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THE LOCAL IMPACTS OF SOLAR ENERGY INVESTMENTS IN HUNGARY
DOCTORAL THESIS

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Extended abstract

The energy transition and the growing share of renewables is not a scenario anymore; it is the current reality and the trend of the next decades. Solar PV is expected to have the largest built-in capacity of all electricity sources by 2050. It already provides 10% of the EU's electricity and one-quarter of all the built-in capacity. For Hungary, the measures are even higher: almost 20% of the total electricity produced in Hungary came from solar PV units, which in total make up 40% of the total electricity production capacity in Hungary. These figures place Hungary among the leaders in solar PV not only in Europe but also globally.

Transitions on such scale and importance as the shift to renewables lead to major changes and challenges in society's social, economic and environmental status on every level and strata. The impacts of the energy transition are manifesting everywhere, from global effects (impacts on climate change) to local communities. As solar PV is highly scalable, solar-based energy production becomes more and more widespread among households both in economically more and less developed countries, on rooftops of major industrial facilities and takes over agricultural lands by the dozens of hectares for each large-scale solar PV power plant. The presence of solar capacities is becoming increasingly the everyday reality, the norm for more and more communities worldwide.

The Thesis explores the potential impacts of solar PV investments on the local level, i.e. the scale of municipalities and microregions. While the potential impacts are relatively well-explored in the literature, actual empirical findings are less common, especially for Hungary and the Central-Eastern European region, despite its peculiarities.

The Thesis groups the potential impacts into three main clusters: Economic, Environmental, and Social. It first identifies which potential impacts, described by the literature, are relevant in the case of Hungary. Then, it offers a way to measure or approximate the relevant impacts with data available from EU-level, national or other datasets. This way, the Thesis produces a unique, comprehensive overview of what

the globally exceptional Hungarian PV-boom might mean for local communities from different aspects.

The Economic impacts in terms of potential additional income and employment on the municipal or micro-regional are modest. Ownership of the commercial-scale capacities is held mostly by either foreign or Budapest-based investors, not local actors. This also limits the potential tax income of the municipalities. Residential solar PV can reduce the electricity costs of households significantly, but this effect adds up to a relevant income effect only in the case of a handful of municipalities.

Environmental impacts are assumed to be two-fold: while commercial-scale capacities use large swaths of land, potentially causing local ecological losses and damages, residential solar units have the potential to replace traditional heating methods, especially solid biomass, which causes significant local air pollution. The study finds that large-scale PV plants are mostly built on agricultural land in Hungary with modest ecological value. Residential PV plants are found to contribute to the reduction of wood use in Hungarian municipalities.

The Social aspect is approached from the social background of the residential PV adopters. It is found that while affluence does not seem to directly and significantly influence PV adoption rates among municipalities, higher social status (higher education, more information, home in a relatively large and newly built detached house) does.

In general, the Thesis concludes that despite the almost unprecedented PV-boom of Hungary in recent years, both in terms of commercial and residential capacities, the actual local impact of solar investments is rather modest, especially in terms of economic impacts, which had the highest potential to contribute to local development and make PV-investments not only a tool for energy and climate policy but also a channel for rural development.

1. INTRODUCTION

1.1. The era of renewables

Renewable energy has a dual historical narrative. Pre-industrial societies relied on rudimentary renewables—waterwheels, windmills, and biomass—out of necessity, while modern societies view them as the cornerstone of sustainability. The industrial era, however, was dominated by high-energy-density fossil fuels, with coal, oil, and gas powering unprecedented economic growth. Renewables remained marginal until the late 20th century, when the oil crises in the 1970s exposed the vulnerabilities of fossil fuel dependence, sparking initial interest in alternatives (Yergin 2012).

This first wave of modern renewables, exemplified by the short-lived solar panels on the White House, faltered due to high costs and low energy density. Fossil fuels, with their superior EROEI metrics (Energy Returned on Energy Invested) and ease of use, retained dominance until environmental imperatives—climate change, air pollution, and resource depletion—shifted the paradigm. The recognition of negative externalities, coupled with policy interventions like carbon pricing and subsidies, has since catalysed the current renewable boom (although the growth of renewables has so far only been sufficient to cover part of the growing energy demand, not to actually displace fossil fuels).

The global energy landscape is undergoing a profound transformation, driven by the urgent need to address climate change, enhance energy security, and foster sustainable economic development. At the heart of this shift lies the energy transition—the move from fossil fuel-based systems to ones dominated by renewable energy sources such as solar, wind, hydropower, and geothermal energy.

The intensive proliferation of renewable energy sources is no longer a speculative vision but a tangible reality. According to the International Energy Agency (IEA), renewable energy accounted for 32% of global electricity production in 2024, and that share is expected to rise to 43% by 2030, becoming the largest source of electricity generation globally (IEA 2025a). Solar and wind energy have been the primary drivers of this growth, with solar photovoltaic (PV) capacity increasing by over 20% annually since 2020, reaching an estimated 2,400 gigawatts (GW) globally by the end of 2024

(IRENA 2026a). Wind energy, both onshore and offshore, has similarly expanded, with a global installed capacity approaching 1,000 GW.

This rapid growth is underpinned by significant declines in the levelized cost of electricity (LCOE) for renewables. IRENA data indicate that the LCOE for solar PV dropped to an average of \$0.044/kWh in 2025, down from \$0.46/kWh in 2010 (96% reduction), while onshore wind fell to \$0.033/kWh (IRENA 2026b). These figures render renewables competitive with, and often cheaper than, fossil fuel-based power generation in many regions, particularly where solar irradiation or wind speeds are favourable. Technological advancements—such as larger, more efficient wind turbines and bifacial solar panels—combined with economies of scale and increased manufacturing capacity have fuelled this cost decline.

The policy landscape has also been instrumental. The European Green Deal, launched in 2019, aims to make Europe climate-neutral by 2050 and has allocated over €1 trillion for sustainable investments by 2030, with a significant portion directed toward renewables. In the United States, the Inflation Reduction Act of 2022 has spurred a surge in clean energy investments, contributing to a record 50 GW of renewable capacity additions in 2024. Globally, the 2021–2030 decade is witnessing unprecedented financial commitments to climate action, with countries pledging \$100 billion annually to support renewable energy deployment in developing nations (CPI 2024).

Although the political drive behind the energy transition has recently somewhat dissipated in both the EU and, especially, the US, the general trend is unlikely to change drastically. Renewables are – as mentioned – cost competitive, and other regions like China and India are also important (in the case of China, actually, the dominant) actors in terms of renewable capacity additions.

Despite this progress, challenges remain. The intermittency of solar and wind energy necessitates advancements in energy storage and grid infrastructure. Battery storage capacity has grown exponentially, with lithium-ion systems reaching 300 GWh globally in 2026 (BNEF 2026), yet costs must further decline to ensure widespread adoption. Additionally, the energy transition's reliance on critical minerals—such as lithium, cobalt, and rare earth elements—raises supply chain and geopolitical concerns, prompting calls for recycling and alternative technologies (IRENA 2019).

The energy transition is not merely a technological shift but a socioeconomic one, with far-reaching implications for economies and communities. Renewables, due to their decentralised nature, can be deployed close to consumption, reducing transmission losses and creating local economic value. However, the distribution of these benefits may remain uneven, and large-scale renewable projects may favour corporate investors, while local communities see limited ownership or economic gains. Empirical research is critical to understanding these dynamics.

Globally, the renewable energy sector employed over 16 million people in 2025, surpassing employment in the fossil fuel industry (IRENA and ILO 2025). This shift underscores the potential for renewables to drive inclusive growth, particularly in regions recovering from the economic fallout of the 2020 pandemic. Yet, the transition also poses risks, such as job losses in coal-dependent regions, necessitating just transition frameworks to retrain workers and diversify economies.

Looking ahead, the trajectory of the energy transition hinges on technological, economic, and political factors. The International Energy Agency (IEA) projects that renewables will account for 50% of global electricity by 2040 under its Stated Policies Scenario, with solar and wind comprising 70% of new capacity additions. In a more ambitious Net Zero by 2050 scenario, renewables could reach 88% of electricity production, supported by breakthroughs in green hydrogen, advanced batteries, and carbon capture technologies (IEA 2024b). However, transitioning non-electricity energy consumption is much harder: heating, transportation, and industrial energy use are either electrified or will require novel technologies, such as hydrogen or liquid biofuels, to actually realise the policy targets.

By 2030, global solar capacity could exceed 3,500 GW, driven by cost declines and policy support, and will remain the most important renewable energy source in terms of installed capacity, on par with fossil fuel-based capacity in developed economies (IEA 2025a).

1.2. Renewable energy and the pillars of sustainability

The primary goal of supporting renewable energy sources is to improve the environmental sustainability of energy production, both locally and globally.

Transitioning the energy system to modern renewables (particularly solar and wind energy, which allow for small-scale, decentralised energy production) also brings numerous positive and negative externalities on global, national, as well as local levels.

This section gives an overview of the potential impacts of renewables using the three pillars of sustainability, Environmental, Economic and Social aspects, to give an overview of the direct and indirect impacts of the growing adoption rate of renewables in general. These pillars have already been incorporated in the 1987 Brundtland report, a foundational text for sustainability, and are at the centre of the United Nations' work on sustainability, especially of the Sustainable Development Goals (Purvis et al. 2019).

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, leading 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.

Renewable energy accounts for USD 4.5 trillion (54%) of the clean energy investment over 2009-2023, likely breaking the USD 5 trillion threshold in 2024 (Teixeira and Demoro 2024). Although such comparisons are indicative at best, that is 600 USD/per capita globally or 40 USD/capita/year over the same period. For the EU those figures are in the neighbourhood of EUR 1 trillion (700 billion between 2010-2019 and 237 billion since 2020 (Frankfurt School-UNEP 2019; IEA 2024a)) or EUR 2,200/capita and EUR 150/capita/year. This is at least comparable to the roughly 1 trillion EUR spent (or planned) within the framework of EU cohesion funds between 2007-2027.

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. However, decentralised energy production and prosumer participation (where consumers are also producers) can have numerous benefits beyond improving environmental sustainability and contributing to the economy:

- It can reduce or eliminate energy poverty. Some form of energy deprivation affects billions of people to varying degrees, not only in countries with poor energy infrastructure and weak economic indicators but also in more developed regions (Bazilian et al. 2014; Bouzarovski and Petrova 2015; Pye and Dobbins 2015). The installation of renewable energy sources, particularly solar panels, solar collectors, advanced biomass boilers, small-capacity wind turbines, and heat exchanger systems (provided the necessary electricity is also locally generated), due to their low operating costs, can often be a solution to energy deprivation if the investment receives significant support (EIA 2010; IEA 2017).
- It can lead to a more democratic energy system. Local energy production empowers communities and individuals with decision-making capabilities that were previously centralized at much higher administrative levels, often with limited transparency and legitimacy (Szulecki 2018; van Veelen and van der Horst 2018).
- The possibility of autonomous energy production improves energy and supply security at both the state and sub-state levels (while also introducing new geopolitical challenges in the renewable supply chain) (IRENA 2019; Scholten 2018).

1.3. Rationale of the study

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.

Despite the strong policy push in Hungary to promote PV investments not only to green the domestic power sector but also as a tool for rural development and poverty alleviation, it cannot be taken for granted that, under the current legislative framework, the widespread installation of PV units would indeed have such an effect. This research aims to assess whether and how renewable energy investments, especially PV installations, contribute to the local economy in Hungary, as well as the environmental and social impacts these investments may have. An aspect that might be paramount is designing future renewable energy support schemes and the legislative environment of renewable energy communities.

The current literature on solar power adoption, as it will be presented in Chapter 2, focuses on peer effects and spatial patterns; public perceptions; and 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 deal with Hungary or any CEE country, for that matter (Vishnu and Joshin 2024).

Ramalho 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 2026c).
- 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 2026a).
- 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 2026a).

- 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.
- In the meantime, according to IRENA and ILO (2024), in 2023, Hungary had 23,000 people employed in the PV sector, or 5.43 employed per MW, or 4.86 employed per GWh produced (2022 value), far below the world average (13.34 and 11.08 respectively), and also below the EU average (12.04 and 23.56 respectively, but omitting Latvia as a strong outlier gives averages close to the Hungarian value: 6.4 and 7.78). That indicates that Hungary, even though it is among the leaders in terms of usage, lags relatively behind in building a strong renewable energy sector in its domestic market.
- The investment cost of the planned solar capacity in Hungary by 2030 is roughly 2.5-3 billion EUR, while the costs for the 12 GW total capacity planned for 2030 are expected to be around 5-6 billion EUR (Baji-Gál Imréné Szarvas 2023). Apart from the Paks II. Nuclear Power Plant project (if it will be realised at all), this represents the largest body of investment in the Hungarian energy sector – especially if one includes at least part of the 1.2 billion EUR grid development, made necessary mostly by the surge in solar capacities (see (Világgazdaság 2023)). The total value of cohesion funds originally allocated for Hungary in the EU budget period 2021-2027 is 22 billion EUR.
- 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.

1.4. Outline of the thesis

The thesis first provides a detailed literature review of the general and local impact of renewable energy sources, focusing on solar PV in all scales. The literature is presented in a tripartite structure following the three dimensions of sustainability: Economic, Environmental and Social. The existing findings on Hungary (if applicable) are presented in separate sub-chapters.

From the literature review, an issue map and relevant questions and hypotheses are derived, forming the backbone of the empirical analyses. From the overview of potential impacts in the literature review, issues are selected that are both relevant to Hungary and researchable given the available data. This provides an issue map listing all topics from which relevant information on their local impacts can be gathered.

The first empirical chapter focusing on the Economic impacts provides insight into the potential size and distribution of the localizable income from the operation of solar PV units from residential to large-scale commercial use (arguing simultaneously that in the case of Hungary, other parts of the life-cycle are less relevant). The impact of ownership of large-scale plants, the income effect of residential solar units, local tax potential, and some indications of local business activity are discussed.

The chapter on Environmental impacts addresses two issues pertinent at the local level: the induced land-use change resulting from the construction of large-scale solar power plants and the potential for residential PV to replace air-polluting modes of home heating, especially firewood.

The Social aspect is examined by analysing the socio-economic background of adopters of residential solar units in Hungary.

All three empirical chapters use distinct methodological approaches and different datasets; therefore, each contains its own subchapter on methodology.

The Thesis concludes with remarks on the way forward.

1.5. Overview of the Renewables and PV policy in Hungary

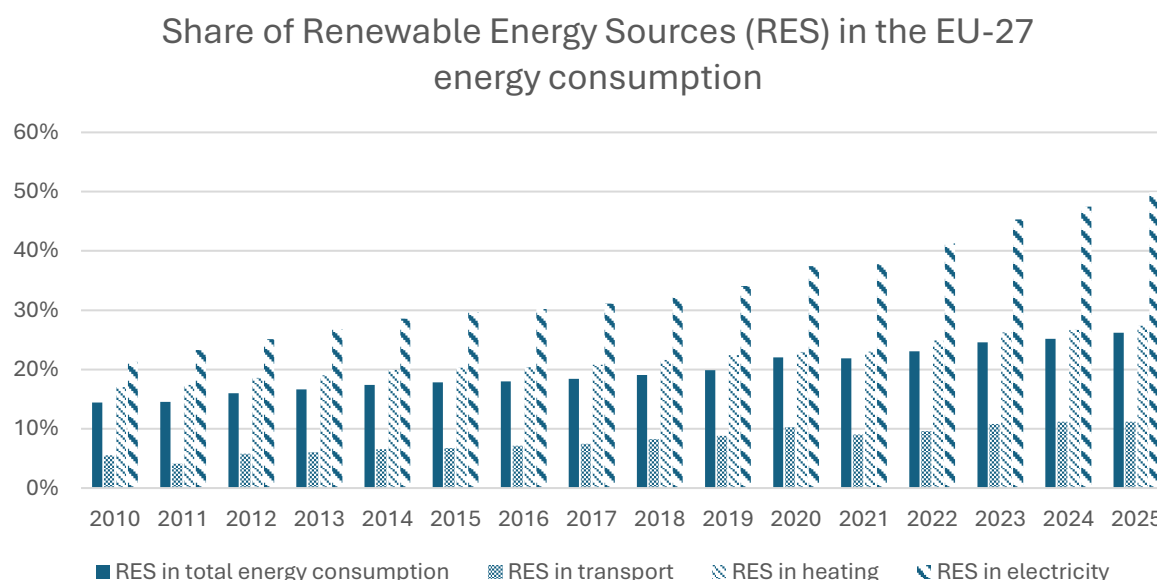
1.5.1. EU policy

The European Union aims to play a global leading role in the sustainable transformation of the energy system, i.e. the energy transition. Hence, intensive support for renewable energy sources is among the EU's primary objectives. This effort can be considered fundamentally successful, as it has increased the share of renewables in the EU's total primary energy consumption to 20% by the end of 2020 (doubling compared to 2005), and within electricity generation, reached an even higher share of over 35%, surpassing coal-based electricity generation (Agora Energiewende and Sandbag 2020; IRENA and EC 2018).

Although the EU's common environmental and energy policy effectively started after the Maastricht Treaty came into force in 1993, the first significant milestone in the targeted support of renewable energy sources was the Renewable Energy Directive, which came into force in 2009, which required a 20% renewable share in final energy consumption at EU level by 2020 (which was accompanied by legally binding targets on the Member State level too) ¹. The new 2030 target system is based on this, which initially projected a 32% renewable share at the EU level, but without Member State level overall binding targets (though it did introduce some sector-specific binding targets). Later, in 2023, by the revision of the Renewable Energy Directive, the binding EU renewable energy target was raised to 42.5% (with the aim to reach 45%). In the even longer term, with a view to 2050, the EU has set the goal of transitioning to a net-zero emission economy and society, which requires the development of a renewables-dominated energy system, with an interim suggested target of 90% GHG-reduction by

¹There was already an EU target before the 2009 Directive, namely an indicative 12% target for 2010 based on the 1997 White Paper on renewables (1997/0599), which was later broken down into indicative Member State targets by Directive 2001/77/EC. In addition to the weak framework and slow progress, the institutional push of the Lisbon Treaty (especially Article 194 of the Treaty on the Functioning of the European Union, which strengthens and redefines the common energy policy) created the need and the opportunity to set a more serious strategic target system for 2020.

2040 (suggesting a steep emission reduction trend until 2040) (European Commission 2025b).



1. Figure Share of Renewable Energy Sources (RES) in the EU-27 energy consumption in different sectors, 2010-2025 (Eurostat 2026b). Provisional data for Transport in 2025 was not available; therefore, the 2024 value was used.

As 1. Figure shows that renewables already form a major part of the EU energy system, covering more than 25% of final energy consumption and almost half of electricity demand. However, while traditional, solid fuel-based electricity generation is relatively easy to replace by renewable capacities, heat and transport production is less so, while these make up 51% and 28% of the total final EU-27 energy consumption, respectively (IEA 2025b).

Electrification of final energy consumption in all sectors is foreseen to bridge this gap. The European Commission projects a share of electricity in final energy consumption of 62% by 2050, with roughly 50% by 2040 (European Commission 2024a). In the same document, the European Commission models an 89% RES share by 2050 (65-75% by 2040, with wind and PV covering 35-40% and biomass roughly 25%), vastly overtaking biomass. IRENA (2025) projects that by 2030, 41% of the EU's total installed power generation capacity will be solar PV, rising to 53% by 2050. However, due to its lower capacity factor, wind (onshore and offshore combined) is likely to be the largest source of power production in the EU by 2050 (CIP 2025; Montel 2025).

