

THESIS SUMMARY

FOR THE DOCTORAL THESIS:

THE LOCAL IMPACTS OF SOLAR ENERGY INVESTMENTS IN HUNGARY

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I. Rationale of the research

The energy transition promises significant environmental benefits but also introduces potential challenges. On the positive side, renewables drastically reduce greenhouse gas emissions, with solar and wind power producing near-zero emissions during operation, helping mitigate climate change and improve air quality by displacing fossil fuels, which are responsible for two-thirds of global greenhouse gas emissions and two-thirds of CO₂ emissions too in 2024 (IPCC 2023). However, their deployment can have adverse impacts: large-scale solar farms and wind turbines require extensive land, potentially disrupting ecosystems, displacing wildlife, and fragmenting habitats, especially in biodiversity-rich areas. The production of renewable infrastructure, such as solar panels and batteries, relies on mining critical minerals like lithium and rare earths, which can lead to water pollution, soil degradation, and high energy use during extraction and manufacturing. Additionally, end-of-life disposal of these technologies poses waste management challenges, though recycling initiatives are emerging. While the net environmental impact of renewables remains overwhelmingly positive compared to fossil fuels, careful planning and innovation are essential to minimise these trade-offs and ensure a truly sustainable transition.

As for the economic aspect, the installation of renewable capacities, as an investment itself, has significant economic impacts at both the national and local levels. Within the framework of building a sustainable energy system, expenditures related to renewables alone could reach \$10-20 trillion by 2050 (equivalent to 15-20% of the global 2023 GDP) (IEA and IRENA 2017). The energy transition in general requires an additional 2-3 trillion USD investment annually compared to the annual 2,5 trillion USD baseline investment in the energy sector (IEA 2021).

Given the scale of these investments, it is essential to examine their direct and indirect impacts across all levels and dimensions of social strata. Historically, the development of energy-producing infrastructure has been highly centralised, affecting only a few regions, municipalities, and communities (albeit intensively). In contrast, a more decentralised energy system necessarily distributes investments more broadly. Additionally, economic activity is generated not only through investment but also through operation and decommissioning. The creation of new (types of) jobs, the production of energy and its economic value, and the demand for new services will create a new reality for local economies, from the scale of national economies to small rural municipalities and urban neighbourhoods.

Concerning the Social aspect, for many, the spread of renewables is associated with the construction of a fairer, more progressive, people- and community-centred, and socially sustainable energy system (Jenkins et al. 2016; Sovacool et al. 2014). However, as with any systemic transformation, the energy transition also has losers (e.g., due to rising prices and the decline of traditional energy systems), and the spread of renewables does not guarantee the elimination of previous systemic bad practices and injustices of the energy sector (Mueller and Brooks 2020; Sovacool et al. 2019; Yenneti et al. 2016).

One of the most important innovations and promises of modern renewables is the potential for energy production and consumption to be located in the same place, even under common ownership at the individual or small-community level, through both small-scale (residential) and larger commercial-scale units that provide energy for households and communities. This offers the chance to also include many more entities into the economic value chain of the energy sector, as previously.

The theoretical existence of local (developmental) effects of renewables also needs to be empirically examined. The question arises: to what extent can renewable energy investments support the objectives of development policy, and in which sectors is this effect stronger? What

is the magnitude, temporal distribution, and primarily who owns the local economic value generated by a renewable energy investment over its full lifecycle? While the literature examines the relationship between renewables and development policy at a macroeconomic, national level relatively widely, the specific local and regional impacts are rarely studied, and even then, not based on extensive empirical data collection.

The current literature on solar power adoption focuses on peer effects and spatial patterns; public perceptions; policies/economics; and technology/innovation (Vishnu and Joshin 2024). Investigating the impact, especially the local impact of solar PV investments, has not been a mainstream topic in the relevant literature. Also, even though one-third (308 of the total 1009) of the papers have their geographical focus in Europe, none of the reviewed papers deals with Hungary or any CEE country, for that matter (Vishnu and Joshin 2024).

Ramvalho et al. (2023, 1) state that “Although there are studies that have addressed these [Economic, Social, and Environmental] impacts, [...] no systematic review was found addressing the three dimensions together.”

Hungary, as a case study, can be of general and paramount academic interest. PV in the Hungarian electricity sector is playing an unusually significant role, and this is expected to increase even further:

- In 2024, Hungary recorded the highest share of solar PV in gross electricity production in the EU, at 24% (Eurostat 2026).
- Hungary ranked third globally among UN Member States in 2025 for the share of solar PV in total installed electricity generation capacity, at 52% (IRENA 2026).
- Built-in PV capacity in Hungary represents 50% of the total electricity generation capacity if residential producers are also included. Commercial-scale grid-connected solar power plants alone already provide 16% of the total domestic electricity generation (MAVIR 2026).
- 35% of the total PV capacity installed in Hungary is residential rooftop solar, 11% is for industrial self-consumption (not grid-connected), and roughly 50% are commercial-scale, grid-connected solar power plants ranging between 0,4 kW and 50 MW. Therefore, Hungary not only has a high share of PV but also has strong built-in capabilities across almost all major sectors and dimensions.
- CEE region and Hungary, however, offer a particularly interesting case as they are relatively late adopters of renewable technologies that could have the opportunity to adapt the adoption rate and dynamics to their own peculiarities and policy targets, which could even include direct or indirect (rural) regional development. Analyses such as this offer an insight into whether this happened and to what extent.

