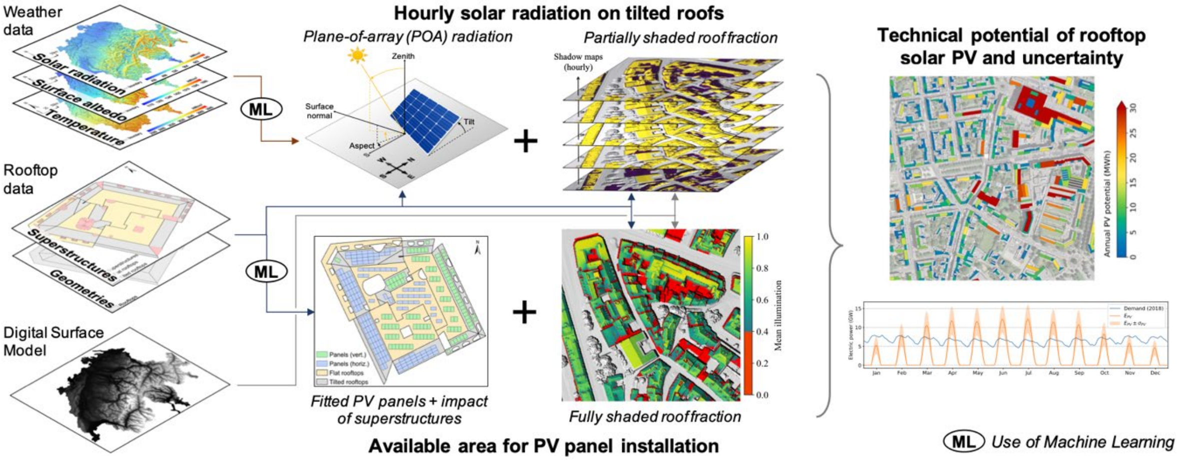

Figure 1. Schematic workflow for the estimation of the rooftop photovoltaic solar potential

The strength of the proposed method lies in the combination of physical models with Geographic Information Systems (GIS) and ML. The former two provide a detailed representation of the physical processes underlying the RPV potential assessment. Using ML techniques and GIS-based methods, we have been able to quantify uncertainty, which has been propagated throughout the modelling process using statistical methods.

Shallow geothermal heat generation potential

The use of geothermal energy is on the rise in Switzerland. To date, around 350,000 shallow geothermal systems have been installed in the country. This makes Switzerland the country with the highest density of installations per land surface worldwide. Many of these installations are shallow ground-source heat pumps (GSHPs), showing depths of up to 400 m. These systems use closed-loop borehole heat exchangers (BHE) that are vertically drilled into the ground and provide thermal energy for heating and cooling applications through a heat pump. In this way, GSHPs make use of the nearly constant temperatures in the ground, which results in high efficiencies of the technology throughout the entire year. Consequently, such direct use of shallow geothermal energy has a significant potential to decarbonise the Swiss building energy sector. While individual cantonal studies exist that characterise the suitability of the ground for geothermal installations, no study has yet quantified the maximum energy that may be extracted from a dense deployment of shallow geothermal installations at regional or national scale for Switzerland. Within the HyEnergy project, the potential for those areas where GSHP installations are possible has been formulated. The strength of the method proposed to estimate the potential lies in the combination of GIS and analytical modelling to simulate the potential effects of a dense deployment of BHEs for multiple scenarios of borehole spacing and depth. The scenarios provide insights into the trade-off between energy and operating power, which is exploited in an optimisation step to suggest an optimised arrangement of BHEs for each individual building property unit (parcel).