To achieve the 2030-2040-2050 goals, the EU – similarly to national governments, but with a narrower scope and palette – can primarily use regulatory and support

instruments. As a legislator, it is most active in exercising its common energy market regulatory powers. One of the main steps in this was the recast of the Renewable Energy Directive 2018/2001/EU (also called RED II), adopted in the winter of 2018 as part of the Clean Energy for All Europeans package. In addition to the 2030 targets and the obligation to prepare Member States' National Energy and Climate Plans, the Directive modifies the previous biomass sustainability criteria, advances the harmonisation of Member States' renewable support systems, and introduces several measures supporting consumer energy production (becoming prosumers), mainly by reducing administrative burdens and introducing new legal categories². The fundamental goal of RED II is to enable and facilitate the spread of renewables in all segments of energy supply (from transport to district heating to electricity) and in its territorial dimension (from households to forms of cooperation between states).

The subsequent revision of the Renewable Energy Directive (RED III), adopted in 2023, focused on the enhanced 2030 renewable energy target and provided the legislative background for it. In addition to the general EU-level and national targets, it defined binding and non-binding sector-specific targets and introduced the concept of Renewable Fuels of Non-Biological Origin (RFNBO). RED III also strengthened and unified the divergent system of Power Purchase Agreements (PPAs) throughout the EU to promote a prominent, market-based tool for signalling long-term demand for new renewable capacity. It also simplified national permitting procedures for new renewable capacity additions and introduced some tools for Member States to designate some areas for streamlined RES and grid development (EASE 2024; Linklaters 2023). These

The longer-term trajectory has also become more firmly institutionalised. The European Climate Law established climate neutrality by 2050 as a legally binding EU objective, along with a 55% reduction in net greenhouse gas emissions by 2030 relative to 1990. In 2026, the European Climate Law was amended to establish a

² One such legal category is Renewable Energy Communities (REC), whose codification in EU law allows citizens, companies and local governments to establish jointly owned associations to finance and operate local renewable investments. Such communities likely have more access to capital and are synergistic, allowing them to implement larger, more scale-efficient investments, while – as intended – paying special attention to the wider local socio-economic development needs and value creation in addition to financial returns (Lowitzsch, Hoicka, and van Tulder 2020) .

legally binding 90% reduction in net greenhouse-gas emissions by 2040 relative to 1990, with at least 85% to be achieved domestically and up to 5 percentage points potentially met through high-quality international carbon credits (European Commission 2026). The 2040 target therefore provides a new intermediate milestone between the 2030 renewable-energy agenda and the EU's legally binding 2050 climate-neutrality objective.

The importance of solar PV investments in achieving the 2030 goals was underscored by the European Commission's 2022 EU Solar Strategy. The Strategy included mandatory rooftop solar installation on new public buildings (from 2026 onward) and residential buildings (from 2029 onward). It also promoted investment in production facilities along the PV value chain and skill development (SolarPower Europe 2022).

The EU's policy instruments have also broadened beyond conventional renewable-energy regulation. RED II and RED III continue to provide the core regulatory framework, while the Net-Zero Industry Act (2024) seeks to strengthen European manufacturing capacity in strategic net-zero technologies, including solar PV, with a benchmark of meeting at least 40% of the EU's annual deployment needs through domestic manufacturing capacity by 2030 (European Commission 2024b). The European Solar Charter, adopted in 2024, similarly seeks to strengthen the resilience and competitiveness of the European solar-PV value chain through voluntary actions (European Commission 2025a). These initiatives reflect growing concern about Europe's dependence on non-EU suppliers, particularly in solar manufacturing, and increasingly connect renewable-energy deployment with industrial policy and technological sovereignty.

In addition to regulatory instruments, the EU also provides significant financial support for renewable energy production. Preliminary estimates suggest that achieving the 2030 targets will require an annual investment of €25-35 billion in renewable energy alone (a third of which will be in solar projects), with the bulk of this funding naturally having to come from Member States and, above all, from markets. The EU contributes to this financing need primarily through its own multiannual financial framework (MFF). Over the period 2014-2020, an estimated €7 billion was spent annually on the energy sector as a whole, only a small part of which was specifically for renewable financing purposes (Williams et al. 2018). For the 2021-2027 period, the MFF was practically

expanded by the Next Generation EU (NGEU) instrument, raising the total EU budget to over 2 trillion EUR. 30% of the MFF and 37% of the NGEU are supposed to be spent on green interventions. Preliminary data shows that just from the cohesion funds (making up only 1/5th of the 2 trillion), 130 billion EUR was spent on green transition, of which almost 18 billion on renewable energy supply (CAN Europe 2025).

Recently, however, the dominant green agenda has lost some appeal and competitiveness, and hard defence issues have come to the forefront, the latter due to the Russian-Ukrainian war and the former distilling around the Draghi and Letta reports. While the politically more relevant Draghi report does not claim that EU targets, policies and fiscal decisions supporting renewables should be reconsidered, it definitely shifts the focus from the climate benefits to the potential of renewables on lower energy prices and contributing to the European economy through localising their value chains (European Commission 2025c). Therefore, investigating the economic effects of investments on such a scale is a pertinent issue, especially with the introduction of the newest EU policy agenda focusing on the competitiveness aspect of green and sustainability policies (Diestelmeier 2025).

This changing policy context makes the economic and territorial consequences of renewable-energy deployment increasingly important. As renewable investment expands from a climate-policy instrument into a central component of European industrial, energy-security and competitiveness strategies, the question is not only how much renewable capacity is installed, but also where investment occurs, who owns the resulting assets, and where the economic value generated by the energy transition is captured. These questions are particularly pertinent for large-scale solar PV, whose rapid spatial expansion can create potentially significant local effects, while ownership and value capture may remain geographically disconnected from the locations where renewable assets are physically deployed.

1.5.2. Hungarian policy

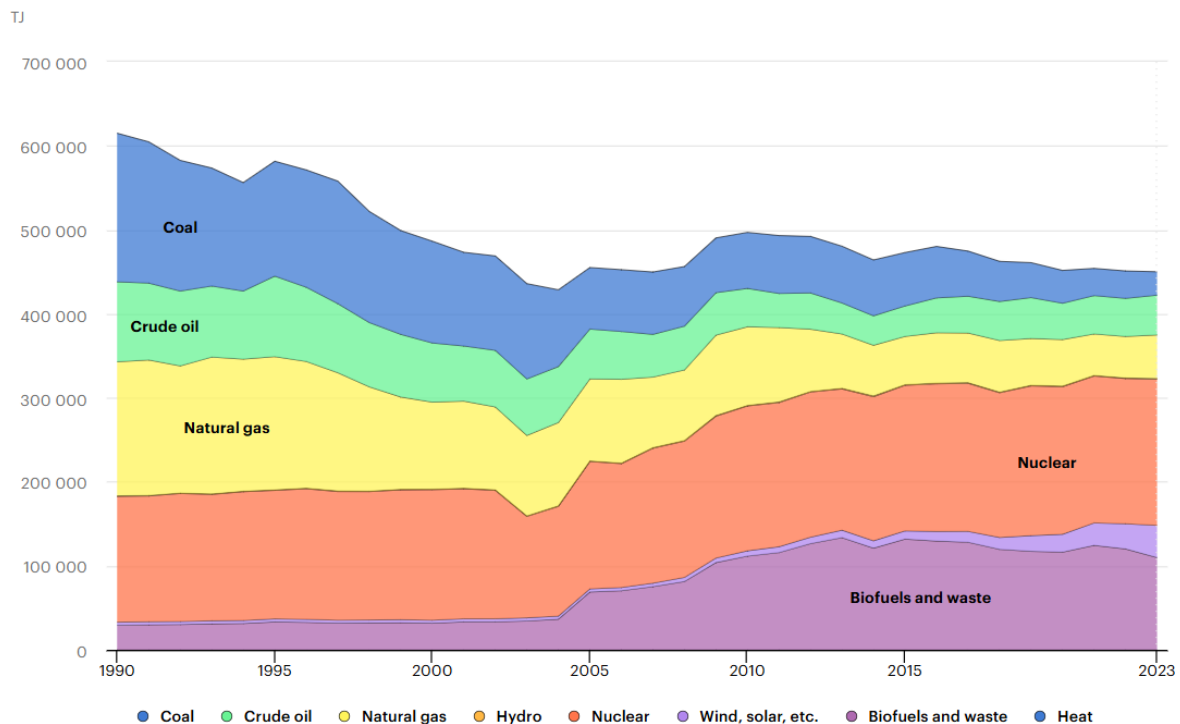
Energy policy overview

The Hungarian domestic energy policy has been primarily determined by four trends and political objectives, uniting most of the political spectrum over the past twenty years. The market opening and liberalisation associated with EU accession, import dependence on Russian natural gas (including Ukrainian transit) and on electricity

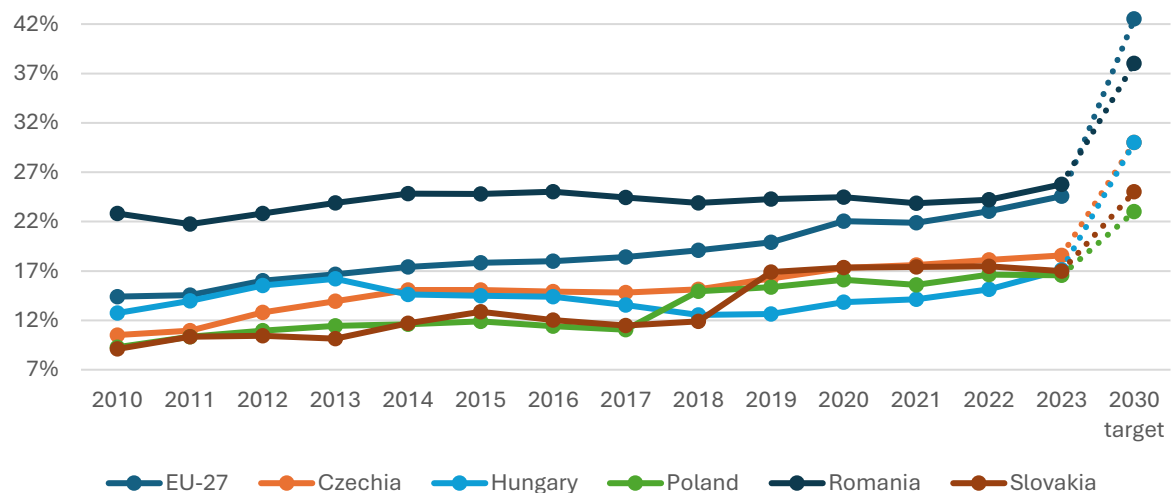
from neighbouring countries, the political demand to reduce consumer prices, and the expansion of the Paks nuclear power plant.

Support for renewable energy sources as a key policy target appeared early, mostly along with the legal and political obligations arising from the EU accession, but it did not become a central policy objective, and in particular, it did not come to the centre of the domestic energy policy discourse to the same extent as, for example, in Germany through the *Energiewende* concept. It was rather an instrument for reducing import dependence, meeting EU targets and partially reducing residential energy costs.

The post-communist Hungarian energy system was dominated by legacy coal and nuclear capacities, along with extensive natural gas import and distribution infrastructure, which spurred the installation of new natural gas-fired power plants (CCGTs) after the regime change. The use of renewables – as shown in 2. Figure – was limited to biomass (fuel wood) use mostly in the residential sector. Even that was enough, however, to allow the share of renewable energy sources in total energy consumption to catch up with the EU-27 average by 2014 (see 3. Figure). Yet, the share has deteriorated since then, going against the macro-regional trend, until 2020, showing that Hungary was a latecomer to modern renewables.



2. Figure Domestic energy production by source, Hungary, 1990-2023 (IEA 2025b).



3. Figure Share of renewable energy in total energy production in the EU-27 and some CEE Member States between 2010-2023 and the 2030 target committed (Genicot et al. 2025; Eurostat 2026c).

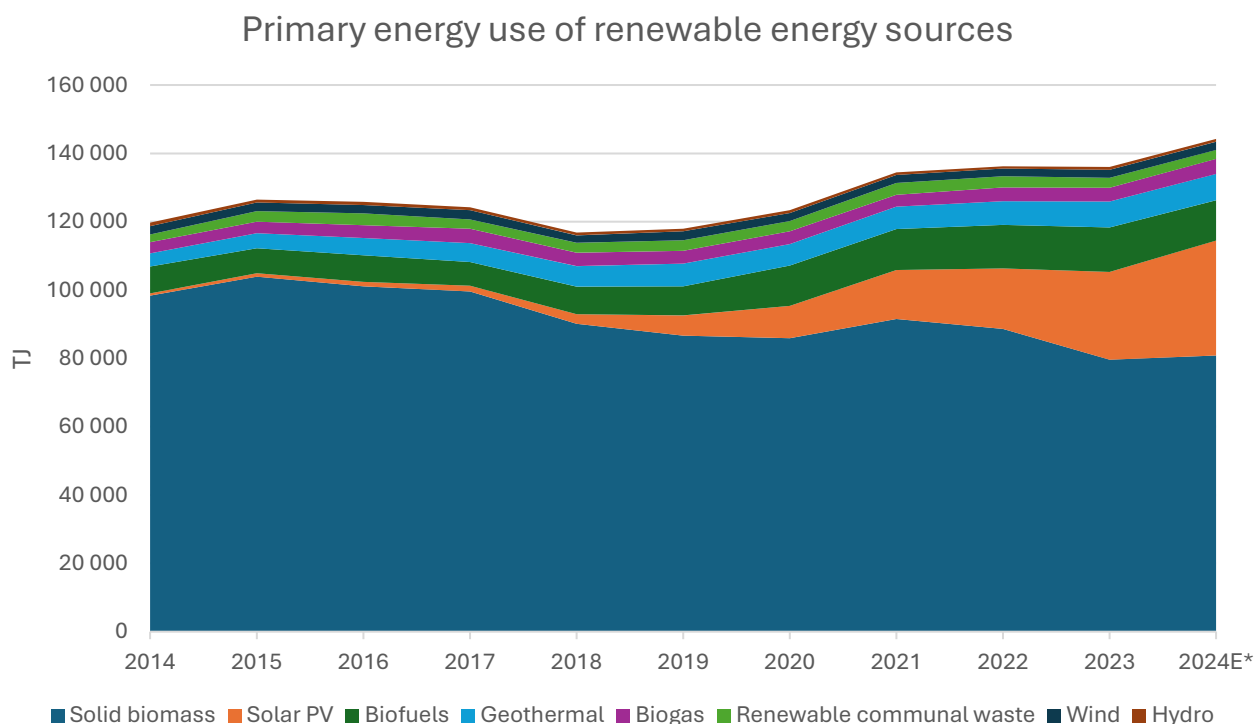
The background to this trend is controversial. Hungarian energy policy has apparently been reluctant to provide intensive central support for renewable energy sources for a long time, not considering it a priority. According to some interpretations, this was a deliberate delay, with decision-making waiting for the predictable price decline of renewable energy sources and the results of European policy 'experiments', so that, building on these, it could effectively provide support frameworks at low cost for

technologies that were already more advanced on the learning curve (Bartek-Lesi et al. 2019a; István Zsoldos 2017) .

In contrast, other approaches suggest that domestic scepticism towards renewables has a deeper political motivation, which is partly due to ideological and attitudinal differences. On the other hand, it is motivated by the desire to ensure the maximum economic and political support for the expansion of the Paks nuclear power plant, which is incompatible with the widespread support of renewable energy sources (Antal 2019). The quasi-complete neglect of wind energy in Hungary is indeed difficult to explain with technical or economic arguments.

There is no doubt that the current structure of domestic renewable energy production is clearly one-sided and does not lean towards 'modern' renewables – see 4. Figure. Domestic renewable energy production is dominated by solid biomass. The combined share of solid biomass, biogas, and biofuels in the total primary use of renewables is almost 70%.

The high biomass ratio is a dubious result in light of the fact that a significant part, almost 80%, is provided by household firewood use, which is hardly a characteristic of a developed, modern, sustainable energy system, especially since it is doubtful to what extent the domestic firewood source can be considered a truly renewable energy source, given the current usage practice (Mezősi, Pató, and Szabó 2017) .



4. Figure Primary energy use of renewable energy sources 2014-2024 (estimate) (MEKH 2025a).

Solar PV policy

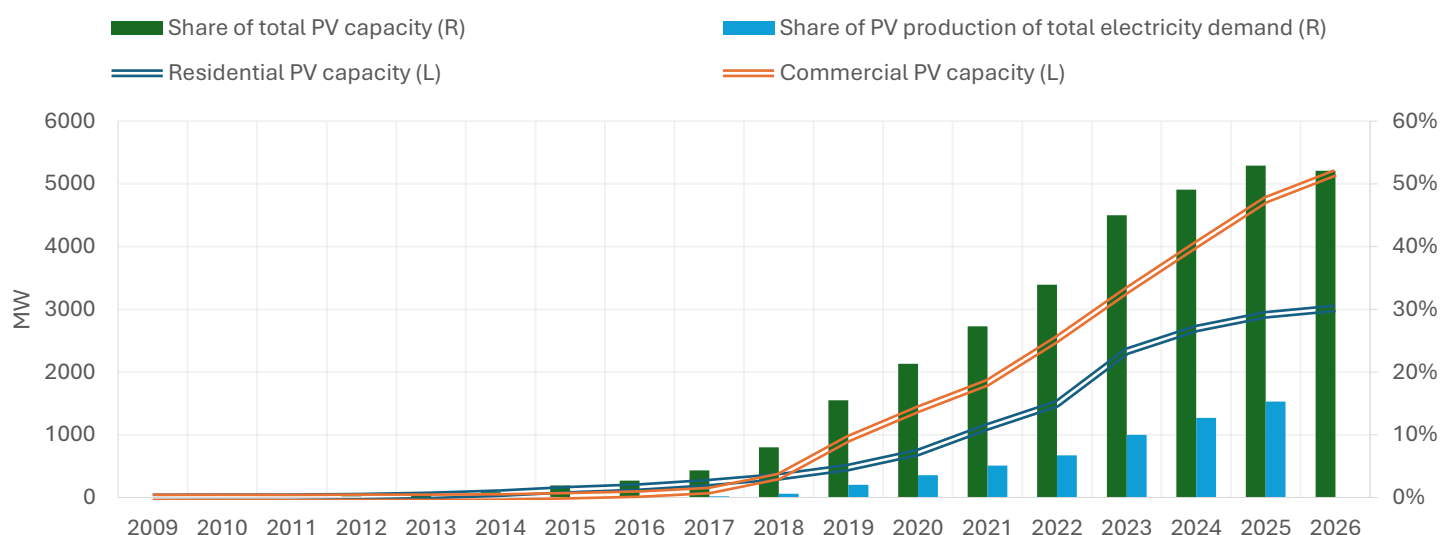
As 5. Figure suggests, the Hungarian legal framework differentiates basically two types of capacities, regardless of the technology used: household-sized small power plants (*Háztartási Méretű Kiserőmű – HMKE*) mainly for residential use with a maximum connection capacity to the small voltage network of 50 kVA (practically 50 kWp power production capacity), and all other capacities above 50 kWp (Act on Electric Energy – LXXXVI of 2007). Latter (so called commercial or industrial solar power plants) capacities belong to three categories, based on their capacity:

- units between 50-500 kW require no license, just notification procedure towards the Distribution System Operator (DSO), similarly to HMKEs; furthermore, these projects are exempted from certain land-use and building regulations;
- between 0,5-50 MW, a combined small-power plant license for establishment and production is required from MEKH (Hungarian Energy and Utility Regulatory Authority - *Magyar Energetikai és Közműszabályozási Hivatal*);

- all power plants above 50 MW require a complete power plant license from MEKH (Gajdics 2021).