Therefore, Hungary, in a certain sense, moved from a laggard to ahead of the curve and has experienced a PV boom resulting in exceptionally high installation rates – rates which other countries with similar socio-economic predicaments will likely witness in the coming years, as renewable energy investments, and especially PV, are expected to grow all around the globe. In that way, the Hungarian case study can offer insight into the results of a rather experimental energy policy and its economic, social and environmental impacts.

II. Questions and hypotheses

Based on the literature review presented above, taking into account the specific relevance and data availability predicaments, the following questions and hypotheses are formulated.

Economic issues

Q1: To what extent can commercial-scale PV investments in Hungary contribute to the local economy of Hungarian municipalities through the incomes produced during their operation?

H1: The ownership (hence the control of revenues generated) of the commercial scale Hungarian PV investments is dominated by non-local (and among them mostly foreign) actors, strictly limiting the potential size of private income and local taxes contributing to the local economy.

Q2: To what extent can residential PV investments in Hungary contribute to the income of households?

H2: Solar PV adopter households see significant avoided costs from the operation of the PV modules.

Q3: Can local PV investments help the emergence/development of local companies and increase employment in the relevant sectors?

H3: The number of PV investments has a significant effect on the number of companies working in the energy sector at the municipality and district level.

Environmental issues

Q4: How do commercial PV plants impact local land-use in Hungary?

H4: In the absence of regulatory incentives, commercial PV plants are located on agriculturally or environmentally valuable land plots at a rate similar to Hungary's general surface cover rate.

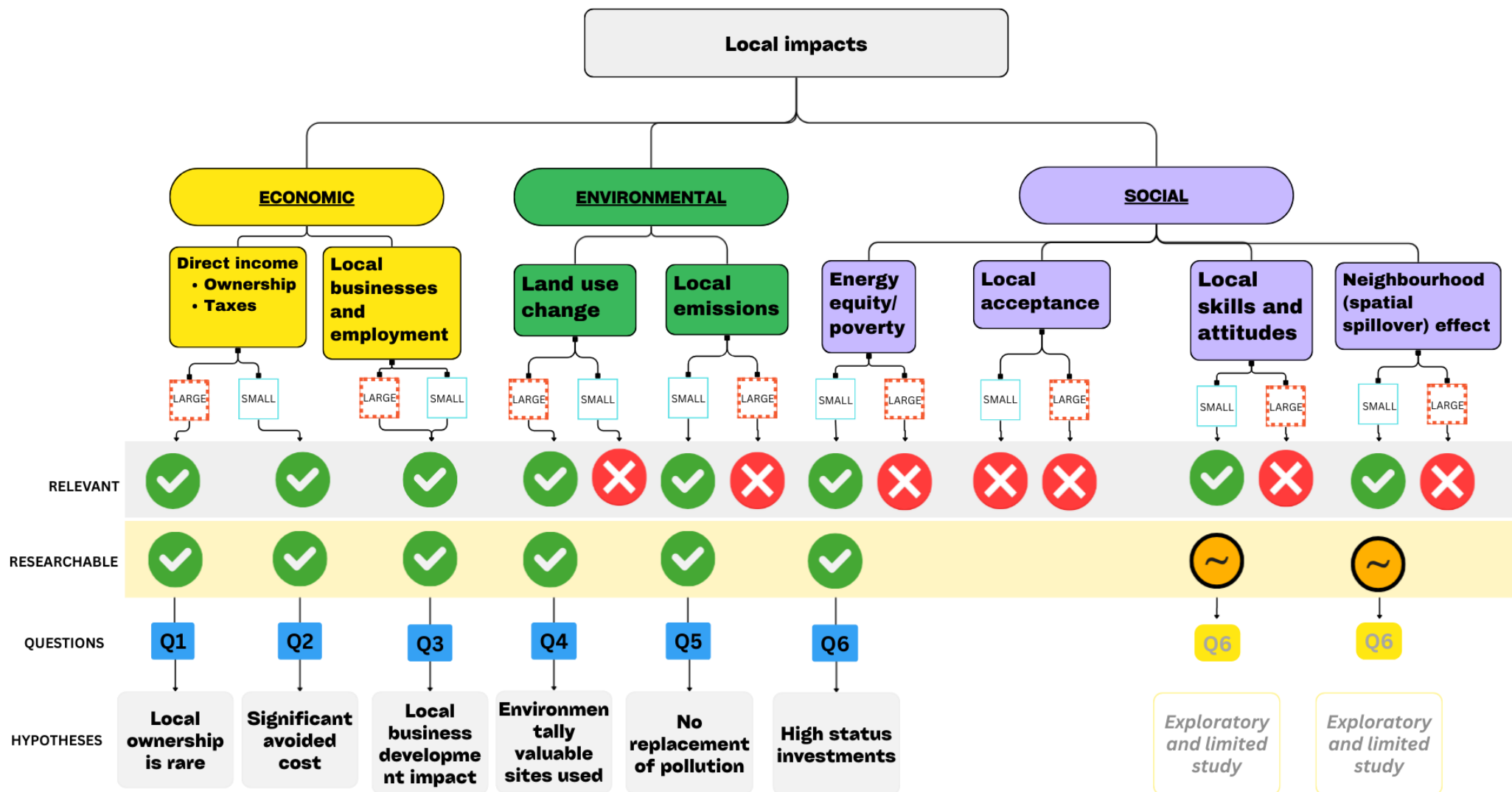
Q5: How do household PV projects affect local air pollution in Hungarian settlements?