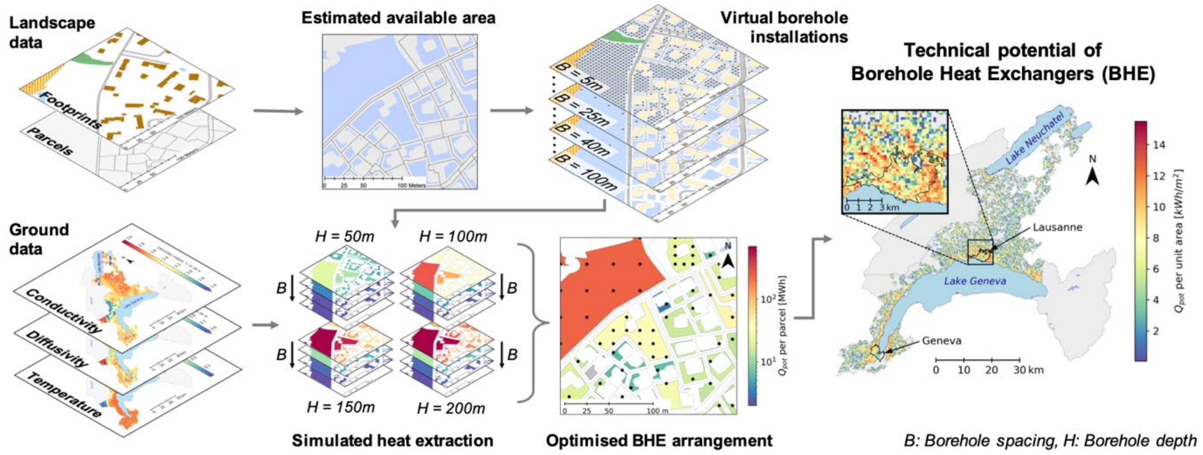

Figure 2. Schematic workflow for the estimation of the shallow geothermal potential

To obtain an estimate of the shallow geothermal potential at national scale, we have developed a Machine Learning framework, which is suitable for estimating the technical GSHP potential with high accuracy. The proposed method consists of two steps, namely (i) a classification of suitable borehole fields and (ii) a regression model to predict the annual heat extraction, the heat extraction rate, and the number of boreholes, from which the average borehole depth can be derived. The use of ML hereby increases the computational efficiency by a factor of 10 compared to analytical modelling, which is nonetheless essential for generating the training data for the ML approach. Furthermore, the impact of a bi-directional use of GSHP installations for heat extraction in winter and heat injection in summer has been addressed. To this aim, we propose an expanded method to account for (i) technical constraints due to the combined heat injection and extraction, and (ii) different operating strategies of GSHP systems. The advantages of the proposed method are that it (i) accounts for thermal interactions between densely installed GSHPs and the seasonal variation of the energy demand, (ii) proposes a trade-off between operating power and heat exchange potential, and (iii) is scalable to thousands of borehole fields. Using a graph-theory based optimization to match building thermal energy demand to technical geothermal potential further permits to quantify the impact of district heating and cooling on the useful geothermal potential.

4. Results

The results of the HyEnergy project provided key contributions in several areas, ranging from the treatment and analysis of spatio-temporal data up to the estimation of the renewable energy potential at country scale at high spatial and temporal resolution.

A framework to model spatio-temporal environmental data

The developed spatio-temporal interpolation methodology, which is adaptable to any ML algorithm, provides several key advantages. First, it allows to precisely reconstruct spatio-temporal fields starting from spatially irregularly distributed measurements. Second, the framework can capture non-linear patterns in the data, as it models spatio-temporal fields as a linear combination of temporal bases with spatial coefficients maps, where the latter are obtained using a non-linear model. Third, non-stationarity, seasonality and other typical behaviours of complex high-frequency temporal data are captured in the temporal bases. Finally, this methodology is also valid for data containing interactions between space and time (non-separable). Overall, the developed methodology can find many applications in multiple research domains where the exploration, understanding, clustering, interpolation and forecasting of complex spatio-temporal phenomena are of utmost importance. Finally, the methodological contributions have been made publicly available through efficient and user-friendly open-source Python and R packages.