Support schemes have either deliberately or implicitly used these thresholds; therefore, it is very common to see commercial (PV) power plants with peak capacities of 499 kW and 49,9 MW.

As presented in 4. Figure and 5. Figure, since 2018, solar PV has started catching up and made up 23% of the total primary renewable use in 2024. Its average growth rate since 2014 is above 150%. The share of solar energy within the electricity sector naturally indicates a similar trend, and in fact, in terms of capacities and not actual production, solar units already represent a clearly visible share at the system level. The figure also shows that the rate of expansion of non-household-sized solar investments has significantly exceeded that of household capacities since 2017. This is fundamentally due to the fact that project costs decreased in 2016 to the extent that the construction of large-scale solar systems was a truly profitable investment within the then-valid support framework, which triggered a wave of dumping-like investments (Bartek-Lesi et al. 2019a).



5. Figure Development of solar capacity and production in Hungary (MAVIR 2026b, 2026a; MEKH 2026a). The left-hand axis shows the actual installed PV capacity broken down into HMKEs (household-sized small power plants) and other licensed and unlicensed solar producers in MW. The right-hand axis shows two ratios: solar capacity as a proportion of the national available electricity generation capacity, and the share of energy produced with solar panels in total domestic electricity demand. 2026 data, when available, is for 2026 July.

The current energy policy targets foresee similar rates of growth for solar capacities. The most recent National Energy and Climate Plan (updated in 2024) projects 12 GW total solar capacity by 2030, practically doubling the 2024 stock. That capacity would

produce ca. 48,000 TJ energy annually (half of the total projected bioenergy use by 2030 or 6% of the total gross final energy demand by then, or somewhat less than the current annual electricity production of the Paks Nuclear Power Plant) (Energiaügyi Minisztérium 2024).

Support policies for household capacities

The initial growth of Hungarian PV capacities is rooted in the residential sector. Commercial capacities overtook household (under 50 kWp) units (HMKEs) only in 2018. While technically, an HMKE could utilise any fuel and technology, solar was already dominant in 2008, since such statistics are available, and quickly became the almost exclusive technology (MEKH 2026a).

HMKEs have received the same operational support from the beginning up until 2023: all residential units participated in the net metering system. The electricity produced was supplied to the grid (where the operator was mandated to take it over), at the same time, the household consumed electricity from the grid, and at certain intervals (usually annually), the volume of the supply and demand of the household was tallied, and the household only had to pay for its consumption over its annual production. This meant that the household could effectively use the grid as its own long-term battery, without losing any of the kWh produced. In case of overproduction, the owner of the HMKE was even compensated at a certain (sub-market) price for the excess electricity, although it had to cover some grid costs (Varga et al. 2024; Gajdics 2021; Atsu et al. 2021).

The relatively stable operational support environment was repeatedly supplemented by investment support programs to help households and kickstart the investments, mostly in the 2020s. These provided either preferential loans or one-off, non-repayable support. Most of these programs coincided with the significant drop in global PV prices, resulting in an investment boom in the late 2010s, early 2020s. By 2024, almost 300.000 HMKE units were in operation in Hungary, almost 10% of the households owning one, surpassing the 2030 target already. This was despite the fact that, due to the strongly subsidised residential electricity price in Hungary, market-based price signals were not a strong incentive.

Hungary was not alone in experiencing such a boom, as in many EU countries, residential PV systems started to become profitable investments with payback periods under 10 years. That also meant that support schemes could be phased out gradually (Varga et al. 2024). The EU Electricity Directive (2019/944) stipulated in 2019 that, as of 2024, no new entrants should receive operational support through a net metering scheme, or any other legislation, that does not guarantee that even the self-producers have to face and cover relevant grid costs, and billing and metering should be separated.

Following that regulation, from September 2023, no newly installed HMKE units in Hungary are eligible for net metering with some limited exceptions³, as it is replaced by the gross accounting scheme. The transition to gross accounting is gradual, as existing projects shift to the new scheme after 10 years of operation. In the gross accounting scheme, the household is billed for its monthly electricity consumption like any other non-prosumer household (including grid fees), and on a separate bill it receives compensation for the electricity its PV system exported to the grid. The current price on which this compensation is calculated is very low (ca. 1 EURcent/kWh) (Varga et al. 2024).

An important aspect of the change in metering schemes is that, under the gross accounting scheme, HMKE owners must also pay a system usage fee for their electricity consumption. Under the net metering scheme, they were effectively exempted, meaning that consumers with no HMKEs installed (who were presumably often less affluent than those with residential PV) had to cover a larger share of the total system cost. This unfairness was one of the key reasons why EU regulation obliged Member States to switch from net metering schemes.

At the same time this new regulation was announced in 2022, grid connection licensing for new HMKE units was suspended throughout Hungary due to concerns about grid capacity and recurring voltage issues in numerous transformer areas. After a thorough grid analysis, in some regions, the suspension was gradually revoked (Portfolio.hu 2025), and later fully withdrawn in August 2025. DSOs, however, can still limit the acceptance of HMKE installation claims for grid security reasons. These developments

³ Those capacities are exempted who submitted their claim to their DSO by 2023 September 13, and the installation is complete by 2026. January 1 the latest. These are also eligible for net metering for the first 10 years of their operation.

certainly eroded households' investment readiness, and while the final rush in 2023 to operate under the net metering scheme did materialise in significant growth in HMKE capacities in 2024, further growth prospects are bleak. To counterweight that, in 2024 the latest investment support program was initiated (Napenergia Plusz) with a total budget of 100 billion HUF, aiming to cofinance 25,000 solar HMKE projects that are either equipped with energy storage solutions or are off-grid (or have backwatt protection) to avoid further strain on the low-voltage grid. In the current legislative and (price)policy framework, residential solar installations that do not receive investment support are often non-marketable; therefore, it is questionable whether the 12 GW total solar capacity by 2030 will be reachable.

Support policies for commercial capacities

While solar power plants have been around since the 1980s, panel prices were too high for decades to enable profitable power production in most countries and regions. Support schemes were required to foster the grid connection of solar capacities. Support options are numerous and should be adapted to the technology and the legal-physical environment, as well as to the desired policy goals (Zsiborács et al. 2023). The first systemic operational support scheme in Europe was introduced in 1991 in Germany, an early feed-in-tariff (FiT) system (Lüdeke-Freund and Opel 2014).

The first similar mandatory off-take support structure in Hungary was created a decade later, in 2002, primarily in order to meet the (indicative) 2010 renewable target undertaken upon accession to the EU (Fodor 2012). After several modifications, this finally became a truly significant support tool under the name KÁT (*Kötelező Átvételi Tarifa* – Mandatory Off-take Tariff) from 2008.

The main purpose of the KÁT was to ensure a return on investment by guaranteeing a fixed purchase price (higher than the market price) for projects prior to the final investment decision. A significant part of the domestic wind energy capacity was established with the support of the KÁT, and the system also supported several biomass-based projects (half of the support went to this technology), but due to the significant bureaucratic burdens and the not very high guaranteed prices, the system was not popular and could only ensure the implementation of 'safe' projects with relatively good business performance (Bartek-Lesi et al. 2019a; Haffner 2018) .

The off-take price depended on the technology used, the recipient unit's capacity, and, most importantly, the production time zone (i.e., valley, deep valley, or peak). Off-take prices were annually increased to take into account last year's inflation (Zsiborács et al. 2023).

Due to changes in EU regulations and the fall in the cost of renewables, it became necessary to transform the system, so the so-called METÁR (*Megújuló Energia Támogatási Rendszer* - Renewable Energy Support System) was launched in 2017. METÁR is a tender-based feed-in-premium system. It pays only a price premium rather than the full takeover price (if the market price at which licensed renewable production is sold in the wholesale market does not reach a predetermined level, the system covers the difference). In addition, initially for projects above 1 MW, and then from mid-2018, practically for all projects, a competitive tendering procedure is prescribed, where producers submit bids for the supported price, and only the most favourable ones are accepted (up to a certain amount or capacity limit), and they are provided with a price premium (Bartek-Lesi et al. 2018).

Both KÁT and METÁR were financed by redistributing their costs among consumers, adding a surcharge to electricity tariffs. In 2013, the residential electricity price was lowered, partially by removing this price component, and since then, only non-residential customers, mostly public and business entities, are burdened with that surcharge. That spurred recurring criticism from the major industrial consumers, especially after 2022, when the rise of European energy prices became a major economic issue in itself, and the non-residential consumers had to cover 0.3-0.4 billion EUR additional costs annually (IEF 2025). That is for 2,900 MW solar and 270 MW other capacity as of the end of 2024, i.e. ca. 10,000 EUR/MW support annually (MAVIR 2025). As a reaction, in 2025 the automatic inflation adjustment was suspended from the KÁT-system, however, the KÁT-licensed power plant owners regard that as an illegal change (Szabó 2025).

METÁR, the tender-based system, was supposed to operate more cost-efficiently than the KÁT. Six tenders have been announced so far, but the fourth was withdrawn, hence only five had results. The fifth (2021 November) was especially targeted at the renovation and repowering of at least partially renewable power plants that have been in operation for 20 years, while the sixth was granting support for projects, which had

a substantial electricity storage (battery) component as well (Lukonits et al. 2022). The five tenders resulted in 930 MW of new licensed capacities (of which 383 were in commercial operation as of July 2025), with a total annual support bill of 6 billion HUF (17 million EUR) (MEKH 2025c). The first tender in 2019 provided lower prices than the previously anticipated (though higher than the EU reference prices) (Diallo 2020; Kácsor 2020); while all-in-all, prices at tenders were 40-55% lower than the mandatory offtake prices of the KÁT system (Zsiborács et al. 2023).

In conclusion, the Hungarian energy policy has placed solar PV at the centre of development plans and support policies for the last one-and-a-half decades. While that development path and the relatively significant resources allocated have succeeded in propelling the Hungarian PV sector to the forefront in global and EU comparisons (see Introduction), biomass is still likely to dominate total gross energy consumption among renewable energy sources.

At the same time, the rapid solar PV investments, both in the residential and commercial sectors, have given rise to ever-increasing issues on grid management, the integrability of those capacities in the local and national networks, as well as potential exaggerated support of certain capacities (especially late-coming KÁT recipients in 2016-2017).

Furthermore, the rapid expansion of solar PV has fundamentally changed the nature of the policy challenge. While earlier policies primarily sought to accelerate investment and increase installed capacity, the increasing penetration of weather-dependent generation has shifted attention towards system integration, flexibility and market value. The rapid concentration of generation in daylight hours has contributed to increasingly frequent periods of low or negative electricity prices and declining capture prices for solar producers. Consequently, further PV deployment increasingly depends on the parallel development of electricity storage, grid infrastructure, demand-side flexibility and market-based mechanisms capable of shifting or absorbing solar generation. In response, the Hungarian government started subsidising not only residential but also industrial electricity storage through the Jedlik Ányos Energy Programme. The policy target was set at ca. 1 GW of storage by 2030.

The ongoing direct policy challenge is to provide appropriate incentives and grid capacity to enable the construction, system integration, and profitable operation of the

foreseen additional 5 GW of solar capacity by 2030. Also, passing the halfway point towards that 12 GW target, as well as a shift in Hungary's political landscape in 2026, is a good opportunity to assess the economic, environmental and social impacts of Hungarian solar developments.

2. IDENTIFICATION OF THE PROBLEM – LITERATURE REVIEW

The impacts associated with the renewables-centred energy transition are profoundly local. Renewables, especially the most common solar and wind installations, are highly decentralised; the energy production and therefore many impacts are highly localised. However, it requires a detailed investigation to see which of the impacts and on what scale are actually local, and what the potential local impact of renewables in theory is. The following sub-chapter provides a detailed overview of the potential local impacts of renewables across the three aspects described earlier: Economic, Environmental, and Social.

In the context of the current Thesis “local” is defined, following (Bajmócy 2011, 21), as the administrative-geographical unit of the municipality (LAU 2) where the actual investments are located. In several explicitly stated cases, the scope of the research also takes into account a wider physical context, i.e. the District (‘járás’ – LAU 1) or County (‘vármegye’ NUTS 3) levels. As local economies are not defined by administrative levels, the local nodes and networks create a more complicated system; data availability limits the potential scope of the research.

2.1. Local economic effects

While studying local Social and Environmental impacts has a straightforward rationale and direct effect on communities’ life and development, focusing on the local economy can be more problematic, especially when the unit of observation is small: the level of communities, i.e. towns, villages, settlements in general. Does a village have its own

economy, its dynamics? Does this local economy affect the locals' everyday life, the local development level, or are they almost exclusively dependent on external forces, since most of the employment, shopping opportunities, subsidies, etc. are external to the boundaries of a small village? Is it worthwhile to develop local, settlement-level economies, or are they too inefficient (in terms of economies of scale)?

Understanding local economies at the settlement and community level is vital for several reasons. Firstly, these are the fundamental units where economic activities occur, offering a granular perspective on economic dynamics that national or regional analyses might overlook. Secondly, studying local economies enables policymakers to tailor interventions to specific community needs, enhancing their effectiveness. Lastly, such studies provide insights into broader economic trends and inequalities, revealing how macro-level phenomena manifest locally.

Empirical evidence demonstrates that local income, especially from local businesses, significantly contributes to economic development in economically more developed countries. The American Independent Business Alliance (AMIBA) found that locally owned businesses recirculate approximately 48% of their revenue back into the local economy, compared to just 14% for chain stores (Civic Economics 2022). This higher local spending multiplier amplifies economic activity within the community. Additionally, local businesses tend to be more labour-intensive, creating more jobs per unit of sales than larger corporations. Neumark et al. (2011) claim that small businesses, which dominate local economies, account for a substantial share of net new job creation.

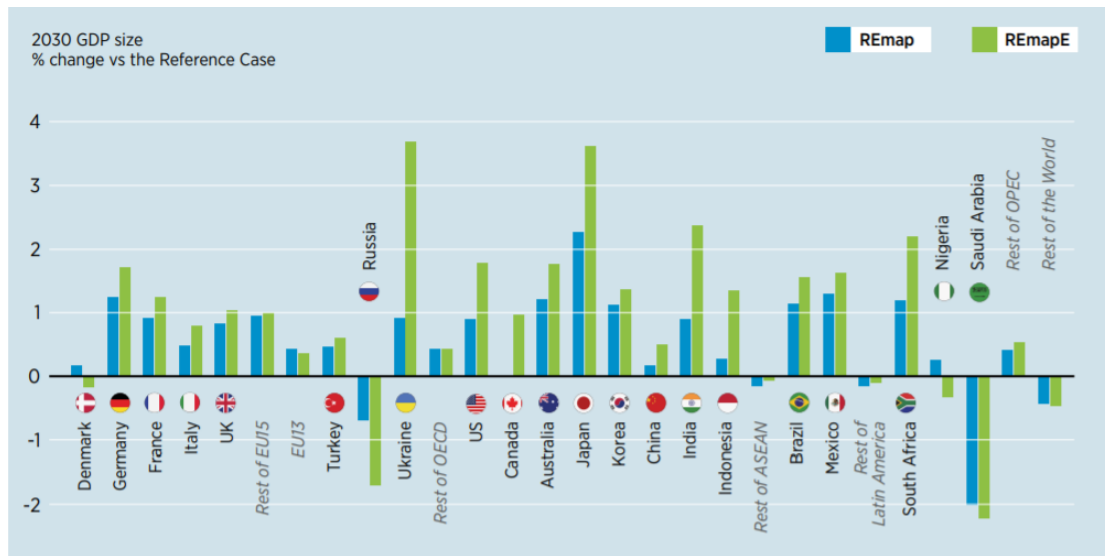
This economic development often translates into social benefits. Increased local business activity generates higher tax revenues, which can be invested in public services such as education and healthcare. For example, thriving local economies in economically more developed nations like Canada and the United Kingdom have been linked to better-funded schools and improved infrastructure (Florida 2018). Beyond material gains, local businesses strengthen the social fabric by sponsoring community events, supporting charities, and providing gathering spaces, which enhance social cohesion and networks. A study on European regions showed that local economic vitality correlates with higher community engagement, underscoring these social dividends (Muringani et al. 2021).

Studying local economies at the settlement and community level is essential for understanding economic dynamics and crafting effective policies, particularly in economically developed nations. Empirical evidence confirms that local income fuels economic development through higher multipliers and job creation, subsequently fostering social development via improved services and community cohesion. Strong local economies can also attract further investment, creating a virtuous cycle. However, more research is needed to refine these insights and optimise strategies for maximising local economic benefits.

2.1.1. Macroeconomic impacts

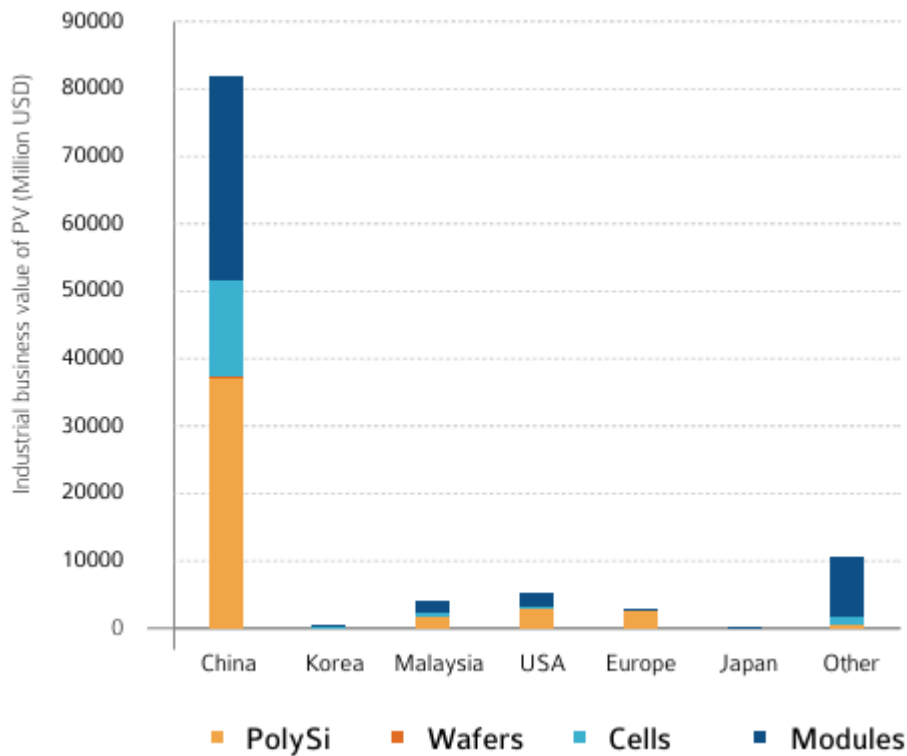
The national economic impacts of renewable energy expansion have been extensively studied in the literature for decades (see for an early example: NREL, 1997, for more recent studies: A. Brown et al. 2016; Inglesi-Lotz 2016; Jenniches and Worrell 2019; Saidi and Omri 2020; Soava et al. 2018; Sahlian, Popa, and Crețu 2021; Ntanos et al. 2018; Asiedu, Hassan, and Bein 2021; Armeanu, Vintilă, and Gherghina 2017). The findings generally - though not universally - attribute a positive GDP effect to the growth of renewable investments, though the effects vary significantly by country and technology. Moreover, the relationship is bidirectional: economic growth also tends to drive an increase in renewable investments. There is, however, a relative consensus that renewable energy investments have positive net economic benefits for most national economies – see 6. Figure.