H5: Household PV investments mostly do not replace polluting heating modes.

Social nexus

Q6: What factors determine PV adoption on the settlement level in Hungary?

H6: Household PV investments in Hungary are significantly more likely to happen in settlements with higher socio-economic status.



1. Figure Graphical summary of the problem-identification matrix, the selected (relevant and researchable) research topics, as well as an indicative summary of the relevant Hypotheses.

III. Methodology

III. 1. Economic Impact

Ownership

To assess how many commercial solar investment projects are owned by local actors, a database was compiled of commercial-scale (larger than 0.1 MW, but mostly between 0.4 - 50MW) PV investment projects in Hungary. The two data sources were the recipient power plants of operational subsidies (either KÁT or METÁR support) and the power plants with operating licences issued by the Hungarian NRA (MEKH). This includes practically all grid-connected capacity in Hungary, either built or planned by mid-2025. The total project database comprises 3,624 PV projects licensed between 2012 and 2024, with a total capacity of 5,880 MW.

The project database is supplemented with the Ultimate Beneficial Owner (UBO) for each project, sourced from national and international ownership databases. For domestic data, the company database Opten was used, and international data was obtained from Orbis. UBO is defined as the “natural person(s) who ultimately owns or controls a customer and/or the natural person on whose behalf a transaction is being conducted” (FATF 2014, 8).

The analysis first uses basic concentration metrics (Herfindahl-Hirschman index and descriptive spatial concentration) to describe the distribution of impacted municipalities and the internal dynamics of the entire segment. Then, it focuses on foreign ownership at the national level, indicating a potential reduction in the economic impact at the national scale.

For the actual analysis of the local ownership impact, it separates two types of UBOs (and assigns owned capacity accordingly) for each municipality:

- UBOs resident in the municipality/district/county, who do not own capacity in the place of residence itself, are referred to as having ‘residential ownership’. In this case, the potential benefits of the ownership can contribute to the local economy of the place of the UBOs' residence but not (necessarily) to the settlement where the power plants are located.
- UBOs who are owners of capacity physically located where their residence is being referred to as having ‘truly local ownership’. In this case, the profit from ownership may remain within the same municipality as the power plant.

Taxes

There are three local taxes to which solar power plants can be subject in municipalities, one levied on business activity, and two on property: 1. Local Business Tax; 2. Land Tax; 3. Building Tax.

The Hungarian State Treasury compiles a monthly updated registry on the size and other regulatory details of the local taxes (MÁK 2025). The analysis uses the most recent local tax data (2025 March).

The analysis cannot estimate actual tax values for the Local Business Tax, as values for the tax base and the number of municipalities the tax needs to be shared with are not publicly available information. Therefore, a score is assigned to each municipality to estimate potential tax revenue.

Cost reduction

For rooftop household projects, ownership is, by definition, local, as owners of the residential building can initiate the investment. Income from the operation of household projects in the Hungarian legal context is mostly the avoided cost in the electricity bill by the power produced for self-consumption. Selling extra production to the grid provides marginal income.

There are several NPV calculations and estimates on Hungarian household PV projects as generalised modelling or examining single case studies (Németh 2022; Zsiborács et al. 2019; Somogyiné 2023; Somogyiné and Kovács 2023; Pintér et al. 2020). Using the findings of these papers, the following method is used by the current analysis to estimate the Local Income Effect (LIE), which is comprised of two main inputs:

1. the total cost of electricity not purchased due to self-production;
2. the income from the electricity produced above self-consumption.

Local businesses

An estimate of business activity development (likely in line with employment dynamics) is used to proxy for the local income effects of construction and operation. It is assumed that if a noticeable increase in income follows local investments, new companies and entrepreneurs in the field will enter the market.

To approximate this effect, panel and OLS regressions are used, with local PV investments as explanatory variables and the number of registered enterprises as the dependent variable. The geographical scope of the data is the municipal (LAU 2) and District (LAU 1) level.

III. 2. Environmental impact

Land use change

For the land-cover analysis, a dataset is needed not just of the location but also of the area coverage of the power plants. TransitionZero's Solar Asset Mapper database is based on satellite data and uses algorithms to detect commercial solar facilities globally. The quarterly-updated dataset's 2026 Q2 release contains over 35,000 km² of solar power plant surface area across 194 countries, with a combined estimated capacity of 1,383 GW.

The TZ-SAM dataset was slightly modified to help the analysis. Therefore, the final number of observed PV polygons on EU territory was 32,636, and 1055 for Hungary, with an aggregated, approximate capacity of 189,290 MW and 5,634 MW respectively.

To enable comparison of Hungarian and EU Member State data, an EU-level dataset was primarily used. EU Land-cover data was obtained from the CORINE Land Cover Database (CLC) 2012 maintained by the European Environment Agency (EEA 2019). The database uses 44 classes in nomenclature, 25 hectares minimum mapping unit (MMU) and 100 meters minimum mapping width (resolution). The data is derived from a combination of satellite observations and national topological maps and datasets.

For the spatial analysis, the open-source software QGIS (version 3.44.12) was used. First, both datasets were transformed to a common CRS (EPSG:3035). To make the algorithms run more efficiently, the CLC raster was clipped by using the TZ-SAM polygons as a vector mask.