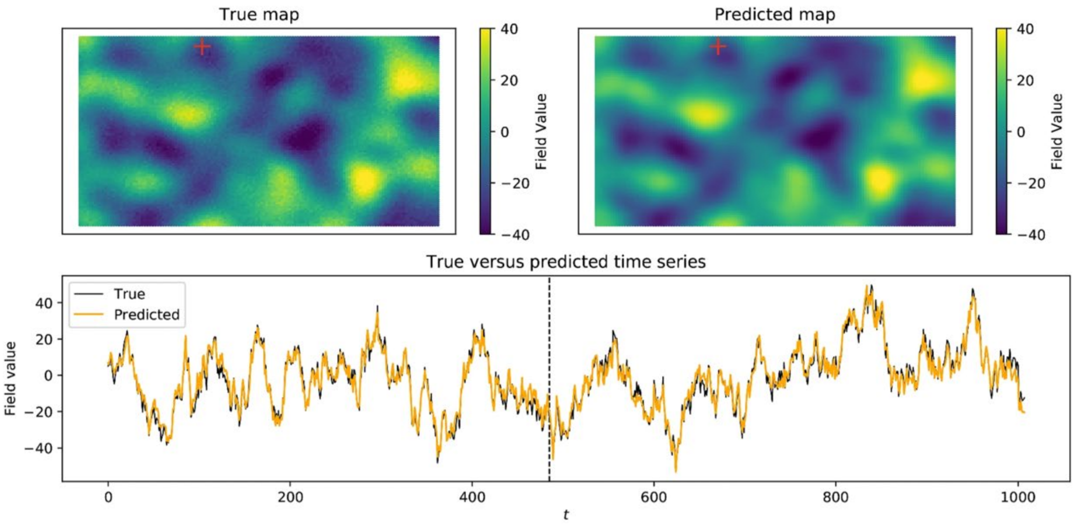

Figure 3. Comparison between the prediction of the proposed spatio-temporal interpolation methodology and the true spatio-temporal field for a simulated data set. Top left: A snapshot of the true spatial field at the fixed time indicated by the vertical dashed in the temporal plot.

<u>*Wind speed and wind power potential for Switzerland*</u>

The potential wind power generation was estimated based on the modelled wind speed to assess the renewable energy potential in Switzerland. This estimation can be easily updated to adapt to different choices of windmills, generating multiple turbine scenarios to support decisions related to the turbine selection. The resulting wind power potential is the first dataset of its type for Switzerland, hence representing an extremely valuable tool for planners to support the design of future energy systems with increased wind power production. Considering the spatial and temporal variability of wind hereby permits to assess the complementarity with other forms of renewables such as photovoltaics. The high spatio-temporal resolution of the results, as hourly values for 10 years for pixels of 250 × 250 m^2, allows for the study of future electricity systems with an increased share of wind power. Across Switzerland, we estimate an annual average wind power potential of 4.4 GWh per potential turbine. In the context of the goals of the Swiss Energy Transition 2050, aiming at a wind power generation of 4.3 TWh by 2050, this would correspond to the installation of around 1,000 turbines. Based on different restrictions identified across the country, we have further assessed different scenarios of national wind power potential. A combination of the wind power potential, its uncertainty and the available area for turbine installation further enables the assessment of the suitability of different areas for future wind projects. With these applications, the presented work aims to support the development of wind power as part of a fully renewable future energy system in Switzerland.

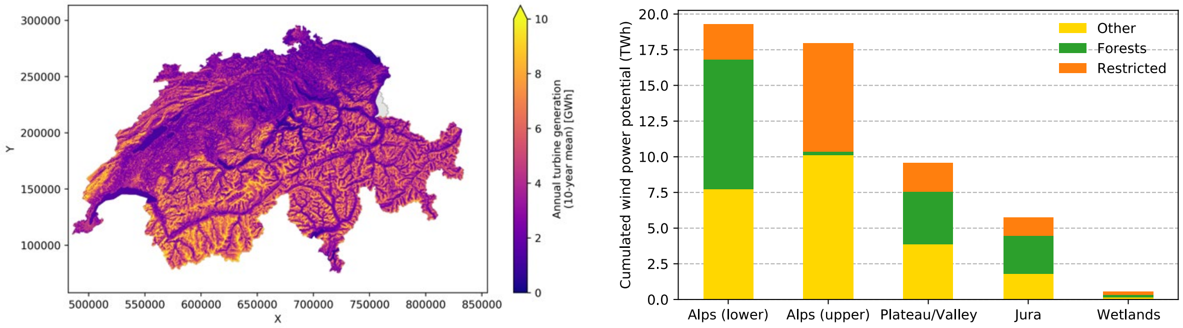

Figure 4. (Left). Annual wind power generation, averaged across all 10 years of measurement data. (Right) Annual total wind power generation of all (virtual) turbines for each part of Switzerland (bars) and for each restriction zone (colors).