The economic life cycle of renewables is typically investment-heavy. Unlike fossil fuels, most renewable power plants (excluding biomass) are more capital- and labour-intensive at the manufacturing and installation phase rather than during operation and maintenance, as they do not require fuel input. Consequently, an important macroeconomic variable is whether a given national economy participates in the manufacturing process or is capable of developing domestic production capacity.



6. Figure Expected change in GDP per country compared to the baseline 2030 scenario, according to two renewable energy deployment scenarios (IRENA 2016).

In this regard, currently, China accumulates by far the largest share of the added value and economic impact of the solar industry. Much of the production value chain is concentrated in China, especially for solar PV, as illustrated by 7. Figure. 65% of the total employment in the global PV industry is in China, while the country has ‘only’ 43% of the total global built-in capacity. The EU PV industry employs only 10% of the workforce of the global industry, while 21% of the total capacity resides there (IRENA and ILO 2024). In 2023, China produced 85% of PV modules, 92% of PV cells and 98% of silicon wafers globally (Masson et al. 2024).



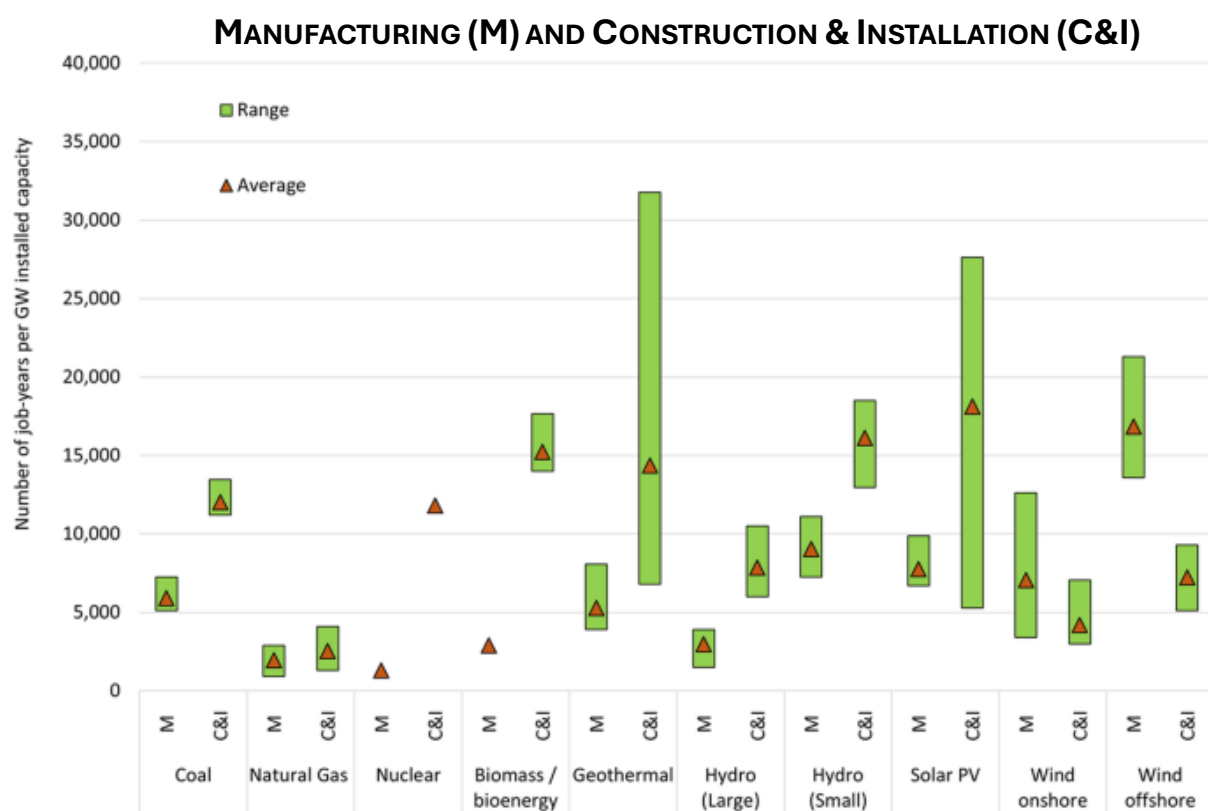
7. Figure Share of different countries and regions on the total industrial business value of the global PV industry, with China dominating (Masson et al. 2024).

The literature extensively examines the job creation potential of the renewable sector, with many studies focusing on macroeconomic impacts through employment effects. The net employment impact of the energy transition can be measured by comparing the jobs lost due to the decline of traditional energy industries with those created in the renewable sector. Studies show that while renewable energy expansion does not necessarily lead to overall job growth, some research has found net positive effects, though strong conclusions cannot be drawn, especially if one factors in not just the direct, but the induced employment effects (Llera Sastresa et al. 2010; Stavropoulos and Burger 2020).

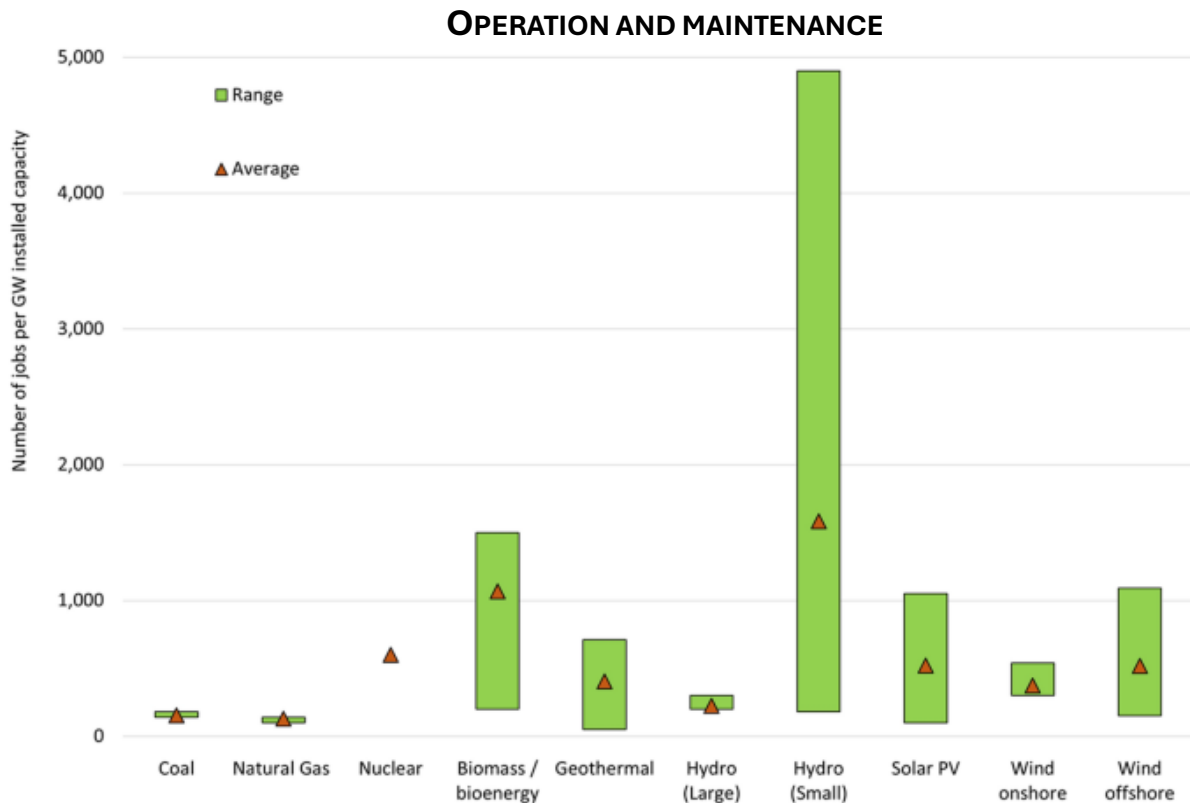
The employment effect varies by technology. Wind energy tends to generate fewer jobs per unit of electricity produced, whereas solar and biomass are more labour-intensive but at different stages of their life cycle. In solar energy, the investment and installation phases dominate employment, whereas in biomass, fuel provision is the primary job creator (Aldieri et al. 2019; IRENA 2016; Ortega et al. 2020; Ramos et al. 2019).

Though for solar, the Construction and Installation segment is more labour-intensive, this does not mean a higher added value in those activities compared to manufacturing

or operation – see 8. Figure (Hanna et al. 2024). However, this can suggest that, at least in terms of employment impact, solar can have relatively large local effects, as construction and installation are more localizable activities than the technology-intensive and concentrated manufacturing. On the other hand, in terms of operation and maintenance, solar PV leads to larger (and also localizable) employment only compared to traditional fossil fuels in terms of installed capacity – see 9. Figure. In terms of jobs created by a unit of investment, solar PV does produce significantly more jobs than fossil fuel-based power sources (roughly two times as many), although less than other renewables or energy efficiency (Hanna et al. 2024).



8. Figure Employment effects of different energy sources in the Manufacturing (M) and Construction & Installation (C&I) segments of the life-cycle from the literature meta-analysis by Hanna, Heptonstall, and Gross (2024).



9. Figure Employment effects of different energy sources in the Operation and Maintenance segment of the life-cycle from the literature meta-analysis by Hanna, Heptonstall, and Gross (2024).

1. Table shows three Life Cycle Cost Assessments of large-scale PV installations conducted on three distinctly different dates and in three different markets: Abu-Rumman, Muslih, and Barghash (2017) examined a potential project in Saudi Arabia, Ranganath and Sarkar (2021) compared 6 Indian PV projects, and Ramasamy et al. (2023) provide a general overview of the US market. Although there are some differences between the studies in cost clustering, it is apparent that most of the life-cycle cost is comprised of the hardware input, especially the PV panels and the inverters (a large part of the Electrical apparatus).

	Abu-Rumman et al. (2017)	Ranganath & Sarkar (2021)	Ramasamy et al. (2023)
Development	4%	2%	6%
PV Panels	34%	26%	35%
Electrical apparatus	17%	34%	28%
Civil Work & Installation	18%	14%	8%
O&M (20 years)	27%	24%	23%

2.1.2. Local economic impacts

The macroeconomic impacts of renewable energy investments are not only thoroughly studied but also are at the forefront of policy-making discussions – see the recent Net Zero Industrial Act in the EU, the state support tools in the US, like the Build Back Better Act and the tariffs imposed on Chinese solar technology imports.

Local (i.e. sub-national) economic impacts of renewables got less academic and policy attention, even though, according to Jenniches's systemic literature review (2018) local economic analyses could help:

- local decision-making, as local and regional government structures can often have an influence on the legal or public policy and attitude context, in which investments happen;
- increase local acceptance;
- understand how regional effects differ from national ones in cases where physical potentials or pre-existing barriers (low capital) or enablers (concentration of skilled workers) are not spatially equally distributed.

What Jenniches (2018) doesn't mention, but some analyses put an emphasis on (see Benedek et al. 2018; IEA 2016; Clausen and Rudolph 2020; Copena and Simón 2018; OECD 2012; Cebotari et al. 2017) is the rural development potential of renewable investments, i.e. how focusing on the local component can help peripheral regions to benefit from local renewable energy investments.

For that to happen, however, local communities or local economies (defined variously in the literature from the regional scale to municipalities or even in the case of cities as neighbourhoods) need to have access to the direct and indirect economic benefits provided by those investments.

The main question of this current chapter, and part of the existing literature, is how and to what extent that happens in a free market environment without significant state intervention.

To answer that question, it is paramount to have a clear understanding of the ways, methods, and tools through which renewable energy investments can have an impact

on local economies. Jenniches (2018) gives an overview of the economic impacts studied in the available literature (54 papers, covering mostly the US, Germany and a few having Austria, Spain and the UK as their spatial focus; 11 studies had their spatial scale on LAU 2, i.e. municipality level; 20 paper targeted solar PV investments, while most of the studies dealt with wind energy projects):

- almost all of the papers (50 out of the reviewed 54) take into account the local employment effect of renewable investments;
- 59% of the publications analysed local tax income;
- 20% took into account the revenues of the owner of the plants and a similar share of the proprietor income of firms.

J. P. Brown et al. (2012) lists the pathways through which a renewable energy project can impact the local economy, i.e. lead to local economic benefits.

- Employment during construction and operation.
- Construction and operation generating demand for potentially locally sourced goods and services (food, consumables, construction materials etc.).
- Lease payments to landowners if the wind turbine owner is not the landowner. The opportunity cost of using the land for other (likely agricultural) activity must be netted with this impact.
- Profits if wind turbines are locally owned. Opportunity costs need to be taken into account in this case too.
- Local taxes.
- Secondary or spill-over (multiplier effects) resulting from the extra local spending from the extra income from the sources listed above
- The effect of the investment on local tourism, land and property prices, and people's willingness to move to/stay in the settlement.
- Any economic change/benefit for nearby communities and the potential feedback loops.

Heinbach et al. (2014) conduct research on the local economic value-added of renewable energy technologies on the municipal level. The paper states that local added value is comprised of three inputs, basically clustering J. P. Brown et al.'s (2012) pathways into three main, easily monetizable categories:

- (1) After-tax profits of the participating enterprises
- (2) Net incomes of the employees involved
- (3) Taxes paid on business profits and on adjusted gross employee income.

Aside from describing the ways of local economic impact, the other key methodological challenge is in defining the spatial scope, as it is often unclear at which geographic scale renewable energy investments produce their impacts and how to delineate territorial units for analysis within national statistical frameworks.

Different renewable energy technologies have different spatial dimensions: biomass energy production depends on feedstock collection areas; wind power plants require relatively small areas for construction while having external effects over larger areas (e.g. visibility, changes in local climate). Solar panels can be installed on rooftops in the scale of m² or in natural environments on the scale of km². In addition to location, the technology applied and the size of the investment also significantly influence local economic effects (Jenniches et al. 2019; Jenniches and Worrell 2019; Ramos et al. 2019).

As a result, there is no single approach in the literature; the spatial focus of studies is mostly defined by the methodology and the data availability. Jenniches (2018) processed 21 different empirical studies in the EU with spatial foci ranging from NUTS 1 (countries or major socio-economic regions) to LAU 2 (municipalities).

Empirical results on local revenue potential

Wind energy is generally more studied for its local impacts, as the local negative externalities are much more readily present, and therefore local acceptance is a much more sensitive issue than in the case of large-scale solar investments (Jenniches 2018). Although there are certain technological differences in the adoption and operation process, it is common for both wind and solar energy (as shown before) that manufacturing is hard to localise, while operation requires no constant feedstock and supply, just maintenance, and both are intermittent with relatively low typical load factors (10-20% for solar PV and 20-40% for onshore wind). Therefore, findings related to onshore wind energy are at least indicative of large-scale solar investments as well (offshore wind, arguably, is generally irrelevant in local economic terms).

An early group of empirical studies on the local economic impacts of renewable energy investments are the ones conducted on Scottish wind and biomass energy projects in the early 2010s. In Scotland, locally (community) driven renewable energy investments have emerged early and currently constitute a noticeable, yet by far not dominant share of the total built-in capacity (more than 1GW out of the 15 GW total renewable capacity), while the official target is 2GW by 2030 (Energy Saving Trust 2024). Slee and Harnmeijer (2017) argue that one of the main causes for the Scottish community renewable energy wave was the 2003 Scottish land reform, which enabled (incentivised) local communities to acquire land. However, the communities soon realised that while local ownership of the land was sentimentally and culturally positive, turning the low-quality agricultural lands into economically prosperous assets was hard. The introduction of renewable energy support schemes in the UK provided a lifeline for these communities by offering a new way to utilise commonly owned land (mostly for wind turbines).

Allan, McGregor, and Swales (2011) find for a Scottish onshore wind farm project (through using a Social Accounting Matrix for the 2003 revenues and expenditures) that with 0% local ownership, depending on the scenario, 76 or 96% of the profit is expatriated from the area. “With zero ownership, the impact on Shetland GDP is £77 million, with an increase in local employment of 270. In contrast, 50% of ownership revenue retained locally gives a total GDP impact of £118 million and increases employment on Shetland by 1,625 FTE jobs” (Allan et al. 2011, 1811).

Van der Waal (2020) claims on Scottish wind farms that without direct community involvement (including ownership), a wind farm can provide a community benefit fund of around GBP 3000–4000/MW to compensate for the negative externalities and about GBP 10,000/MW rent for the landowner. Meanwhile, a community scheme can generate over GBP 100,000–150,000 per MW per year.

However, extra local income does not necessarily mean sustainable local economic development. Phimister and Roberts (2012) in their own study on Scottish wind farms confirm that local ownership increases local income, but emphasise the importance of the usage of the extra income produced by local ownership. “In these simulations, where extra income is used primarily for extra consumption, most leaks out of the regional economy with no extra benefit. [...] significant spill-over effects from wind

developments only occur if additional factor income associated with local ownership is reinvested in the local economy” (Phimister and Roberts 2012, 351).

Slattery, Lantz, and Johnson (2011) in their analysis of Texas wind power investments, they find that in some cases, wind power plants can be built with little local (in this case, 100-mile radius or state level) economic value, and local ownership in wind projects can increase construction and operation period jobs 1-3 times.

Delicado, Figueiredo, and Silva (2016) find that Portuguese wind farms and solar power plants are mostly (70%) owned by large national and international companies, which are generally seen as the main beneficiaries of the local exploitation of renewable energy sources, while locals can have the perception of being subordinated to external (national or large enterprises) interests. Argenti and Knight (2015) use the concept of Extractive Economies on solar and wind investments by foreign (or non-local) companies in Greece in the context of major international players using local land for the advancement of their own economic benefit.

Brouwer et al. (2025) examined Dutch wind energy projects and found that those were realised quicker and with less local resistance than those that had at least some local ownership in the form of renewable energy cooperatives (REScoops). That is, however, just a recent example in the literature that confirms that local (economic) benefits (and their perception) are among the most influential factors, if not the most influential factor, in local acceptance of renewable energy projects (see the recent meta-analysis of Milani, Dessi, and Bonaiuto (2024)

While studies on wind energy are more abundant, the research on solar PV (mostly on commercial-scale projects) is in line with the findings on the local added value of wind energy, i.e. that local ownership is the key factor. Heinbach et al. (2014) find that for the modelled standard German city, the total local value added is highest for PV plants, almost 4 million EUR, of which less than 1.4 million EUR (34%) is after-tax profits, nearly 2.3 million EUR (57%) is net income, and 0.3 million EUR (9%) is local taxes. The paper concludes that “for example, a municipality with a wind farm within the municipal boundaries but no local companies or investors will only profit from part of the trade tax and the lease income. The largest share of the value-added effects will flow off to other regions” (Heinbach et al. 2014, 8). However, it needs to be noted that the study estimates the local added value for a hypothetical ‘standard’ German

municipality of 75,000 inhabitants with the same renewable manufacturing capacity and built-in renewable capacity as the 2011 German national per capita average. In the study, most of the net income (i.e. the wages) comes from Systems Manufacturing (component production), which, however, currently happens basically 100% outside not only the local and municipal economies but also, in the case of Hungary (and many other countries) external to the national economy itself too. It is unreasonable to hold the assumption any longer that a typical German (and even more Hungarian) city would have its own PV manufacturing capacity of any kind, with few exceptions. Therefore, most of the net income in the case of PV can be neglected, leaving after-tax profits as the main source of value addition, with some local taxes in addition.