For this step, a 100m buffer was added around the geometry of the PV facilities to avoid creating empty areas that overlay the actual areas due to the low resolution of the CLC raster layer.

The resulting raster layer, with data covering only the PV parks and their buffer zones, was polygonised. Then, the Intersection algorithm was used to measure the area of each of the 44 CLC classes that intersected with the actual PV polygon, and the results were aggregated by polygon.

Local emissions

To measure the effect of PV installation on local non-GHG emissions, local pollution data should be used. Local pollution metrics are directly not available; no such data is collected on municipal level. Since household heating in Hungary is responsible for the largest share of local pollution and produces almost all particulate matter emissions, analysing household heating practices and dynamics can approximate pollution levels.

Hence, a linear regression analysis is conducted using the 2022 household PV prevalence on the municipal (LAU 2) level as an explanatory variable on the change in the number of households using wood/coal/other solid fuel for heating from 2011 to 2022 (the statistic includes households using solid fuel *and* other heating methods too, but excludes the ones that use only natural gas, electricity or district heating or the combination of these). As a third dependent variable, the share of dwellings using electricity and wood in combination for heating (or other heating source that is not district heating or natural gas – except for wood, the other options are negligible) is included. This is to see whether households haven't replaced wood when installing solar panels, just combined it with electric heating. Data for the PV prevalence and heating is derived from the 2011 and 2022 national censuses in Hungary (KSH 2022).

The analysis is done using a simple linear OLS regression with fixed effects (to filter out regional differences by including Districts – LAU 1 - as a variable). Control variables were also added to a second OLS model to control for the typical socioeconomic effects behind the change of heating modes.

III. 3. Social Nexus

Following the literature, the analysis of residential PV adopters in Hungary first uses descriptive statistics to present and visualise the spatial distribution of residential solar units, updating Horváth et al.'s (2021) findings. Following that, it uses two linear regression models (OLS and fixed effects) to evaluate the impact of various variables on the distribution of residential solar units in Hungary.

The unit of observation – as for most analysis in the Thesis – is the municipal (LAU 2) level. District (LAU 1)- level research, conducted by Baranyai et al. (2021) and Szép and Tóth (2025), is among the least granular in terms of population/observation, whereas using municipalities (LAU 2) can provide an analytical level more refined than is common in the literature. While this kind of research would require an investigation on the household level, not on the level of administrative units, it is still reasonable to choose the best available socioeconomic status (SES) measure for capturing the economic and social resources (Sommerfeld et al. 2017).

Data availability in the Hungarian context presents a dilemma: time-series data on residential solar installations is available only at the district level, while municipal-level data is available only for 2022. The time-series data is published by the Hungarian Energy and Utility

Regulatory Authority, while the 2022 data is from the National Census. To conduct an analysis on the lowest possible administrative level, the one closest to the households, and to create added value compared to the available literature, National Census data is used in this analysis.

In general, all socio-economic and infrastructure-related data is sourced either from the National Census of 2022 and 2011 or from the official Land Information System (TeIR – Területi Információs Rendszer).

IV. Main results

IV. 1. Economic impacts

Ownership

The main impact in the case of Hungary, through which solar investments can affect the local (municipal or District level) economy, is the income/profit generated from the operation of the power plants, either on a residential or commercial scale.

25% of the Hungarian municipalities host at least one licensed commercial-scale PV project. The capacities are relatively well dispersed geographically. For counties, the average spatial density of the licensed capacity is 57 kW/km², in a range of 28-127 kW/km². Counties with higher-than-average capacity density have a lower-than-average GDP/capita, suggesting that economically less developed counties host more licensed capacity. That would, in theory enable using PV investment partially as a rural development tool.

The analysis of the Ultimate Beneficial Owners of the licensed Hungarian commercial-scale solar capacities, however, shows that only 11% of Hungarian municipalities can potentially see any benefit from local ownership of Hungarian PV plants in general. On the one hand, roughly half of the total licensed capacity is in foreign ownership, likely eliminating the country's potential economic benefits altogether. On the other hand, Budapest is dominant in UBO share, far above its economic or social share, as residents of the capital own two-thirds of the domestically owned capacity. And if Budapest is excluded from the 11%, then only an average 7 MW licensed solar capacity falls on each of the ca. 300 municipalities, with large deviations between settlements.

The share of truly local ownership, i.e. when the UBO and the licensed capacity share the same location, is even smaller: 3% of the total licensed capacity if the locality is the municipal level or 8.5% if the locality is the district or county level. On average, for the 148 municipalities with local ownership of licensed capacities, the average size of locally owned plants is 1.2 MW/settlement or 0.96 kW/capita.

It is noticeable how truly local ownership increases by a factor of 1.7 if the scope of the shared locality is expanded from the municipal to the district level or from the district level to the county level, while from the county level to the national level, the change is almost six-fold (although that includes the total domestically owned capacity). Of the total domestically owned capacity, excluding Budapest, 636 MW is owned by domestic entities in other counties (not in Budapest), while 530 MW is owned by UBOs in the same county as the licensed capacity. This suggests that domestic PV investors, even if they are not located in Budapest, are looking for opportunities all over the country; the spatial horizon of the investors is not confined to their relative neighbourhood.