Rooftop PV solar electricity potential for Switzerland

The technical solar potential is defined as the electrical power that could be produced by PV panels installed on roofs. It is the result of correcting the geographical potential (i.e., the flux of solar energy falling on suitable roofs) by the solar panel efficiency and the performance factor. These factors account for efficiency (computed for each time step) and other losses such as degradation. To obtain a realistic potential, roofs with a small available area (less than 8 m^2) are excluded, as this value is the threshold for the minimal economic feasibility. Also, all the north-facing roofs are discarded from the computation, given the relatively low contribution to the potential. These criteria reduce the suitable fraction of the available roof area to about 57 % of the total roof surface available on the 2.3 millions of Swiss buildings. The estimated maximal yearly technical potential which can be extracted from them is estimated to be 25 ± 9 TWh, corresponding to an electricity generation able to match 40 % of the Swiss electricity demand recorded in 2017. The approach quantifies the impact of each of the parameters used in the computation of the technical PV potential. The horizontal radiation and the fraction of available roof area are the most sensitive parameters: their variation of 50 % can cause up to 40 % change in the final PV potential. Therefore, in a hypothetical future scenario where climatic conditions and urban settlements are supposed to evolve, it is possible to forecast the expected order of magnitude of the generated electricity.

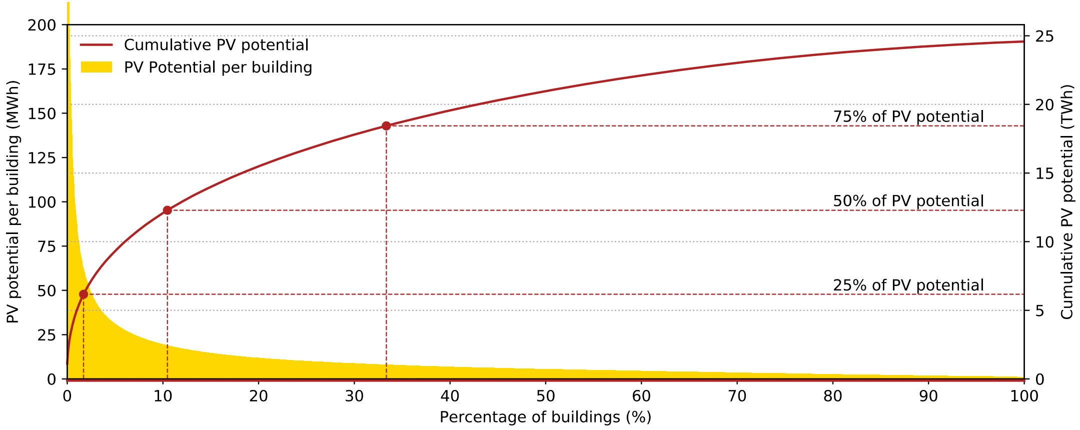

Figure 5. RPV potential per building and cumulative technical potential as a function of the percentage of buildings considered appropriate for RPV installation.

The realization of the potential shown above is strongly dependent on the level of integration of PV in the built environment. Figure 5 shows how 25% percent of the estimated potential can be realized by installing PV panels on less than 2% of the highest potential buildings, which turned out to be those with flat roofs. A total of 50% of the potential can be realized from around 10 % of the buildings, and 75% of the potential can be reached by installing PV on roughly a third of the buildings.

The above potential is dependent on several assumptions, for example the definition of rooftop "suitability" for installing PV (here defined as all flat and south-facing tilted roofs), the PV geometry (here: "standard" panels of 1 x 1.6 m^2) and the installation of PV panels on flat roofs (here: individual south-facing rows). Changing these assumptions thus impacts the estimated PV potential. For example, the potential increases to around 35 TWh if all roofs of up to 20° tilt angles are considered suitable, independent of their orientation, and PV panels are installed as "hat-shaped" adjacent rows. To reach the target of the Swiss Energy Transition of 34 TWh of solar PV electricity by 2050, 50 - 55% of all roof area on south-facing roofs and roofs with tilt angles below 20° must be covered with PV panels. This corresponds to an area of around 220 km^2, or 34 % of the *entire* Swiss roof surface, but technological advances leading to increased efficiencies may reduce these space requirements.