Jenniches and Worrell (2019) follow-up on Heinbach et al. (2014), and examine the potential regional economic effects of different-sized PV plants in Städteregion Aachen using 2014 data. The values are modelled based on a life cycle approach and are not the result of empirical measurements. The spatial scope is a 700 km² large region with almost 600,000 inhabitants. The analysis separates the three phases of the life cycle (Planning, Operation & Maintenance, and Decommissioning) and summarises the generated local income by industry as shown in 2. Table. The research investigates three sources of money streams: profits, income (i.e. wage), and local (regional) taxes, following (Heinbach et al. 2014).

Stage	Industry	Profits	Income	Taxes	Share total	of Person-year
Planning	Planning companies	0.3%	1.0%	0.1%	1.4%	0.4
Planning	Wholesale companies	0.5%	1.4%	0.2%	2.1%	1.7
Planning	PV installation companies	0.5%	3.0%	0.2%	3.8%	1.6
Planning	Grid service companies	0.4%	0.5%	0.1%	1.0%	0.2
O&M	Financial institutions	1.1%	1.4%	0.3%	2.8%	0.5
O&M	PV installation companies	1.1%	6.6%	0.5%	8.2%	3.5
O&M	Wholesale companies	0.2%	0.6%	0.1%	0.9%	0.3
O&M	Grid service companies	0.1%	0.1%	0.0%	0.1%	0

O&M	Plant operators	19.3%	11.0%	2.9%	33.3%	4
O&M	Insurance companies	0.0%	0.1%	0.0%	0.2%	0
O&M	Landlords	38.2%	0.0%	1.7%	39.9%	0
O&M	Tax advisory companies	0.6%	1.8%	0.2%	2.5%	0.7
Decommiss.	PV installation companies	0.5%	3.0%	0.2%	3.8%	1.6

2. Table Modelled total money streams of the PV plants larger than 100 kW (n=8) in the region operating in 2014 for 20 20-year lifespan (Jenniches and Worrell 2019).

The results show that the largest added economic value is controlled by plant operators (i.e. owners) and landlords, covering almost 75% of the total value. However, land-lease income can be somewhat exaggerated, as the study presumes the lease of rooftops, assuming 33 EUR/kW/year rental fee (roughly 3,5 EUR/m²). However, for most commercial PV plants, it is more customary to be ground-mounted, mostly on agricultural land, with much lower land-lease rates (as an illustration, land-lease price for Hungarian arable land in 2014 was ca. 4 HUF or 0,01 EUR/m²). Assuming the project owner is either the owner of the land used itself or the lease is significantly smaller, the plant operator's profit rises significantly.

These studies show the importance of ownership in the localization of value-added: the control over profits from the operation, as well as the land/real estate the plants require, means controlling those direct money flows which are most commonly available for smaller municipalities or even regions having no or marginal involvement in the manufacturing or even the construction industry.

There are several other studies confirming that statement. Nakayama, Raupach, and Morotomi (2016) in their study replicating Heinbach et al. (2014) in the Japanese environment state that the largest part of the value added is after-tax profits of participating enterprises and local ownership through an increase of the local investment ratio is, therefore, the most important factor for regional value-added creation and regional sustainable development.

Suwa (2020) confirms this, but it mostly derives this conclusion based on local tax income (which is significantly higher in Japan than e.g. in Hungary on the municipal level, see (Raupach-Sumiya et al. 2015)), finding in 2012 a 20-22% rate range for Japan and a 13-15% rate range for Germany on the share of tax income from the system operation of PV plants.

Inagaki (2018) (cited by (Suwa 2020)) used financial information to analyse corporate level value added of two particular renewable energy projects in Japan, finding that in the case of the PV project, 25% of the value added can be localized by local ownership (7% local tax, 18% net profit), and the case of a small hydropower plant, the figure was 68% (5% tax, 63% net profit). The rest of the added value was employee salary, which can also be localised to some extent, but that is less subject to local ownership.

Kienbaum and Farrell (2023) model the net present value (NPV) of a household and a large-scale (1300 MW) solar project in the US differentiated by local self- or community ownership and external ownership. They find a multiplier on the NPV for local entities of roughly three for local ownership as opposed to non-local ownership.

Clausen and Rudolph (2020, 3) in their study comparing the literature on Danish and Scottish community-based renewable energy investments, they find that “Local and regional income streams during the operation phase, without financial participation of local stakeholders and community benefit schemes, are usually limited to tax revenues, lease payments for landowners, and job opportunities for local businesses.” They also note that while income can be generated through ownership in the projects or the land, it is up to the goodwill of the land- and asset owners to use these incomes within the framework of the local economy initiating local economic development.

The literature focuses on large, commercial-scale investments, units producing for the grid mostly when researching potential local economic impacts. While the costs and revenue structure for residential and commercial scale investments cannot be scaled linearly, the ‘profit’ in both cases stems from electricity production at similar rates (similar number of hours and conversion efficiency). Assuming that residential PV-owners can offset the retail price of electricity by autoproducing, and the commercial-scale producers receive the retail price, their profit rate is practically the same.

2.1.3. Findings for the Hungarian case

So far, no comprehensive empirical analysis has been conducted in Hungary on the local economic effects of renewable energy projects. Some previous studies have touched on related topics but have not directly examined local economic impacts.

Some studies provide a somewhat, but not fully localised overview of the potential impacts, like Czene and Ricz (2010), who outlined the theoretical possibilities of local

economic development impacts (such as job creation, reduced energy costs, increased property values, and mitigation of energy poverty) but did not conduct an empirical investigation, although they briefly introduced some pilot energy-producing projects as case studies. Koncz and Nagyné Demeter (2015) described the social and community impacts of local renewable energy investments and analysed the concept of renewable energy regions through a literature review. Koncz, Deme, and Kerényi (2015) performed a similar literature review on the connection between renewable energy and rural development without conducting an empirical study.

The Hungarian public sector is decentralised, and municipalities have a relatively strong yet declining role and capacity to lead local energy communities and to attend to the potential benefits of local investments. Mezei, Suvák, and Varjú (2013) conducted a survey-based study on the role, opportunities, and activities of municipalities in supporting local sustainable energy expansion. They find that surveyed Hungarian municipalities often see themselves as relevant and important players in local energy developments. Therefore, even if capacities are not always provided, municipalities should be considered local actors.

The Hungary-focused literature is also scarce on analyses of the macroeconomic impacts of renewables. Koncz (2014) examined the economic development potential of renewables at a micro-regional level, but the study primarily focused on general energy production potentials rather than the direct and indirect economic impacts of energy generation. Černý et al. (2022) find in their EU-wide assessment on the employment creation potential of renewables, that Hungary is expected to see the highest share of job growth in the renewable energy sector, however the capital formation performance of the Hungarian renewable energy industry will be among the worst in the EU, suggesting, that employment increase will focus on economic activities with low added value.

As the Hungarian rural economy and employment, especially in the least developed regions, are still connected to agriculture, some studies focus on bioenergy, especially agricultural biomass. Lukács (2009, 2011) conducted a comprehensive analysis of local, agriculture-based energy production potential (biomass, biogas, biofuel), and the effects on local energy communities, with a specific focus on rural development and policy recommendations, yet without actually conducting empirical analysis strictly

on the economic impacts. Magda (2011) also focuses on the general potential of renewables (biomass mostly) in rural development. Kohlheb et al. (2010) find that biogas plants have the highest employment potential, but the jobs created are primarily related to the production of the feedstock. Among the higher value-added operation and installation activities, only hydropower plants are clearly more labour-intensive than PV systems.

Concerning solar PV, Zsiborács et al. (2019) analyse the profitability of a hypothetical grid-connected PV plant in Hungary within the framework of the Hungarian policies and support schemes. Zsiborács et al. (2023) extends that by focusing on the permitting and construction process of large-scale solar PV investments, however only from an administrative and legal point-of-view. Lados, Somossy, and Tóth (2020) use survey results to describe the different factors behind the location decision of solar power plants in Hungary, finding that in projects without state subsidy, investors are looking for cheap land with good access to the electricity grid.

2.1.4. Summary

Renewable energy investments represent a significant share of the global GDP and the national GDP of many countries, and this share is only expected to increase. These investments have two distinct, contradictory localization potentials.

On one hand, the manufacturing segment is highly centralized to certain regions of China, and local value-added from the input materials and systems manufacturing is practically non-existent for most countries, regions, and especially sub-regional entities, like municipalities.

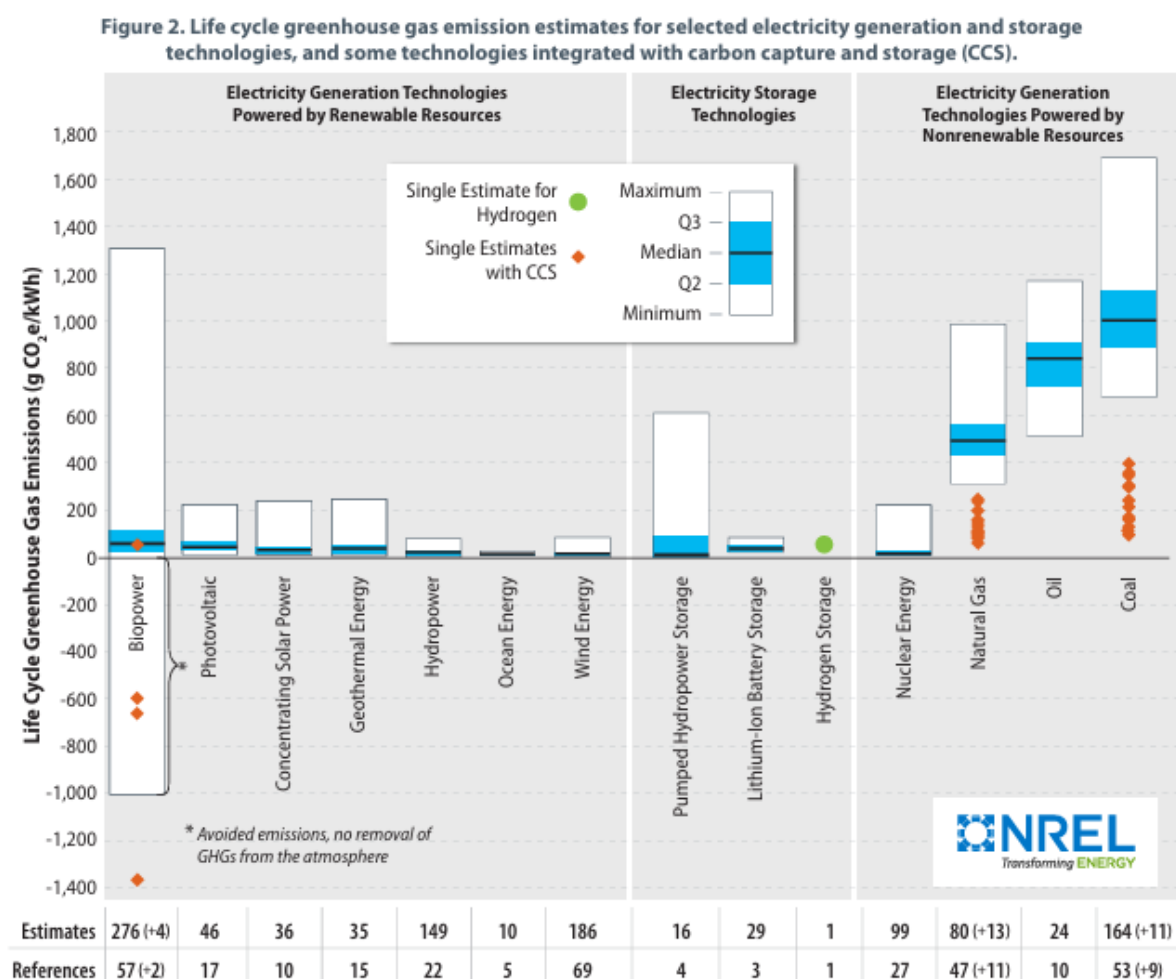
On the other hand, to a lesser extent, installation and operation, and to a larger extent, the ownership can be localized to the lowest administrative levels, allowing even small communities to participate in the investments and/or to reap their benefits. This requires any of the following to be true for the particular investment:

- The companies planning and installing the capacity are locally owned and/or employ local workforce.
- The companies providing operational services are locally owned and/or employ local workforce.
- The owners of the capacity are local actors.

- The local community can receive taxes from either the construction or the operation of the units.

2.2. Environmental impacts

Renewable energy sources are at the centre of the energy transition for their supposed positive environmental performance relative to fossil fuels, mostly in terms of Greenhouse Gas Emissions. GHG emissions from renewables, even when considering their full life cycle (including mining of minerals, production of energy-intensive parts like silicon wafers or wind turbines, transportation, etc.), are considerably lower than those of fossil fuels, as shown in 10. Figure.



10. Figure Life-cycle greenhouse gas emission estimates for selected electricity generation and storage technologies (NREL 2021).

As Nugent and Sovacool (2014) find, 71% of the total life-cycle emission for PV plants comes from the fabrication of the components (mostly the solar panels themselves, including mining and pre-processing of the required input materials), 19% from the actual construction of the plant and only 13% from the operation (cleaning, repairs, replacement).

The manufacturing of PV components is a geographically highly concentrated sector, with China controlling 74-96% of the total manufacturing capacity of the different steps, and Europe controlling only 3-8% (IEA 2022). There are no up-to-date figures for Hungary, but a recent sectoral report lists no active companies located in Hungary along the PV manufacturing value chain (Fraunhofer Institut 2024).

Most of the construction-related emissions are from the transportation of components as well as the input materials and the manufacturing of mounting, wiring, switches (any component external to the panels themselves), usually referred to as the Balance-of-System (Nugent and Sovacool 2014).

Therefore, in the case of most Hungarian PV investments, the manufacturing and most of the construction aspects are negligible from the perspective of local environmental effects. For construction, only the emissions from final-mile transportation and from site clearing could be accounted for on the municipal level mostly, however that is rather negligible (Szilágyi and Gróf 2020).

Decommissioning, in general, is an issue after 15-25 years of useful lifetime; therefore, in Hungary, the first years when large amounts of PV-waste will need to be managed can be expected for 2030 at the earliest. Currently, there are no companies specialised in managing PV waste, except for glass, and currently, most of the waste is either deposited or burnt (B.H.L. 2024).

As the manufacturing, construction, and decommissioning have no or only minor local impact (and similarly, decommissioning likely also has negligible local effects as panel recycling/dumping happens spatially concentrated in a few locations), the focus of any analysis on the local (sub-regional level) impacts should be on the potential effects of the operation.

From an environmental perspective, the largest impact large-scale commercial PV plants can have is through their size: one MW capacity requires a land area on the

scale of 20.000 m² or 2 ha. There is no evidence that electromagnetic radiation, noise, water consumption (apart from some extreme cases), or other effects arising from the actual operation would be significant (Tell et al. 2015; Bošnjaković et al. 2023).

Small-scale rooftop installations can have even less local environmental impact, especially negative ones, as their size is small and they are predominantly located on artificial surfaces. However, rooftop PVs can not only reduce emissions globally or on the level of the national economy (where GHG reduction matters), but by replacing conventional heating modes, especially heating with solid fuel, they can theoretically contribute to the reduction of locally (too) relevant emissions, like NO_x and SO_x, and PM_{2,5-5-10}.

Hence the current chapter focuses on two main issues:

- the land-use effect of commercial-scale solar power plants;
- local emission reduction enabled by rooftop PV installations.

2.2.1. Land-use change by commercial-scale PV plants

The life-cycle greenhouse-gas footprint of solar power is low compared to traditional sources of electricity generation. Its physical footprint, the area it requires per unit of capacity or generation, is, however, larger than those (IRENA et al. 2026)). Van Zalk & Behrens (2018), in their meta-study of life-cycle-based studies, find that while solar power has the highest power density among renewable sources, it is still below that of nuclear and fossil fuels by two orders of magnitude. Nøland et al., in their subsequent study, put the land required for powering the global economy exclusively by solar power at 1.26% of the total landmass, two orders of magnitude more than what would be required by conventional energy generation (2022). It should be noted, however, that Nøland et al. do not use a full value-chain approach for nuclear and natural gas power; they assess only the spatial density of the power plants themselves, rather than the broader value-chain data for solar power. The meta-study by UNECE (2022) finds a smaller difference between traditional and renewable sources: while the most widespread option of polysilicon ground-mounted PV, they find 13.7-40 m²/kWh with a mean only slightly higher than hard coal, but again more than one magnitude higher than nuclear or natural gas.

While there are no studies for Hungary measuring energy density, a related estimate puts the land requirement for harnessing the total technical solar capacity in Hungary (a total of 26.2 GW) at 1% of the country's total area (Energiaklub 2022). This is not a life-cycle-based approach, but it can illustrate that, from a local perspective, total value-chain land use is less relevant than the land use most impactful for the given locality. And in most cases, since PV's land use is most visible in the operational part of the value chain, in most countries, especially Hungary, this and the associated impacts shape the perception of society and policymakers.

Those land-use figures suggest that it is reasonable to raise the question whether there is a potential conflict between different essential land use purposes like agriculture, forestry, nature protection, and energy infrastructure, in this case, PV (Ascensão et al. 2023; Nordberg et al. 2021). As the subsequent literature review shows, conflict is not inherently necessary and is highly dependent on the design, technology and the *in situ* natural environment of the individual solar projects.

Zhang et al. (2024) conducting a similar analysis to this paper, but using global and 2018 data, estimates that as of 2018, 4.9% of the total large-scale solar PV capacity (in terms of area) installed globally has a potential land-use conflict with forests (i.e. built by either replacing previously forested areas or in previously deforested areas).

A more recent analysis by Kiesecker et al.(2024) on wind and solar land-use conflicts in the EU posits that by 2050, meeting the EU targets on renewables will require land used by onshore wind and PV installation roughly equal to the size of Sweden. They use a custom classification that divides land areas into conflict and low-conflict territories based on their initial land use and inherent natural value. The paper finds that the land area required for those investments is available in low-conflict areas, although the suboptimal siting would require an increase in total territory by 7-16%.

Ascensão et al. (2023) find that the majority of commercial-scale PV projects on the Iberian Peninsula are located in areas with high Human Footprint Index, i.e. areas less likely to have higher biodiversity and lower ecological value. However, still 10% of the projects are located in protected areas, mostly Natura 2000 sites.

As Van de Ven et al. (2021) point out that the land-use conflict has a potentially negative spill-over to other areas. In their analysis, they find that in different energy production scenarios for 2050 in the EU, 0.5-2.8% of the land area will be occupied by

solar installations, at the maximum, covering a slightly larger area than all urban land coverage was in 2010. As most of the new PV capacity is expected to be located on managed land (used for agriculture and timber production), the original activity needs to be replaced with other, previously unmanaged land areas, likely not inside the EU, but elsewhere, increasing the demand for imported goods and hence increasing the production area of these goods, mostly in previously unused, in many cases forested areas.