Truly local ownership is generally more common for early, pre-2020, and smaller projects at the municipal and district levels, suggesting that early project developers focused more on

local resources and opportunities, while later-stage developers, often with foreign ownership, optimised at the national level. The ownership structure also indicates that only a few domestic private actors became prominent and competitive actors in the Hungarian solar sector, but in general, foreign private and state-owned actors took over most of the Hungarian market, especially concerning truly large-scale projects.

At the same time, the Hungarian solar market is highly competitive, not oligopolistic, according to the HHI calculations. Therefore, the entry barrier is not legal or stemming from market structure, but likely from a lack of capital and/or know-how among domestic private actors. Nevertheless, the Hungarian case shows that without explicit policy support for local actors, in small and open economies that come relatively late to the renewable boom, the renewable sector becomes dominated by mostly non-local, especially foreign, actors.

Local taxes

Hungarian municipalities have the legal option to receive tax revenue from PV projects either located on their territory or from the operations of the project owner companies. Municipalities can levy local taxes on the land used for PV plants and on the project companies' revenues, and they can also exempt them from these local taxes. However, there are only a handful of municipalities where, according to the model used in the analysis, the potential land tax income would represent more than 5% of the total municipal income. Land and Building Tax as local income from commercial PV plants is highly underutilised by municipalities, limiting the local added value.

The tax potential of business activity is not monetised in the analysis, but the introduced scoring system suggests that municipalities with a high share of potential business tax income mostly have an above-average economic situation, with Budapest dominating. The tax potential is almost fully utilised by municipalities, so local income can only be increased if the 2% maximum tax rate is increased by national law. The data suggest that a higher local business tax rate is not a decisive factor in site location for investors; therefore, increasing their tax burden marginally is not likely to initiate a tax race between municipalities.

It should be noted that local taxes paid by locally owned companies do not create additional local income; they simply redistribute profits to the municipal budget.

Residential PV

Household solar panels do not generate a significant local income effect on municipal level, based on the model used in this analysis. For households equipped with solar panels, the avoided cost of electricity and, to a lesser extent, the income from surplus production can, however, be noticeable as it can generate an income effect roughly equivalent to 2% of the total per capita income in Hungary (as a share of the total household income).

The local income effect in nominal per capita terms is largest in mostly wealthy, socioeconomically developed suburban regions, suggesting that household solar income is unlikely to reduce poverty or income inequality significantly.

The introduction of the gross accounting scheme in 2024 basically annuls even these relatively small impacts too, unless either households can adapt and increase significantly behind-the-meter consumption or the off-take price of the generated electricity increases.

Business activity

The empirical analysis of the impact of solar investments on local business activity and employment provides only indicative results. The panel data regression shows that local

commercial-scale capacities have a significant positive effect on the number of local businesses active in the electricity sector, as well as their employment (with one and three year lag from the issue of the license for the project, respectively), but have no significant impact on their profitability. The employment effect is, however, rather small, reinforcing the findings from the interviews that commercial capacities provide only 1-2 low-added-value local jobs during their operation.

The OLS regression, including not only the commercial-scale capacities but also the residential units, shows no significant effect on the commercial-scale units but a significant positive effect on the residential units for the number of local businesses active in the electricity sector. However, the effect is rather small in both cases, whether the spatial unit of analysis is the municipality or the district.

The results, combined with the findings from the interviews, suggest that districts are the more natural spatial dimension for local PV markets and entrepreneurs – local economic/administrative centres can form and sustain local businesses in the local PV market; smaller markets are non-viable.

General

The research confirmed Hypothesis 1 (“The ownership, hence the control of revenues generated, of the commercial scale Hungarian PV investments is dominated by non-local (and among them mostly foreign) actors, strictly limiting the potential size of private income and local taxes contributing to the local economy.”). Local ownership is not the norm but the exception in Hungary, as almost half of the licensed capacity is foreign-owned, and two-thirds of domestic ownership is concentrated in Budapest. As a result, according to the model used, local tax revenues can have a significant impact only on the budgets of several settlements.

The research partially confirmed Hypothesis 2 (“Solar PV adopter households see significant avoided costs from the operation of the PV modules.”). While the avoided cost may be significant for households, on the municipal level, it is not a significant source of local added value, as the residential POV penetration rate is low for most settlements, and adopters are relatively well dispersed in the country.

The research could not confirm or reject Hypothesis 3 (“The number of PV investments has a significant effect on the number of companies working in the energy sector at the municipality and district level.”). The analysis yielded somewhat contradictory results but suggested a slight positive effect.

While the current analysis did not monetise the potential added value to the local economy by commercial-scale investments, it is apparent that the Hungarian solar PV boom likely did not provide a significant economic development opportunity for most of the Hungarian municipalities. It is unlikely that policymakers intended solar investments to act as such tools, and it is not necessarily an issue. Foreign ownership, for example, reduces the potential added value from ownership on the local or national level, however, it has likely helped reduce the investment costs and, through that, the costs burdening the state budget for renewable energy subsidies (Kácsor 2020).

IV. 2. Environmental impacts

Renewables and solar PV are considered environmentally friendly energy sources and beneficial for reducing GHG emissions. Most of their environmental footprint, both in terms of induced GHG-emission and water use, use of toxic chemicals and so on, is concentrated in the production of the input materials and the manufacturing of the units (PV modules)

themselves. These activities themselves are highly concentrated geographically and, in the case of Hungary, basically non-existent. From the point of view of the hosting municipalities and districts, both the construction and the operation of PV plants have mostly negligible environmental impacts, except for two possible scenarios analysed in the Thesis.