Nevertheless, a close look to the potential for all of Switzerland shows that the PV generation would be insufficient during winter and night hours, while there would be a surplus during peak hours and summer. Therefore, an ad-hoc combination with other sources of renewable energies (like wind and geothermal) and energy sector coupling must be studied to exploit the solar at best. The hourly estimate of the potential for each month of the year is useful to design future energy systems with large shares of PV to match production with electricity demand. The high spatial resolution enables urban planners to assess the electricity demand which could be covered by installing PV in a certain neighbourhood. Policy makers can aggregate the results at different spatial scales, like regional or national, to formulate effective policies to integrate PV in the built environment.

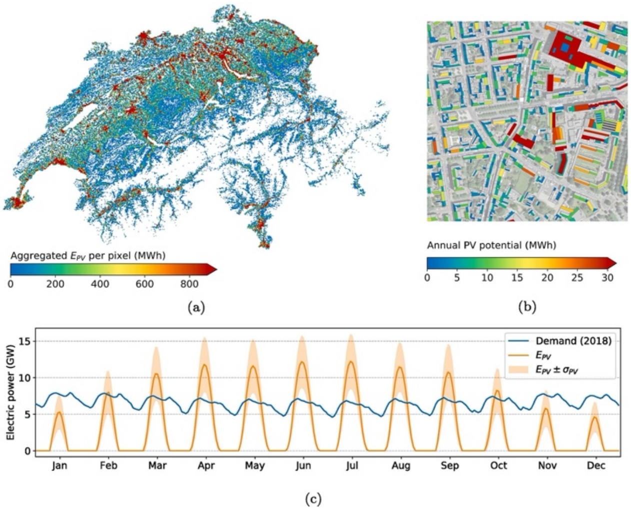

Figure 6. Spatial distribution of annual RPV potential, aggregated to pixels of 500 x 500 m² for visualization purposes (a), annual RPV potential for the suitable roofs of a randomly selected 500 x 500 m² pixel in the city of Geneva (b), monthly-mean-hourly profiles of RPV potential, summed for all suitable roofs, and the Swiss electricity demand of 2018 (c).

<u>*Shallow geothermal heat generation potential for Switzerland*</u>

The technical geothermal potential is defined as the maximum energy that can be extracted annually from the ground using GSHP technology. Respecting the norm SIA 384/6 (2010), the technical potential hence represents the energy that can be extracted sustainably, without over-exploiting the heat capacity of the ground. A case study has been carried out for the Cantons of Vaud and Geneva, where high-resolution data of the thermal properties of the shallow ground are available.

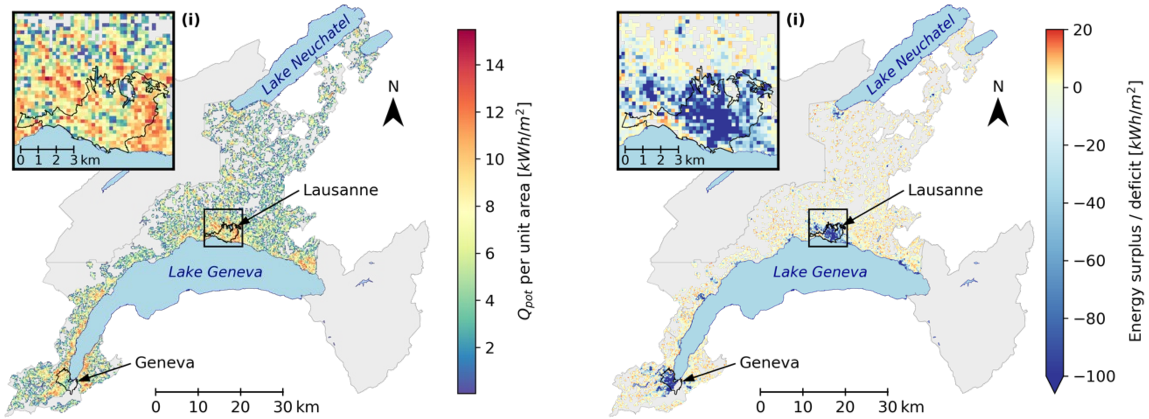

Figure 7. (Left) Annual heat demand density (logarithmic scale) for pixels of 200 x 200 m². (Right) Surplus (positive) or deficit (negative) of potential heat extraction from BHEs compared to the heat demand.