II.2. Land-use impact of commercial-scale PV

A greenfield commercial-scale PV installation can have many potential, theoretical impacts on the environmental quality of the land it is situated on (Bošnjaković et al. 2023; IPCC 2022; IRENA et al. 2026; Tawalbeh et al. 2021):

- the construction usually starts with land clearing and soil compacting that significantly reduces incumbent vegetation (at least temporarily);
- the shade of the panels can also limit or change vegetation growth, and impact biodiversity;
- panels change the albedo, the local temperature, wind and precipitation dynamics, and humidity levels, altering the local micro-climate;
- PV power plants are often fenced, limiting wildlife access to the area, including nesting opportunities;
- regular washing of the panels introduces extra water, though its distribution is not uniform;
- the soil that is otherwise left mostly undisturbed and underutilised (agriculturally) can regenerate under the panels; fire hazard can be reduced, and more intensive grazing can contribute to food supply.

However, the current literature offers only a few empirical studies that measure the actual impact of solar investment on the ecological value of the land it occupies.

Zaunbrecher et al. (2018) focus on wind and biomass installations, using Corine Land Cover data to assess the potential land-use effect of certain technologies. Although the paper does not examine commercial-scale PV parks, it suggests that the self-

defined ecological value of pastures and forests where wind power was installed was reduced to half or one-third of that in undisturbed areas.

Concerning PV, Szilágyi and Gróf (2020) in their case study on the life-cycle environmental footprint of a Hungarian commercial-scale PV find that around 90% of the total footprint is related to the production of the components of the panels and the metal structure, and claim that the local environmental footprint of construction, auxiliary buildings, transport of components, installation, and soil preparation is negligible. Mehedi, Gemechu, and Kumar (2022) come to a similar conclusion as Szilágyi and Gróf on the relative irrelevance of land-use change in the total carbon footprint of solar investments.

Similarly, Zhang et al. (2023) find in their literature review that the effects of a solar power plant on soil parameters were generally not significant. Actually, “in most studies, solar power plant construction has been found to increase plant productivity (as aboveground biomass) and vegetation cover, except for in woodlands, where woody plants are removed during construction” (Y. Zhang et al. 2023, 6). This is mostly due to changes in the local climate. However, the impact on biodiversity varies much more among studies, with more papers reporting negative effects.

On the other hand, the preliminary results of a study on several large-scale Hungarian solar parks show that the Biological Quality of Soil value was lowest under the panels, while larger in the rows between the panels, and in the reference fields, showing that not only the construction reduces soil quality, but the shading and rain-exclusion of the panels themselves hinder its regeneration (Seres et al. 2024).

Some European case studies (Lambert et al. 2022; Moscatelli et al. 2022) suggest negative, although not dramatic effects on vegetation and soil quality due to PV cover (either compared to abandoned land or comparing the gaps of the panel rows to the areas under the panels). Vervloesem et al. (2022) find that intensive wheat production has a greater land-use impact than a PV installation, due to the intensive use of fertilisers and pesticides, water management issues, and the general environmental problems associated with monocultural and industrialised agriculture. De Marco et al. (2014) find in their case study in an Italian region that commercial-scale solar power plants reduce the CO₂-sequestration capability of the land they are constructed on. However, this is significantly offset by the avoided emissions from the clean electricity

production. Hernandez et al. (2014) also suggest that the impact on ecosystem productivity and carbon accumulation depends on the preexisting land cover and land use, as potential losses are smaller on previously disturbed or contaminated land.

There are also numerous studies from arid and desert-like areas where PV parks have, to some extent, increased soil or vegetation quality (Chang et al. 2018; Zhaofeng et al. 2016; Liu et al. 2020). Another Chinese study finds increased plant species diversity and soil microorganism activity in grassland (Bai et al. 2022). Adeh et al. (2018) find increased water efficiency and late-season biomass under solar panels in a water-stressed pasture area. A Hungarian study finds that solar parks provide a more heterogeneous habitat for certain arthropods than agricultural land (Hamřík et al. 2026). A study on Dutch solar parks provides, however, more mixed results on the biodiversity of certain flower and insect species, suggesting that the soil disturbance during the construction erodes most of the benefits these species could enjoy in a PV park (Kocsis et al. 2025). A longitudinal study in the US found increased ecological value for the solar park investigated compared to its former agricultural use (Walston et al. 2024).

Based on these findings presented above, it can be hypothesised that solar panels are in general a worse alternative from an ecological point of view to diversified and ecologically highly active land uses (like forests, shrubs, some pastures in general), but can actually provide ecological benefits for territories with low inherent ecological value or with intensive agricultural use. This is especially the case if the construction is designed in a way that incorporates the principles and practices of agrivoltaics and ecovoltaics or contributes to the multifunctionality of solar landscapes. Land-use changes due to increasing commercial-scale PV can, however, have negative land-use change impacts far from the place of installation by increasing land competition and fostering the cultivation of previously unmanaged lands. Yet, the literature is still not abundant in empirical studies, and it is hard to generalise from the available data.

2.2.2. Household PV reducing local emissions

The energy transition to renewables is primarily motivated by meeting climate targets and reducing GHG emissions. However, apart from the globally relevant GHG-emissions factor, the literature focuses mostly on the environmental problems related to renewable energy investments, almost exclusively covering negative impacts and

taking the positive potential (global and local) effects for granted (Virah-Sawmy and Sturmberg 2025).

This is evidenced by how most of the current literature focuses on measuring the life-cycle GHG emissions of household PV, not the potential positive effect of local emission avoidance (Fthenakis and Kim 2007; Hsu et al. 2012; Zheng Wang et al. 2025; Wassie and Adaramola 2021). Also, Vrînceanu et al., while giving a detailed overview of the potential positive and negative effects of PV, do not take into consideration the avoidance of local pollution by replacing fossil fuel-based heating (2019).

Local emission avoidance by solar power is mostly discussed in the literature in the context of avoiding indoor air pollution from inefficient and highly polluting cooking and heating stoves (Odoi-Yorke et al. 2025). This is a relatively rare issue in economically more developed countries, where the pollution from heating and cooking with solid or liquid fuels is affecting the local public airspace. A household installing a residential PV system is hypothesised to be more likely to switch to electric heating and cooking appliances and either reduce or completely abandon the use of solid and liquid fuels and hence reduce their local air pollution. Whether that hypothesised effect actually happens has been analysed by only a handful of studies so far:

- Tang et al. (2024) find that in their sample of 298 Chinese cities, an increased share of renewables (ratios not specified) in the local district heating systems have reduced the concentrations of key pollutants: SO₂ by 28.31%, CO by 7.57%, NO₂ by 5.72%, and PM_{2.5} by 7.15% between 2014-2022. The results do not cover the impact of residential renewable power plants, yet are indicative of the magnitude of air pollution reduction the avoidance of fossil fuels (in this case, mostly coal) can provide.
- Jenniches and Worrell (2019) their regional economic analysis on small-scale PV investment takes into account avoided air pollution (SO₂, NO_x, NMVOCs) as well, finding a limited 0,2 EUR/person benefit for the Aachen region.
- Cansino et al. (2019) find in their case study on a Chilean town that replacing the firewood heating homes (80% of the total) with PV would result in a 29-45 USD/per capita health benefits increase.

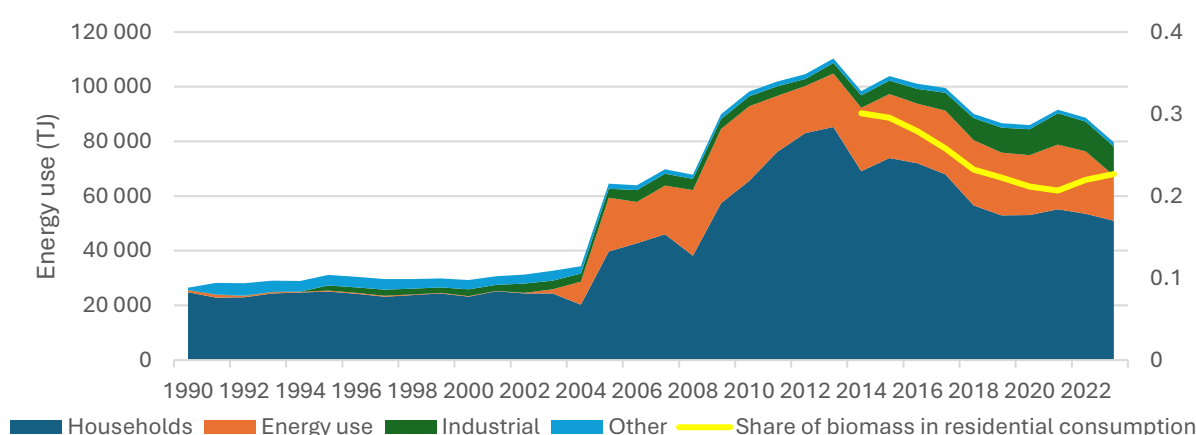
- Sokolowsky (2023) shows via an econometric model that in Poland, household PV installations caused a decrease of PM 10 emissions by 0.01–0.09 µg, on average (0.4% decrease, compared to the average monthly emissions in 2020).
- Millstein O'Shaughnessy and Wiser (2024) examine PV and wind deployment impacts on the national emission levels of air pollution in the US, finding that PV plants provide a health benefit of 15-20 USD/MWh and wind and solar generation helped avoid ca. 1,400 premature mortalities in 2022.
- Couvidat et al. (2020) look at the EU-wide impact of renewable deployment since 2005 on local air pollution. According to their findings, while the increase in wind and solar capacities led to small reductions in PM2.5 concentrations, resulting in 1,500 premature deaths avoided in 2016, the increase in the use of wood for heating resulted in 10,700 premature deaths in 2016 compared to 2005. That is to be compared with the figure of 60,000 fewer premature deaths due to PM2.5 pollution in 2018, compared with 2009, which is the result of all the air quality measures and policies in the EU. Wood heating is the largest source of PM 2.5 emissions in the EU.

In Hungary, the situation is similar. In 2022, 95% and 93% of PM2.5 and PM10 pollution, as well as 100% of SO₂ pollution by households originated from heating appliances. Household heating was responsible for 78% of the total PM2.5 emissions and 56% of the total PM10 emissions in all economic sectors in Hungary (SO₂: 29%, Ozone precursors: 19%, NO_x: 2%) (Eurostat 2025a). In terms of per capita emissions, Hungary is the 8th largest emitter of both household PM2.5 and PM10 in the EU27 (with 159% and 151% of the EU27 average, respectively) (Eurostat 2025a). In 2022 PM2.5 emissions led to an estimated 8,570 premature deaths in Hungary, roughly 0.9/1000, almost double the EU27 figure (0.53/1000) (EEA 2024). An earlier study estimated a 3.3% GDP loss from the premature deaths from PM2.5 emissions in 2019 (note that the estimated number of premature deaths was only 1,631 in 2019) (Koltai et al. 2021).

In Hungary, residential wood heating is common, especially in rural areas and among poorer households with lower education and income levels (REKK 2023). According to 2020 data, in the lowest income quintile, 40% of the households used only solid biomass for heating, as opposed to less than 10% in the highest quintile. Interestingly, the share of households using a mix of natural gas and biomass is roughly 20% in

each quintile. In villages, 42% used solid biomass only, and 31% used a mix of natural gas and biomass, while in cities, the share is significantly smaller (Bajomi et al. 2022).

The overall trend of intensive fuel wood use in Hungary is shown on 11. Figure. Solid biomass use doubled between 2005 and 2013 and then decreased due to the fixing of residential gas and electricity prices, but not wood prices and possibly due to energy efficiency and renewable energy investments. However, as gas prices increased in 2022 and the residential price cap was somewhat liberalised, the ratio of biomass use started to increase again (despite a significant increase in fuelwood price as well – see (Ámon et al. 2023)).



11. Figure Gross energy use of primary solid biomass by sector and the share of primary solid biomass in total household energy consumption (right-hand scale). Note that the sudden increase in biomass consumption in 2005 is due to a change in accounting (Eurostat 2025b; MEKH 2024a).

An additional issue is the quality of the solid fuel use: according to a representative survey, households, on the one hand, mostly use wood with high moisture content (only 5 months of drying), and on the other, many households burn residential waste, including plastics combined with wood (REKK 2023). Both practices increase the harmful emissions. There are also serious concerns about the sustainability of fuel wood used in Hungary, as official statistics cannot account for the total estimated biomass use. Therefore, these are either sourced from illegal or grey logging, or some other solid fuel is used, like residential waste (Bódis et al. 2021). There is no available estimate of the GHG emissions and land-use effects of illegal logging in Hungary for household fuelwood use, but they can be considered significant.

2.2.3. Summary

Renewables are mostly praised for their contribution to reducing emissions from fossil fuels, which are mostly responsible for anthropogenic climate change. Renewables, on the other hand, can cause certain environmental concerns and issues, especially through component manufacturing and possibly by land-use impacts. In terms of local environmental footprint, the former is mostly negligible for almost all countries and sub-regional territories, while the latter can have both local (in terms of the location of the installation) and, through induced land-use change, non-local impacts – not necessarily negative. Actual measurements and empirical studies in this field are rare.

A similarly neglected aspect is the local emission reduction effect of solar panels. While GHG-emission reduction contributes globally, offsetting local emissions from polluting heating sources by installing residential PV systems can have a significant health effect in areas with a high share of solid fuel-based heating, as is the case in most parts of rural Hungary.

2.3. Social nexus

As countries strive to meet climate goals and transition to renewable energy, the localised social impacts of such technologies have garnered increasing scholarly attention. The energy transition is not only a technical or economic process; the governance of energy systems has a profound effect on communities on different scales, from global to local (Aleh et al. 2011). Rooftop PV systems, which allow households to generate their own electricity, represent a decentralised approach to energy production that intersects with issues of energy (and general) poverty and equality, energy justice, local awareness of the different aspects of energy transition, employment effects, and attitude changes.

Rooftop solar PV has significant potential to alleviate energy poverty, understood as the lack of access to affordable, reliable, and modern energy services (while definitions vary) (Bazilian et al. 2014). Studies in developed economies indicate that solar adoption can reduce household energy costs, freeing up income for other essential needs. For instance, in the USA, research by Forrester et al. (2024) demonstrates that low- and moderate-income households with rooftop PV installations can experience a

reduction in electricity bills by up to 20%, enhancing economic resilience. Similarly, in Germany, part of the EU's robust renewable energy framework, the "Energiewende" has facilitated widespread solar adoption, with households reporting savings that mitigate the effects of rising utility costs (DIW Econ 2024). In Japan, government subsidies for solar PV have been linked to decreased energy expenditure in urban households (Chapman and Okushima 2019). At the same time Wang et al. (2020) find that, in China, the poverty-alleviation program using household solar power was less effective than the broader poverty-alleviation policy framework it was part of.

In contrast, in economically less-developed countries, the impact of poverty is often more pronounced due to a baseline lack of electrification. In rural South-East Asia, solar systems have been shown to electrify not only households but also agricultural activities, advancing the local economy and employment (Saha 2025). But solar PV, especially off-grid PV will likely have the most potent impact in Sub-Saharan Africa, where 85% of the global population without access to electricity resides, and where off-grid solar was responsible for 55% of the electrification between 2020-2022, with an outlook to play a similarly decisive role in the future electrification programmes on the continent (ESMAP 2024). However, the scale of poverty alleviation remains constrained by high upfront costs and inadequate financing mechanisms, in contrast to the more systemic support found in wealthier nations.

The academic literature also examines peer effects (learning effects) in the spread of renewable energy, particularly household solar PV systems. These effects act as investment incentives and contribute to the further expansion of the local renewable energy sector. Numerous quantitative case studies confirm that a single installation can significantly increase the likelihood of further installations within a local radius of approximately 0.5–4 km. This means that the spread of small-scale power plants (such as rooftop PV systems) can be described using contagion models—where one installation encourages additional investments. This effect is usually referred to as Neighbourhood-effect. Interestingly, large-scale renewable energy projects can also stimulate further small-scale investments in household solar PV systems (M. Graziano and Gillingham 2015; Marcello Graziano et al. 2019; Matsuo 2019; Rode and Weber 2016).

Energy justice, encompassing distributional, procedural, and other aspects, became a widely used lens for evaluating the energy transition and rooftop PV's social impact. While energy justice acts more like an umbrella term for many different definitions and operationalisations, it provides a conceptual framework for approaching the inequality embedded in and generated by the energy transition's multitude of impacts (Goldthau and Sovacool 2012; Jenkins et al. 2016; Sovacool et al. 2014). In developed contexts, the adoption of solar PV has raised concerns about inequitable access. A study by Sunter et al. (2019) found that in the USA Black and Hispanic communities are less likely to install rooftop solar, even when controlling for income, pointing to systemic barriers in policy and outreach. The EU has sought to address the issue of inequality in participation and involvement, as well as benefit sharing, through the implementation of the legal framework of Renewable Energy Communities (RECs). RECs are mostly citizen-led initiatives that pool resources to deploy renewables, involving the participating community in the financing, the decision-making processes, and governance, as well as often in the ownership structure too (Becker et al. 2017; Heldeweg and Séverine Saintier 2020; Standal et al. 2023).

The proliferation of rooftop PV, as the most decentralised and scalable to household-use renewable energy source, also influences local knowledge, attitudes and awareness of energy and climate challenges, as well as acceptance of renewable energy investments (for a thorough systematic literature review and evaluation see Berka and Creamer 2018). Beattie et al. (2019) find in Australia that rooftop solar adoption can impact not only the attitudes and knowledge of the adopters on climate and energy issues but also of their neighbours and members of the local community. Similarly, in the EU, RECs serve as hubs for knowledge dissemination. A case study in Belgium by Bauwens (2016) highlights how community solar projects foster discussions on sustainability, enhancing climate literacy among participants.

Despite the potentially positive local social impacts, renewables are often met with resistance and NIMBYism, especially wind energy and often large-scale solar power plants. The causes and forms of this resistance are relatively well-researched (see Sanchez Nieminen and Laitinen 2025; Van De Grift and Cuppen 2022). Concerns about impacts on land and nature, effects on tourism, and even health issues dominate discussions. However, as Argenti and Knight (2015) present using the concept of Extractive Economies, local resistance can even stem from a feeling of subjugation

and exploitation. The exploitation and appropriation of local resources legitimised by potential environmental benefits are also discussed in an evolving branch of the literature as “green grabbing” (Fairhead et al. 2012; Klingler et al. 2024).

As presented, the social impacts of renewable energy deployment in the local context can be diverse, while operationalising and measuring them is especially challenging compared with economic and environmental impacts.

The short summary of the potential social impacts shows that large-scale solar power plants have a moderate local effect in the social context. The literature suggests that commercial solar investments have two general channels of influence on local households and communities (apart from economic and potentially environmental aspects):

- if there is no connection to the local community through ownership, involvement in the decision-making process or governance, then simply through their presence, potentially establishing/strengthening local rejection and negative attitudes, or might actually foster the deployment of small-scale rooftop panels;
- if the community is involved (via Renewable Energy Communities or other means), the large-scale projects might invoke social impacts generally considered to be positive, like reducing energy poverty, increasing local acceptance, and contributing to local skill development and attitude change.