Land-use

The land requirement of solar panels is excessive, compared to traditional energy sources. the current policy targets will likely require using ca. 1-5% of the total available land for solar parks both in Europe and in Hungary. The induced land-use change has the potential to decrease locally available natural capital and cause a significant environmental footprint for the investments (also not only locally but through induced land-use competition and change in distant countries too).

The results show that agricultural land constitutes the dominant location for commercial-scale PV deployment in the EU. However, the analysis also demonstrates that industrial, commercial, transport, mining, and brownfield sites are utilised far more intensively than would be expected given their share of the total land area. While it is hard to generalise the potential ecological impact of a land-use shift from agriculture to PV, it can be assumed that using artificial surfaces for PV sites has a lower potential for negative impacts. However, there are certain EU countries where forest areas and shrublands are utilised more generally than the EU average.

While the current study did not focus on causality, this likely reflects both the extensive availability of agricultural land and the technical and economic suitability of relatively flat, open areas for solar development. The literature presented suggests that using arable land, and especially artificial land surfaces, does not lead to significant adverse environmental impacts from the land-use point-of-view; to the contrary, it might even increase the areas' ecological quality compared to intensive farming. Though, introducing solar farms for agricultural areas might induce land-use change either in other regions or countries to make up for the missing agricultural capacity.

Concerning Hungary, there are only a few sparsely populated settlements where solar power plants cover considerably large territories, and their land use might lead to significant local ecological loss through land-use change. Forest and semi-natural areas account for only a small share of total PV coverage, and Natura 2000 sites are also uncommon as PV locations compared with their overall rate of occurrence (as opposed to certain EU members). However, larger plants are more often located on ecologically sensitive land covers than smaller ones, suggesting a negative trend. This is in line with the findings of Harmat and Munkácsy (2021), who analysed the first three tenders under the METÁR-scheme and concluded that the share of brownfield projects was constantly declining from 23% in the first tender to 12% in the third (in terms of capacity). In Hungary therefore, the shift in the coverage of 0.1% of the total land area is less likely to cause significant ecological value loss, but most likely the abandonment of agricultural lands with land quality similar to the national average.

Local emission reduction

In Hungary, local air pollution (NO_x, SO₂, PM 2,5-10) is a serious concern in numerous rural areas. The most significant source of these emissions is solid-fuel-based heating, especially the use of wood (coal use had almost disappeared by 2022). While solar installations typically provide the most electricity during periods where heating is less required (from spring to autumn and during daytime), with the net metering scheme in place until 2022, there was a

strong incentive for households installing solar panels to switch at least partially to electric heating. If the switch from wood were to occur, residential solar units could reduce local air pollution.

The OLS regressions used to measure this effect suggest that the emergence of rooftop solar installations in Hungarian municipalities has significantly contributed to the decrease in the use of solid fuels, especially wood, for heating, both as an exclusive source and as a supplementary source. Therefore, it also contributed to a possible decrease, but at least a limitation to local air pollution from solid fuel heating. This is, however, somewhat offset by the fact that the results of the regressions also show that PV installations have similarly contributed to the increase of combined electricity+wood heating, possibly even for households that did not use wood before (although the number of such households is smaller than the ones abandoning wood use altogether).

The actual decrease in air pollution is hard to estimate, as there is no available data for either the actual level of emission on the municipal level or the consumption of fuel wood (and other solid fuels). Nevertheless, between 2011 and 2022, roughly 80,000 households stopped using wood as their exclusive heating source, and roughly 200,000 homes abandoned wood as a supplementary heating source. Based on the econometric models, it can be assumed that this is at least partially due to the installation of ca. 170 000 rooftop PV units in the same period.

However, the descriptive statistics suggest that this change did not help the municipalities and households most affected by local air pollution, as the share of solid fuel heating increased in several hundred, mostly disadvantaged municipalities during the observed timeframe. This is also evidenced by the fact that 12% of the municipalities seeing the increase in the share of solid fuel heating are in the program of “Felzárkozó Települések” (catch-up settlements), a program targeting the most disadvantaged settlements in Hungary, covering only 9% of all the settlements.

General

The research partially confirmed Hypothesis 4 (“In the absence of regulatory incentives, commercial PV plants are located on agriculturally or environmentally valuable land plots at a rate similar to Hungary's general surface cover rate.”). While agricultural land and some forms of artificial coverage are overrepresented, forests and non-managed lands are underrepresented compared to their occurrence rate in Hungary. However, the share is higher both for non-managed land and agricultural land when focusing on larger, more recent projects.

The research rejected Hypothesis 5 (“Household PV investments mostly do not replace polluting heating modes.”). The analysis showed that residential PV adoption rates have a significant impact on reducing the use of fuel wood in Hungary.

IV. 3. Social nexus

Social impacts of solar PV investments are the hardest to identify, operationalise and measure. The analysis could not be considered a valid social impact assessment but as a preliminary analysis identifying the social patterns behind the typical solar PV adopters in Hungary on municipal level data. This helps designate what types of social impacts can be expected in the Hungarian case and which aspects future research could focus on.

Both the available literature and the descriptive statistical analysis indicated that the most important factors explaining residential solar PV adoption were household affluence and the type of dwelling (large, relatively new, and detached).