The case study area shows sound thermal properties for GSHP installations, with ground temperatures of around 13°C for borehole depths of 200 m. The results suggest that across the two cantons, a total of 4.6 TWh of heat could be extracted annually from the ground, which is sufficient to supply around 40 % of the current building energy demand in the two Cantons. The application of the developed ML framework for the estimation of GSHP potential at national scale yields a GSHP potential of up to 97 TWh, of which 56 TWh occurs outside of areas with likely or possible restrictions for GSHP installation. Most of this potential arises from natural and agricultural areas, with only 20 % located in urban areas. These results suggest a geographic mismatch between heat supply potential and demand, as the potential is highest in suburban and rural areas, while the demand is concentrated in urban areas where space to install GSHPs is scarce. District heating networks (DHN) may be a solution to balance this geographic mismatch, as they allow to transport heat from suburban and rural areas with high potential to cities with high demand. A follow-up study conducted in the same area has demonstrated that district heating networks can almost double the amount of heat that can be provided to buildings directly. Furthermore, the study investigated the increase in the potential use of GSHP systems for a combined use of heating and cooling. The simulations determined the impacts of the injection of excess heat from space cooling of service-sector buildings into the ground during summer. This bidirectional use of GSHPs in combination with DHN would allow to cover around 85 % of the expected heating and cooling demand by 2050 renewably.

The first regional-scale studies of technical geothermal potential provide insights into the use of geothermal energy in the Swiss plateau. As the study has shown, GSHPs exhibit an important potential to cover space heating demands in suburban and rural areas. The study further shows that it may be possible to quantify a technical limit for the maximum installed borehole length per hectare to avoid an over-exploitation of the ground. The results suggested to limit BHE to 2 km/ha (max. 200 m depth). For the use of shallow geothermal energy in cities, the bi-directional use of GSHPs through the injection of heat, from space cooling or other sources, must be considered to achieve a considerable potential. To realise the potentials, district heating and cooling technology to distribute energy within cities efficiently has been identified as key technologies. In view of the Swiss Energy Transition, which aims for the installation of 1.5 million heat pumps by 2050, we estimate that around 30 – 70% of their heat demand could be covered from GSHPs, or even more if seasonal regeneration is considered. Furthermore, GSHPs in district heating networks may account for 10 – 20% of the target district heat supply for 2050. In conclusion, there is still a high potential for GSHPs to decarbonise the building stock. However, this needs to be complemented with other renewable heat sources especially in city centres and areas where GSHP installation is not possible due to geological conditions and national and regional regulations.

5. Significance of the results for science and practice

The strength of the methods proposed in this project lies in their data-driven approach, combining Machine Learning (ML), geospatial processing and physical models. The use of ML allows to include knowledge extracted from data with only partial spatial or temporal coverage, and hence improves the accuracy of the results. The use of ML also outlines an approach for using sparsely available datasets for an assessment of the renewable energy potential in other regions. We further propose a structured method to estimate and propagate uncertainty for large-scale renewable energy potentials. We thus improved the quantification of the uncertainties related to the data sources and individual processing steps compared to previous work.

Wind energy. The results show a significant potential for wind energy in Switzerland, particularly in the south part of the country, where population density is lowest. The estimated potential is sufficient to achieve the target set by the Swiss Energy Transition 2050, but political and social concerns towards wind energy may pose a significant barrier for future large-scale wind turbines. Alternatively, the potential of wind generation in urban areas should be considered for small-scale electricity generation. Vertical-axis wind turbines may represent a promising technology to harvest wind energy in urban areas, but due to high turbulence in urban canopies further work is needed to quantify this potential at national scale. The analysis of the temporal patterns of wind generation shows that the production potential is higher in winter than in summer, due to higher wind speeds expected in the winter months. This suggests a promising complementarity with solar energy.