In Hungary, community involvement is virtually non-existent, and apart from a few minor pilot projects, no major investments have been realised so far under the Renewable Energy Community framework. An early project called ‘Social Solar Power Plant’ was initiated by the Hungarian Maltese Charity Service, serving 60-70 households with local, PV-based electricity from a large-scale project; however, this is not labelled as an Energy Community. The first Energy Community was registered in Hungary in October 2023, and as of August 2026, only 18 Energy Communities were officially licensed (MEKH 2026b). Rescoop, the federation representing a network of 2,500 energy communities across Europe has 1 member and 1 supporter from Hungary in total. Prior to the start of the official registration process, a grant was available in 2021 for the development of Energy Communities in Hungary with a total of 4 billion HUF budget – however many of the grant recipients were less traditional actors of Energy Communities (like major, nation-wide energy companies MVM and

E.On, as well as several for profit and state owned enterprises) (NFFKÜ 2022). The grant applications are not publicly available, hindering the evaluation of these initiatives.

At the same time, in Hungary, no major resistance to large-scale solar power plants is evident. Landowners and project developers did have some conflicts in the case of a few large-scale projects, but none of these has evolved into major local resistance movements and has become a community issue (SZGK 2021). The results of a representative survey in Southern Hungary in 2017 and its follow-up in 2022 confirm that solar PV has the highest acceptance and support rate among renewables (Rodríguez-Segura et al. 2023; K. Németh et al. 2024). Innovations like balcony solar systems are also favoured by the residents (less so by the regulator) (Molnár and Szép 2025).

Therefore, the following chapter focuses on the social context of small-scale, household solar PV installations, especially on identifying the adopter profile of Hungarian household PV owners. Understanding who the owners are, what their socio-economic context is, and where they live largely determines what impact rooftop PV installation can have. A major impact, alleviation of energy poverty, can be mostly neglected if the vast majority of PV-owner households are wealthier than what would be generally considered as a risk factor of energy poverty (though Ámon et al. (2023) show that some forms of energy poverty can be present even in the highest income deciles in Hungary).

2.3.1. Adopters of residential PV

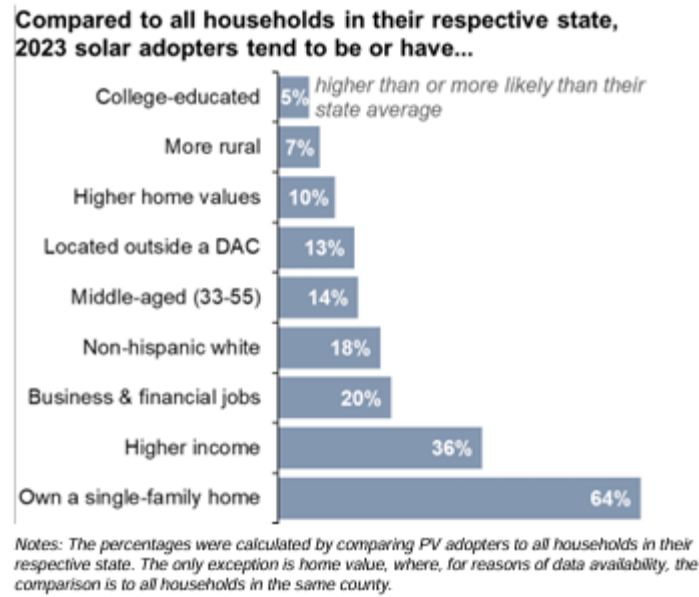
The following sub-chapter presents an overview of the academic literature on residential solar-PV adopters, focusing on sub-national, but mostly above household spatial units of observation. The papers presented most often use some form of regression analysis to measure the effect of certain socio-economic variables on the likelihood of residential solar-PV adoption in a certain population. The current literature on residential solar power has a strong focus on the distribution patterns of solar PV investments and the social factors influencing these patterns through enablers and barriers (Vishnu and Joshin 2024). The research conducted in Chapter 6 fits into this branch of the literature.

A recent systematic literature review by Konzen et al. (2024) provides an overview of 87 studies focusing on the effects of wealth and income on household solar PV adoption. Most of the papers analysed focus on more economically developed countries, primarily the US and Europe. Only three studies were identified in the EU from the CEE region, one (modelling, not empirical) on Lithuania and two on Poland. The vast majority of the articles find a positive correlation between PV adoption and variables describing household wealth and income; however, some studies find no, or a negative correlation (like one in the case of Poland). Among the analyses, 14 papers discussed changes in the equality of PV adoption (whether the explanatory power of household affluence decreased over time as late adopters entered the sector). The results are mixed: 2 papers found that inequality increased, 5 found no change, and 7 found that inequality decreased.

Currently, the work by the Lawrence Berkley National Laboratory (Forrester et al. 2024) is the most comprehensive study on the socio-economic status of residential PV adopters. The longitudinal research uses a representative sample of the US population, uses households as a unit of observation, and has been ongoing for over a decade.

Since its start in 2010, it has consistently found that PV adopters have a higher median income than the national (or state) average. However, the difference is steadily decreasing as solar modules become increasingly affordable. The median income of adopters in 2023 was only 105% of the national median for homeowner households, compared with 122% in 2010.

Further factors, where PV adopter households tend to have a higher value on average than all the households in their respective states, are summarised by 12. Figure.



12. Figure Socio-economic factors of residential solar PV adopters in the US have a higher value (DAC=Disadvantaged Communities) (Forrester et al. 2024, 29).

The numerous studies on the same issue in the international sphere arrive at largely similar, but in several cases concurring conclusions. This suggests that differences in national or local socio-demographic features and the legal framework can have a substantial impact on adoption patterns.

- Dharshing (2017) in their spatial autocorrelation analysis on German counties (NUTS 3) find that affluence is an important factor in explaining the likelihood of PV adoption, and the decision is likely based on economic rationale (available state subsidy) and less on attitudes or social aspects (like age).
- Sommerfeld et al. (2017) find, in their analysis of a sample of Australian postal code areas, that the size of dwellings is the most influential factor (a possible proxy for affluence), although other variables associated with higher socio-economic status (like education) play a less significant role in explaining differences in adoption.
- Sunter et al. (2019) find that in the US, even after controlling for economic disparities, belonging to certain ethnicities (black and Hispanic) significantly reduces the likelihood that a household installs a PV unit.
- Graziano et al. (2019) find that on a relatively small sample area in the US, household income and dwelling size strengthen the spatial spillover (neighbourhood) effect.

- Thormeyer et al. (2020) study Swiss municipalities. They do not consider explanatory variables strictly covering affluence or socio-economic status but find – concurring with most of what the literature suggests – that agricultural employment and the share of the population over 65 positively affect PV adoption.
- Müller and Trutnevyte (2020) confirm Thormeyer et al.'s (2020) findings that in the case of Switzerland, income is not a significant factor (to the contrary, income has a small negative effect on PV installation rate, mostly due to the lower share of installation in more affluent urban regions). They also confirm that the share of the population aged 65 and above has a positive effect (which is generally considered to coincide with lower socio-economic status). This is likely explained by the general affluence of the Swiss population, allowing for PV investments even for relatively less wealthy households.
- Balta-Ozkan et al. (2021) find that higher education and self-employment increase the chance of adoption in the United Kingdom. At the same time, income in itself has a negative effect (likely due to higher income but less prevalence in urban areas). In general, the findings suggest that rurality (share of detached homes, lower population density) is a stronger predictor.
- Lan et al. (2021) find that, in the Australian context, income plays a role only when other variables (mainly the availability of rooftop space, population, and housing density) are not constraining PV deployment.
- Collier et al. (2023) find that a higher share of the population over 45 (and especially the share of retirees) is a predictor for household PV adoption; also, higher education level and the number of skilled manual workers have positive effects, too, as do lower housing density and higher dwelling and household size. In the model, income – consistent with the Swiss findings – has a significant negative effect on adoption. Zhang et al. (2023) mostly confirms these findings in their own research on Australian PV adoption.
- Zhang et al. (2023b) find in the Netherlands a strong positive correlation between income and PV adoption, as well as with the size of the households, increased population density and new housing stock.
- Some non-representative survey-based studies (using a smaller sample size) also indicate similar findings. (Du et al. 2024) identifies higher income,

education, and larger dwelling size, as well as certain green attitude aspects, as important factors behind the adoption decision. (Ruokamo et al. 2023) finds that early adopters are more likely to be wealthy, young males living in a rural setting (although higher education is not a factor).

For Hungary specifically, three studies have analysed PV adopter profiling, all three at the national scale using statistical tools. One used municipal-level data, while two used Districts (LAU 1 EU administrative level) as spatial units of observation.

Horváth et al. (2021) use 2020 municipal-level data acquired from MEKH (the Hungarian energy regulatory authority) that includes not only the number but also the capacity of installed household units per municipality. They find that the mode of all installations is 5 kW, the average size is 6.1 kW, and the average municipality has 38.6 kW of residential capacity per 1,000 inhabitants. They find above-average per capita values mostly around Lake Balaton and Lake Velence (partly resort areas), and in the vicinity of Pécs and Szeged (major southern cities). The number of residential PV per 1000 detached houses reveals a similar spatial distribution, but the agglomeration of Budapest also shows high rates in this comparison. They correlate municipalities' per capita income with various dependent variables describing residential solar penetration, finding the strongest correlation with the number of units/1000 detached houses. They conclude that smaller and wealthier municipalities are more likely to see higher levels of residential PV installation.

Baranyai et al. (2021) use simple correlation calculation and stepwise regression analysis on residential PV data on the District level (LAU 1) from 2019 and District-level socio-economic and infrastructure indicators from 2018. The selection of explanatory variables is based on two government decrees identifying municipalities (105/2015 (IV. 23.)) and districts (290/2014 (XI.26.)) as beneficiary areas, based on their territorial development level, expanded by several variables on electricity supply, commercial and business activity to measure the local economic and infrastructural variances. The paper used the number of residential PV units/1000 inhabitants as the dependent variable and found a moderately strong correlation with the following explanatory variables:

- total budget expenditure of local governments per 1000 population;
- number of household electricity consumers per 1000 population;

- quantity of electricity supplied to households per 1000 population;
- number of electricity consumers per 1000 population;
- number of operating commercial accommodation units per 1000 population;

A different regression model, using exclusively the identification variables of the government decrees identifying municipalities and districts as beneficiary areas, showed that the quantity of PV HMKEs per 1000 population was explained by the proportion of the total number of homes at the end of the period built in the last five years and the proportion of public streets/roads maintained by the municipalities that are paved.

Szép and Tóth (2025) in their paper use spatial autocorrelation to analyse the spatial distribution of residential solar power plants based on data from 2019-2023 on the District (LAU 1) level. The different models find positive spatial autocorrelation (i.e. systemic similarity in neighbouring units of observation in terms of PV adoption rate) in several regions, like the neighbourhood of Lake Balaton, the vicinity of Székesfehérvár, Pécs, and Szeged, and also Győr-Kőszeg-Szombathely. Negative autocorrelation was found in the less affluent North-Eastern part of Hungary, the region close to the Ukrainian border and the vicinity of Szolnok.

Szép and Tóth (2025) also conduct an OLS regression analysis and a spatial error model (SEM) analysis, using several socio-economic variables on the District level. They find that the SEM model has greater explanatory power than OLS regression. They find that in the SEM model, the spatial error term has the highest explanatory power, i.e. there is some non-linear spatial dependency, some sort of neighbourhood effect (though it can stem from the regulatory ban on licensing new residential rooftop installations in Hungary between late 2022 and early 2024). Otherwise, higher education level, the share of newly built apartments, and the share of apartments 100 m² or larger have a positive and significant effect on solar PV adoption, while housing density has a negative and significant effect.

The literature largely agrees that affluence and proper housing are the two most important determinants of residential PV adoption. However, for different countries and regions, the relevant socio-economic variables can vary greatly (even the effect of affluence is not universal).

Earlier results in Hungary are consistent with the literature and with each other, indicating that average socioeconomic development, as well as the affluence of the observed units, has the greatest effect on PV adoption rates. However, the earlier studies can be further developed by using more up-to-date and granulated data and regression analysis. While Horváth et al. (2021) use municipal-level data, their analysis lacks the depth of statistical analysis and model building. Therefore, it is hard to account for potential confounding. Baranyai et al. (2021) and Szép and Tóth (2025) use more refined analytical methods, however their analysis focuses on the District (LAU 1) level only.

2.3.2. Summary

Social aspects, especially the impacts of renewable energy installations, are much harder to grasp and measure than the economic or environmental impacts. Local impacts are mostly propagated through direct involvement in the projects, as part of some form of community renewable energy framework in case of large-scale projects, or as the owner (sometimes the neighbour) of residential units (mostly for PV). In lieu of participation, the most common social impact is inducing NIMBYism in local communities.

For residential projects, the impact is highly likely dependent on the social status of the adopter household itself. The potential for the alleviation of energy poverty or change in (green) attitudes is mostly relevant for adopters who are less affluent or have a lower level of knowledge on and openness to sustainability issues.

The available literature shows significant variation in what explains adopters' decision to install residential PV. While the affluence of the households and the dwelling type is often decisive, this is not the case for all populations analysed. The social background of the typical adopter changes significantly from country to country and also over time. Approximating the potential social impacts of residential PV adoption shall start with identifying the background of the adopters.

3. QUESTIONS AND HYPOTHESES

3.1. Overview

This research is centred on gaining deeper insight into how solar investments may impact local communities in Hungary in various ways. Its main question is: How can solar PV investments contribute to local development? Local development is often considered to emerge from the interplay of three pillars, the same pillars that underpin sustainability, a concept that gives the very rationale for renewable energy investments, namely the Social, Economic and Environmental pillars.

Hence, the main question can be subdivided into three basic and general assumptions covering these aspects:

- 1. PV investments can contribute to local economic development through direct and indirect effects (Economic aspect).**
- 2. PV investments are at least not harmful to the local environment while supposedly contributing to large-scale (global) environmental sustainability (Environmental aspect).**
- 3. PV investments contribute to social inclusion and the reduction of (energy) poverty locally (Social aspect).**

PV investments, in general, but especially in the Hungarian legal context, have two basic scales: household investments that aim to cover the self-consumption of households and are located predominantly on the rooftops of residential buildings. And commercial scale, which are investments driven by companies on a larger physical scale, either to reduce their demand for wholesale electricity or (more commonly) to actually participate in the electricity market as suppliers and produce electricity for different consumers. The investments of these scales have distinctly different features and, as a result, distinctly different (local) effects. Yet both need deeper understanding and research, as both are prevalent and will likely stay relevant for the future development of any electricity sector going through the current energy transition.

The three aspects and the two scales presented above outline the following matrix that structures the research aiming to get a deeper understanding of the local effects

of PV investments. This matrix helps to show which research directions are more relevant, and strictly in the case of Hungary, which are under-researched. The potential impacts are derived from the literature (see Chapter 2).

The problem-identification matrix below uses the following colour-coded categories to signal relevance and reserachability.

- Based on the literature and the Hungarian context, relevant, researchable potential impact, therefore the Thesis addresses it as a separate question.
- Based on the literature and the Hungarian context, either relevant but not researchable (lack of data) impact or seemingly less relevant but researchable with the available datasets; therefore, an exploratory investigation is done to help future research.
- Based on the literature and the Hungarian context, there is no relevant impact (so far) requiring research; therefore, the Thesis ignores it.

Local Impact			
Dimension	Factor	Household scale	Commercial scale
ECONOMIC	Income from the operation of the power plant (profit through ownership and local taxes)	In Hungary, household PV owners are almost exclusively the private owners of the dwellings and, therefore local by definition. The potential economic benefit for households is basically the avoided cost in electricity bills. Addressed by Question 2.	Ownership on this scale is currently unknown, but it is relevant and impactful, as these installations are basically for-profit and their total, potentially localisable economic value is dominated by the income of the solar power plant. No similar research has been done either in Hungary or in the international context. Addressed by Question 1.
	Contribution to local businesses and employment	Literature suggests that this can have a significant effect either on a local or a sub-regional scale. For the Hungarian case, no similar research has been conducted. Addressed by Question 3.	Literature suggests that this can have a significant effect either on a local or a sub-regional scale. For the Hungarian case, no similar research has been conducted. Addressed by Question 3.

ENVIRONMENT	Land-use change	As household PV systems are predominantly built on rooftops, this is not a relevant issue.	Highly relevant, as the large-scale PV boom affects significant territories in Hungary. However, the size of the effect and even its direction (ecological damage or benefit) are not clear. No similar research has been conducted in Hungary so far.
	Reduction of local emissions (heating)	Avoided wood (and other solid) fuel consumption can benefit the local environment and health. The effect of PV investments on heating patterns has not been studied so far in Hungary. Addressed by Question 5.	Not relevant, as commercial PV plants are not replacing usually any local electricity production (i.e. fossil fuel based small power plants) but produce for the national grid or offset purchased electricity from the grid in case of self-consumption covering PV plants for businesses.
SOCIAL	(Energy) poverty/energy justice	In Hungary, electricity access is almost universal. However, the affordability aspect of energy poverty is highly relevant. On energy poverty, there is no municipal data available (like arrears on utility bills). We can only estimate the general 'poverty' of the settlements and use it as an indicator. Addressed by Question 6.	For profit-seeking investments, this aspect is not taken into consideration. Also, these produce mostly for the national grid, therefore, won't have any direct effect on local energy supply security or access. Consumer prices also aren't affected by the potential price effects of commercial PV production (either locally or nationally), as household prices are (mostly) fixed.
	Local acceptance	The literature suggests that residential solar rarely faces local opposition. In	It is highly relevant in general, yet in Hungary, there has been no

		Hungary no systemic negative sentiment has been recorded so far; the available data suggests general support for household renewables, although in several districts of Budapest, local regulations prohibit installations for city sight protection (Gajdics 2021).	(mediatised) example of resistance towards commercial PV plants; therefore, it can be assumed that it is locally less significant (so far). It can be expected that as major investments are realised in the coming years, potential local or national refusal (NIMBYsm) emerges.
	Local skill development and attitude change	Local attitude change is attributed to household PV investments in the literature. However, no relevant and accessible data describing municipal-level green attitudes exists in Hungary. Also, no nationwide dataset is available that would enable even an approximative study on the skills or knowledge gained by PV adopters during the process. Social profiling of PV adopters can offer some insights. Touched on by Question 6.	Literature suggests this is more the case of community-owned/driven solar investments, which in Hungary are basically non-existent.
	Neighbourhood (spatial spill-over) effect of new investments	Following many international studies, it would be highly relevant to study local distributional patterns; however, no time-series data on household PV deployment is publicly available (or was made available upon specific request), therefore only an indicative analysis is feasible. Touched upon by Question 6.	Based on the literature, this is not an important factor for investors in selecting a location.

3.2. 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.