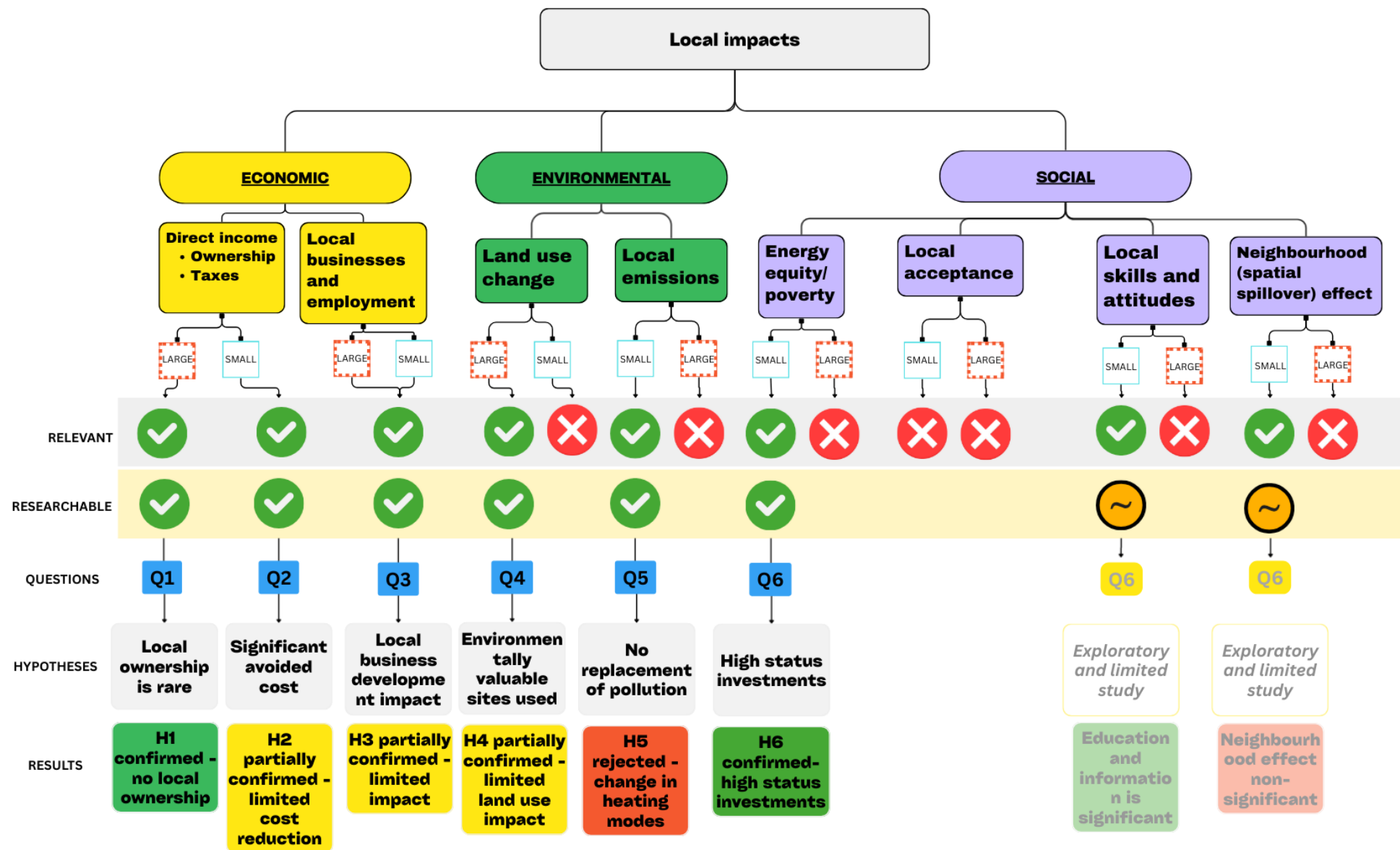
This was, however, only partially confirmed by the regression analysis. The model found that the variables used to describe household affluence at the municipal level (personal tax base, employment rate, number of active businesses, and the municipality's economic status) had no significant impact on solar PV adoption. This is either because of methodological shortcomings (the variables are inappropriate for such approximation and/or the household level differences are cancelled out in the municipal level data), or in the Hungarian case, affluence is not as important as was assumed.

The results suggest that PV adoption is instead influenced by social status (middle-aged, university-educated, medium-high digital activity, living in areas with relatively low housing density and in detached houses built relatively recently). These features are strongly correlated with household affluence. However, it is also possible that wealth is only an enabler in this case, and the actual cause stems from status instead; equally affluent households with different social statuses are less likely to adopt solar PV. Also, the (expected) introduction of the regulation for net-zero buildings in Hungary might also had an important, maybe even dominant, influence on the adoption of new-build dwellings.

The regression analysis also suggested that some factors expected to be relevant were not significant. According to the results, the neighbourhood effect of either residential or commercial PV capacities does not influence residential PV adoption. Also the influx of EU funding to the municipalities for energy projects (not residential, but for SMEs and public institutions) since Hungary's EU accession did also not foster local private investments, even though it could be assumed that they increased local knowledge (as for example PV systems were installed on local schools and administrative buildings as it happened for many municipalities) or simply advertised the option visually.

General

The research conducted partially confirmed Hypothesis 6 ("Household PV investments in Hungary are significantly more likely to happen in settlements with higher socio-economic status."). While affluence did not seem to directly influence adoption significantly, municipalities in high-status environments (city agglomerations, Balaton Lake, Velence Lake) are definitely overrepresented in terms of residential PV ownership, and several socio-economic variables associated with higher socio-economic status (higher education, more access to information, larger and newer dwellings) did have a significant influence.