Solar energy. To effectively advance the large-scale integration of PV solar in the built environment, the roofs with the highest potential should be prioritized. About 25 % of the estimated potential can be realized by installing PV panels on less than 2 % of the buildings with the highest potential, which turns out to be primarily large industrial or commercial buildings with flat roofs. Hence, policies for PV integration should focus on incentives for installations on large buildings, which may have shared ownerships. The hourly profile of the potential shows that the PV contribution across Switzerland would be insufficient during winter and night hours, while there would be a surplus during midday and in summer. A prioritization of east and west-facing roofs to reduce the midday peak only has minor impacts on the potential generation. Therefore, an ad-hoc combination with other sources of renewable energies (like wind and geothermal) and energy sector coupling must be studied to best exploit the solar potential.

Shallow geothermal energy. The studies of technical geothermal potential suggest that Ground-Source Heat Pumps (GHSPs) using vertical Borehole Heat Exchangers (BHEs) may exhibit an important potential to cover space heating demands in suburban and rural areas. For the use of shallow geothermal energy in cities, the bi-directional use of BHEs through the injection of cooling needs or other sources of excess heat must be considered to achieve a considerable potential. To realize the potentials, district heating and cooling to efficiently distribute energy within cities has been identified as key technology. There is a high potential of GSHPs to decarbonize the Swiss building stock. However, this needs to be complemented with other renewable heat sources, especially in city centres and in areas where GSHP installation is not possible due to geological conditions and national and regional regulations.

The HyEnergy visualisation platform. A visualisation platform has been designed for the spatio-temporal exploration of the renewable energy potential databases developed in this project. The alpha version of the platform is currently available under restrict access for internal usage and shall be made publicly available by the end of the year. The platform is conceived to communicate the results of the HyEnergy project, primarily to the public. Maps show the renewable energy potential for individual buildings, entire communes (depending on the zoom level) and as pixel maps at the national scale. A database integration has been implemented such that the hourly time series for each building or commune can be shown when one building/commune is selected.

Beta version under finalization

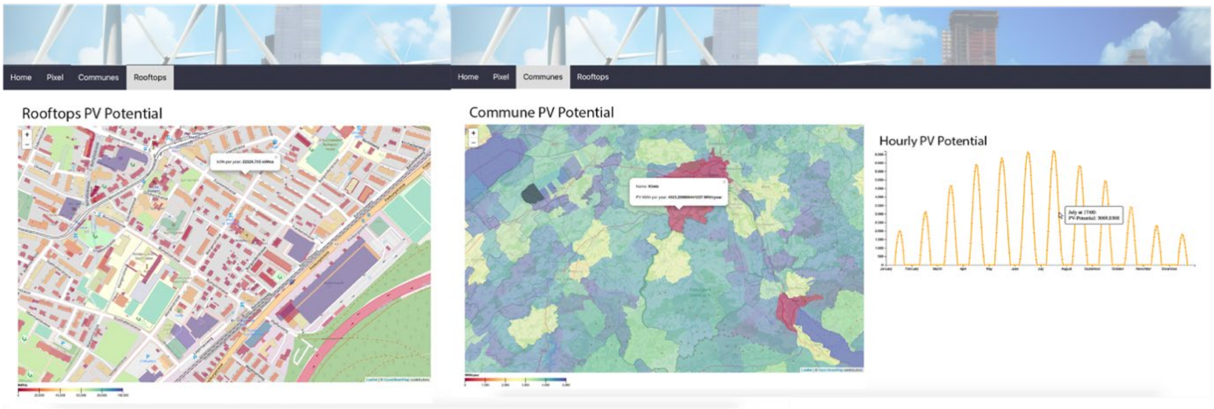

Figure 8. Screenshots of the HyEnergy visualisation platform for solar PV, showing the screen for the building-scale visualisation (left) and the commune-scale visualisation (center), as well as the time series of the solar PV potential for one selected commune (right).