2. Figure Graphical summary of the problem-identification matrix, the selected (relevant and researchable) research topics, as well as an indicative summary of the relevant Hypotheses and the results.

V. Discussion

V. 1. Novelties of the research

The Thesis provides several additions and novelties to the existing literature.

There are only a few studies on the potential impacts of renewables in the Central-Eastern European region, especially Hungary. The CEE region and Hungary, however, offer a particularly interesting case, as they are relatively late adopters of renewable technologies and could adapt the adoption rate and dynamics to their own peculiarities and policy targets, which could even include direct or indirect (rural) regional development. Analyses such as this offer an insight into whether this happened and to what extent.

Such land-cover analysis has not yet been conducted, not only in Hungary but across Europe, especially at this resolution and with this range of data.

There have been no studies so far that have conducted an impact analysis of renewables and the development dynamics of the renewables sector using Ultimate Beneficial Owner data. Hence, this thesis not only provides new insight but also helps future research that uses such data.

The regression analysis introduced and tested new variables that had not been used in the literature. It also used higher resolution socio-economic data (by focusing on municipalities), as most of the literature does.

The main novelty is the approach itself, which provides a general and as comprehensive an overview of the (potential) impacts as possible.

V. 2. General conclusion and recommendations

While the energy transition, electrification, and the rise of solar PV generation transform global and national energy systems, profoundly affecting the basic system that enables the social and economic operation of industrial civilisation, their local impacts are less obvious.

Hungary quickly turned from a relative laggard (at least in the EU) in integrating solar into its energy system to a frontrunner, even globally. That was achieved by substantial policy support for both commercial and residential capacities; however, most of the increase occurred during a significant reduction in PV panel prices, so the Hungarian system avoided the subsidy trap of heavily subsidising expensive investments. The fast-paced investment rate, however, consumed the grid's free capacity, necessitating strong policy intervention and sizeable grid development investments.

Nevertheless, the local impact of PV investments remains limited – and this is a mixed result.

Probably most importantly, Hungary is basically missing out on the rural development impact potential of commercial-scale investments. Local ownership is almost non-existent in Hungary, so the profits generated by these units are less likely to contribute to the local economy. Tax income from these plants can be a sizable contribution to municipalities' budgets, mostly for the smallest (and often disadvantaged) settlements, and some very limited employment effect can also be seen. However, the revenue from ownership potential is larger than these by several orders of magnitude.

These revenues are private property, so forcibly redistributing them locally presents many challenges and might not even be effective. Fostering the formation of local energy communities could be a way; however, Hungarian policymakers have not favoured this option

so far. And even if they could, it is questionable whether truly local communities (even at the district level) could gather the required capital and know-how to install and operate commercially viable, large-scale power plants. Some other options worth considering could be:

- large-scale projects would be obliged to offer a fraction of their capacity for ownership of the local municipality;
- project owners could deduct some national taxes if they pursued local infrastructure investments (e.g. road renovation, contribution to local)
- business tax levied on these power plants could be exempted from the 2% upper limit;
- should there be future rounds in METÁR or other operational subsidy auctions, projects with local ownership (also brownfield projects) should be prioritised;
- the Hungarian Development Bank or other national financial institution could provide subsidised loans for local (at least Hungarian) project developers.

The distribution of commercial-scale capacities is rather uniform in Hungary. It cannot be claimed that either affluent municipalities or highly disadvantaged ones would be significantly overrepresented. This suggests that PV investors are not exploiting the resources of disadvantaged municipalities, but it could also be argued that increasing the share of localised revenue from plant operations would not only make rich settlements even richer but could also serve as a rural development policy tool.

At the same time, the research conducted in this Thesis also shows that the negative environmental externalities from commercial PV investments are mostly limited in Hungary. Therefore, most settlements do not have to be financially compensated for serious environmental harm caused by either the construction or the operation of such power plants. Increasing localised revenues is not a matter of basic fairness and is not necessitated by granting any form of justice. Certainly, the previous subsidy policies (KÁT and METÁR schemes) could have had strong incentives built in to favour brownfield sites and locations with even lower ecological and/or agricultural value than those chosen in a relatively *laissez-faire* manner.

Residential solar investments were expected to favour affluent households. The analysis on the predicament of rooftop PV adoption did not support that expectation, but showed that status and wealth (education, information access, and new housing) seem to be more important. In Hungary, while the residential pricing scheme provides a low retail electricity price for most households compared with the EU, supporting PV investments for social equity and energy poverty purposes does not seem to be a priority. Though certainly, existing grant programs could have a stronger affinity towards such aspects (while to some extent, such considerations were included in the most recent residential grant scheme).

The newly introduced gross accounting scheme, however, counteracts such potential policy targets, and favours households that can also spend on batteries and/or restructuring their intraday consumption patterns. Pensioners, poor and/or small households, or even families with no means to finance both roof renovations and PV installations, are largely excluded from the potential income benefits of residential PV systems. At the same time, a grant scheme targeting those households should have a broader scope: a PV installation without proper renovation is not an actual solution to (energy) poverty, just a beauty patch. But a program that would provide financial support for a thorough renovation would be highly expensive or could address many fewer households than a program supporting the PV installation of affluent/relatively high-status households.

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