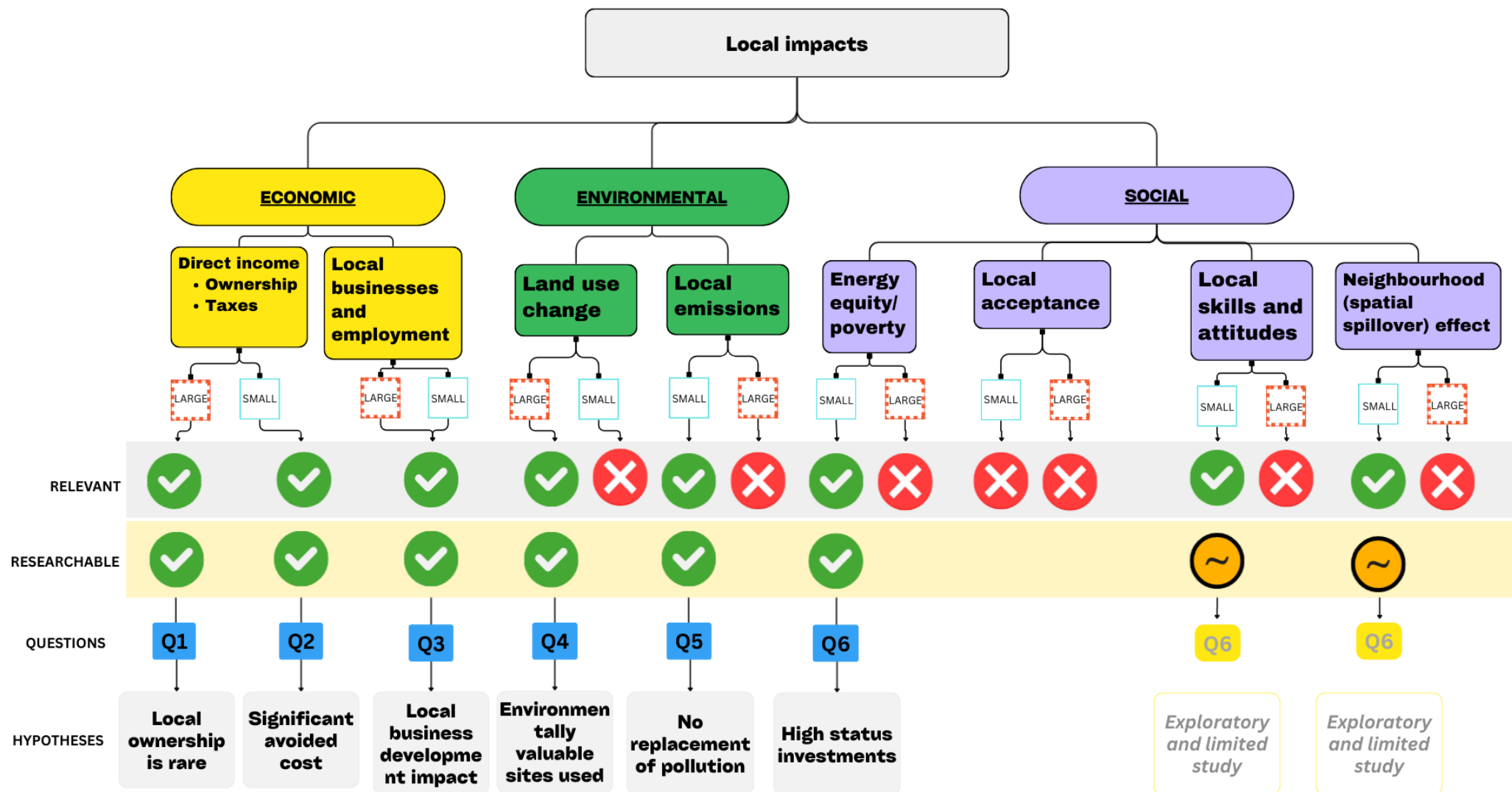
Q5: How do household PV projects affect local air pollution in Hungarian settlements?

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.



13. 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.

3.3. Notes on Methodology

The Thesis builds on two distinct methodological approaches. It is primarily a data-driven, quantitative research approach aimed at producing findings using national-level datasets to foster generalizability. The details of these quantitative methods are presented in the first subchapter of each empirical section to improve readability, since all questions formulated in Chapter 2 merit their own distinct analysis and data collection methods.

To incorporate some benefits of the qualitative approach, several stakeholder interviews were also conducted.

During the preparatory research phase of the Dissertation, several experts were interviewed under anonymity to help define the research objectives and methods:

- a senior lawyer specialised in Hungarian and EU energy law, engaged with commercial-scale renewable PV investments;
- a mid-level electrical engineer in a company providing the electricity and software infrastructure for commercial-scale PV plants in Hungary;
- a senior academic with decades of research on renewable energy from the engineering and policy aspects;
- head of an NGO group advocating for Renewable Energy Communities in Hungary.

To validate the quantitative research and gain better insight into the case-by-case specifics of the impacts studied, a second set of interviews was conducted in August 2025 with leaders (majors, notaries) of 9 Hungarian municipalities most affected by various solar PV investments. These served as limited case studies with the actors having the most comprehensive knowledge on the local economic, environmental and social impacts.

For the case selection, all Hungarian municipalities were ranked along four PV-related aspects, and the top 10 in each rank were contacted (resulting in 36 potential municipalities due to repeated appearance of several municipalities in different top 10 rankings). Municipalities with a population under 500 were not contacted due to concerns about being extreme cases. The four defining aspects were:

1. Share of the total area covered by commercial PV plants.
2. Share of inhabited homes with residential solar PV.
3. Total licensed commercial-scale capacity.
4. Total truly locally owned commercial-scale capacity (on District, not Municipal level, i.e. capacity owned by residents in the municipality that is located in the District of the municipality).

Out of the 36 contacted municipalities, 15 responded positively, and 9 interviews (personal or telephone) were conducted. Prior to the interview, a questionnaire was sent out addressing questions on the local employment/business activity of the PV sector, the municipality's own PV (HMKE) capacities and activity in the field, the municipality's relation with the owners and operators of local commercial capacities, the realised income from large-scale capacities, and the social characteristics of local residential PV adopters.

Municipality	Population	County	Rank in land-use	Rank in residential capacity	Rank in commercial capacity	Rank in local ownership
Bóly	3721	Baranya	517	44	533	93
Budajenő	2337	Pest	-	23	-	-
Diósd	11627	Pest	-	76	-	-
Inárcs	5022	Pest	4	332	28	158
Kardoskút	724	Békés	600	778	221	12
Királyegyháza	839	Baranya	25	1627	3	-
Oroszlány	18078	Komárom-Esztergom	193	1863	159	24
Szászberek	915	Jász-Nagykun-Szolnok	18	712	7	-
Töttös	530	Baranya	177	629	151	17

3. Table List and data of municipalities interviewed in August 2025. ‘-’ indicates no ranking (e.g. no licensed commercial capacity on the territory of the municipality).

4. ECONOMIC IMPACTS

In general, to assess the local economic impacts of renewable energy investment, the literature uses mostly Input-Output models, Social Accounting Matrix and Computable General Equilibrium Models (Allan et al. 2015).

These are methodically advanced models, however, there is no data available to pursue such investigations on the level of granularity proposed by the Thesis (LAU2 –

municipalities): IO tables in Hungary are only available on the national level, while the other approaches would require both systemic data on the projects themselves (supply-chain analysis) and the municipalities' economies on levels, that only allow for case studies.

Locality in the literature is usually considered regional, especially because, at smaller scales, data acquisition is cumbersome, to say the least. However, as the environmental and social effects of a power plant investment in the tens of MW are usually confined to the municipality or its direct neighbourhood, it can also be suggested that the analysis of economic effects should focus on the same spatial level. Therefore, this Thesis offers a way to approximate at least part of the local value addition at very fine spatial granularity, while still using available national-level datasets.

The Thesis follows the distinction proposed by Heinbach et al. (2014) to capture the potential for local economic benefits from the investments:

- Profit – operationalised as the share of commercial PV projects owned by local entities and the avoided utility expense by households (subchapter 4.1.1)
- Tax – operationalised as the range of potential tax revenue collected by municipalities (subchapter 4.1.2).
- Income – operationalised as the estimated impact on local employment and business activity in the relevant branches of the economy (see specification in subchapter 4.1.3).

The following chapter presents the empirical findings on the potential local economic impacts of solar PV investments in Hungary.

First, it looks into the ownership structure of the Hungarian commercial PV plants, finding a large share of foreign ownership, growing with the average capacity of solar parks, and among the domestically owned capacity, a low rate of locally owned units.

The second analysis provides an approximation of the local tax impact of these capacities at the municipal level, finding that only a handful of settlements are likely to see any locally significant tax income from the operation of a solar power system with one of the largest per capita capacities globally.

A third analysis focuses on the potential income impact of residential solar PV, finding that this effect in nominal per capita terms is largest in mostly wealthy, socioeconomically developed suburban regions. Therefore, residential solar income is unlikely to significantly reduce poverty or income inequality.

The fourth sub-chapter presents an indicative inquiry into the potential impact of solar investments on local business activity, suggesting that both commercial and residential solar investments can spur local businesses and employment in related fields.

4.1. Impact through ownership (commercial-scale)

4.1.1. Methodology

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. This dataset was complemented by the MEKH data on the grid connection points of solar PV plants above 0,5 MW capacity (including the location, name of the license owner company, capacity and status of the investment) (MEKH 2025b).

The lists of METÁR-awarded and licenced power plants are publicly available from the website of the Hungarian National Energy and Public Utility Regulatory Authority (Magyar Energetikai és Közműszabályozási Hivatal, MEKH for short) (MEKH 2022, 2026b). However, the list of KÁT-recipient power plants (and also the actual list of METÁR-recipient power plants, excluding the awarded but license-not-received projects) can only be compiled from the official and public collection of the Resolutions issued by MEKH. That required the semi-automated processing of roughly 10.000 individual MEKH Resolutions for more than 3300 individual projects. The cut-off date for data collection was 28 June 2025. Errors from Resolutions that are missing from the database or uploaded to incorrect categories can persist.

MEKH Resolutions are official and published decisions of the Authority that regulate specific activities and entities providing or revoking licences for different regulated activities, as well as specifying the contents and limits of these licences. For commercial PV plants, MEKH usually provides a license for operation and a separate or combined license for receiving operational support from the KÁT or METÁR framework. Multiple Resolutions can relate to a single project, as any change in deadlines, ownership, or location requires official approval from MEKH.

As these are licensed but not necessarily (yet) built projects, the database covers more projects than the actual built-in commercial-scale PV capacity as of Q1 2025.

The total project database consists of 3624 PV projects licensed between 2012 and 2024 with a total capacity of 5880 MW. In Q1 2025 in Hungary the total built-in capacity of non-household, grid-connected PV plants was 4204 MW and an additional 730 MW for commercial autoproducers (PV for self-consumption above household scale) of which 409 MW is subject to permit (MAVIR 2026a). Part of the difference is likely the result of the belated construction or grid connection of the 2 GW capacity licensed between 2022 and 2024. Baji Gál et al. suggest a 3-4 year project cycle even for smaller projects (under 0,5 MW), while they see a realisation rate of 90% by 2020 (2021). Some capacities, however, certainly do not get built due to issues with land acquisition or financing.

Year	Projects receiving MEKH approval	Average built-in capacity (kW)	Total capacity (kW)	Share of total
2012	2	449	898	0.02%
2013	11	432	4,748	0.08%
2014	16	1,410	22,554	0.38%
2015	49	477	23,391	0.40%
2016	419	539	226,041	3.84%
2017	2,132	581	1,238,679	21.07%
2018	253	1,159	293,164	4.99%
2019	194	2,060	399,728	6.80%
2020	160	6,355	1,016,782	17.29%
2021	72	5,341	384,572	6.54%
2022	107	8,581	918,134	15.61%
2023	111	7,163	795,059	13.52%
2024	92	5,469	503,161	8.56%
2025	6	8,818	52,907	0.90%
Total	3,624	3,244	5,879,817	100%

4. Table: Basic descriptive statistics from the project database of the licensed Hungarian PV power plants.

The project database lists the following data points for each project:

- number and date of the original Resolution, granting KÁT or METÁR support and/or operational licence;
- name, official residence and registration number of the recipient (legal entity);
- approved built-on capacity;
- location of the power plant (address, mostly parcel/lot number).

The project database is supplemented by the Ultimate Beneficial Owner (UBO) of each project using 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). In each case, the UBOs of the licensed company were manually obtained. In cases where a UBO could not be identified (e.g., Hungarian legislation on private equity funds does not require disclosure of UBOs; Foundations are their own UBOs), the locality of the last known legal entity or entities in the ownership chain was considered. Roughly 1/6th of the total capacity, 1 GW, belongs to such entities. For publicly traded companies, the locality of the publicly traded company was considered. For UBOs, their official residence was included in the combined project-ownership database – municipality for Hungarian residents and country for foreign natural persons. For each project, a maximum of five UBOs were registered to represent the total ownership structure (355 projects; 10% of all project owners had more than 5 UBOs). The 5 UBOs were selected so that their share in each locality matches the overall share of UBOs. This approximates the industry practice of using a ca. 20% ownership rate for defining a UBO (see below).

The legal definition in most jurisdictions, and hence the industry’s practice, is to consider an entity UBO with a minimum of 10-25% share of capital or voting rights in the owned entity (SWIFT, n.d.). However, for the vast majority of companies, such data was not available in the two company databases used. Therefore, every ultimate owner was considered a UBO, and they were considered to have an equal share in the company controlled. This was represented by dividing the total capacity of the power plant owned by the particular company by the number of owners and assigning to each owner the same share (capacity/owner).

Apparently, no study has yet been conducted using Ultimate Beneficial Ownership data to determine the locality of renewable energy projects, especially not on a national scale. Most of the available research focuses on case studies of certain community-owned investments and identifies their potential or realised local benefits. Estimating the local benefits of existing projects at a national scale is currently missing from the literature.

The current study cannot account for ownership-related income from land use, whether through a lease or a purchase. There is no publicly available database on land value or ownership below the county (NUTS 3) level. It is also unknown what share of PV plants are built on leased or owned land. Therefore, ownership revenues from land use are not considered in the current analysis.

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 on the national economy.

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.

The literature on renewable energy communities suggests that the proximity of ownership increases local economic or social benefits (Bauwens and Devine-Wright 2018; Berka and Creamer 2018b; Callaghan and Williams 2014; Capellán-Pérez et al. 2020) – this is also echoed by the relevant EU regulation (Directive 2018/2001).

A third type of actor is also defined, although used only for illustrative purposes: the project owner company and where it is seated. However, the economic impact from ownership is, of course, not associated with these entities but with their UBOs.

The analyses use descriptive statistical methods to show in which spatial units the ownership effect is relevant, to what extent, and what the socio-economic status of these spatial units is. Ownership is expressed by the total capacity owned by the UBO.

4.1.2. Ownership and spatial concentration

The following analysis uses the dataset of 5.8 GW of solar PV capacity, each above 50kW, licensed by the Hungarian Energy Regulatory Authority between 2012 and 2025 (though not necessarily built yet). For all projects, the Ultimate Beneficial Owner and their residence were identified to find which settlements are more likely to profit from the operation of commercial-scale solar capacities, assuming that the profits generated are more likely to contribute to the local economy of the owners' residence than to any other location.

The 5.8 GW total licensed capacity is owned by 1,890 companies (most of them project companies), owned by 1828 distinct UBOs (excluding the owners above the 5 number threshold, 1,640 domestic and 188 foreign entities).

This suggests that the ownership concentration is low, and ownership is spread out among the projects relatively evenly, making it more likely that local entities, not only major companies, can be owners.

The Herfindahl–Hirschman Index (HHI) is a commonly accepted market concentration metric that sums the squares of the market shares of individual companies. A HI below 1,000 is generally considered to describe a market that is not concentrated; concentrated markets are indicated by a value over 1,800 (US DoJ 2015).

The HHI score calculated for the concentration of the total 1890 companies is only 59. However, it is more relevant to calculate the HHI of the UBOs. That result is shown in 5. Table for the total UBO population. To evaluate ownership concentration among the largest owners in terms of owned capacity, the HHI was calculated separately for the top 10, 50, and 100 largest UBOs, emulating a market with only those UBOs present. Neither calculation indicates high market concentration; only the market segmentation of the top 10 owners can be considered moderately concentrated.

	Top 10 owners	Top 50 owners	Top 100 owners	All owners
Total capacity (kW)	2,137,790	3,821,958	4,492,949	5,859,841
Share in total capacity	36%	65%	77%	100%
HHI	1,579	556	407	251

5. Table HHI calculation for the Ultimate Beneficial Owners of the Hungarian commercial solar power plants, calculated for the total population as well as for three distinct subsets.

The licenced commercial PV capacities are similarly well dispersed spatially. According to the database, the 5.8 GW licenced projects are located in 808 different municipalities. There are 22 municipalities hosting at least 1% of the total licenced capacity, accounting for 32.3% of the total capacity (while representing less than 3% of Hungary's total population and less than 2% of its total area). 6. Table shows the top 10 municipalities by licensed capacity from the total, as well as their share from the total capacity of licensed power plants above 0.5 MW and 5 MW.

<u>Top10 municipalities by licensed capacity</u>	<u>Capacity (kW)</u>	<u>Share of total</u>	<u>Share in 0.5MW+</u>	<u>Share in 5MW+</u>
Mezőcsát	234,494	4.0%	5.3%	5.9%
Szolnok	163,252	2.8%	3.5%	3.9%
Kaposvár	101,054	1.7%	2.2%	2.5%
Mezőberény	100,395	1.7%	2.3%	2.5%
Inárcs	97,198	1.7%	2.2%	2.4%
Sajószöged	96,000	1.6%	2.2%	2.4%
Paks	95,092	1.6%	2.1%	2.1%
Kiskunhalas	91,845	1.6%	2.0%	2.3%
Tét	86,206	1.5%	1.9%	2.3%
Söjtör	73,771	1.3%	0.8%	0.9%

6. Table Top 10 municipalities by total licensed capacity and capacity above 0,5 MW and 5 MW.

Of the 808 municipalities hosting commercial PV plant projects, only 284 host at least one unit with a larger capacity than 0,5 MW (representing 73% of the total licensed capacity). 106 municipalities host projects with planned/built-in capacity above 5 GW, composing 60% of the total licensed capacity.

7. Table shows the concentration of licensed power plants for Hungarian counties (NUTS3 administrative level). The county-level distribution shows that Borsod-Abaúj-Zemplén and Jász-Nagykun-Szolnok counties have a noticeably higher share of licensed capacity, especially for projects above 5 MW capacity. Irradiation levels in the different countries suggest that the differences are explained either by socio-economic characteristics, land price or the availability of the infrastructure, but not the number of

hours with sunshine. Counties above the mean power density of 57 kW/km² have an average 71% GDP/capita value compared to the national average, while the counties below 86% - or 74% excluding Budapest.

<u>County (NUTS 3)</u>	<u>GDP/capita rel. to nat. avg. (2023)</u>	<u>Licensed capacity (kW)</u>	<u>Share in total capacity</u>	<u>Share of area</u>	<u>kW/km²</u>	<u>Share in 5MW+</u>	<u>Solar irradiance (W/m²)</u>
Borsod-Abaúj- Zemplén	64%	922,037	16%	8%	127	22%	1218
Jász-Nagykun-Szolnok	63%	614,051	10%	6%	110	14%	1260
Tolna	69%	311,569	5%	4%	84	7%	1276
Szabolcs-Szatmár- Bereg	58%	497,769	8%	6%	84	7%	1229
Komárom-Esztergom	98%	174,411	3%	2%	77	3%	1240
Nógrád	44%	181,823	3%	3%	71	3%	1236
Fejér	88%	295,867	5%	5%	68	5%	1263
Pest	85%	370,420	6%	7%	58	5%	1255
Mean kW/km²=57							
Bács-Kiskun	74%	447,021	8%	9%	53	7%	1279
Győr-Moson-Sopron	103%	222,347	4%	4%	53	4%	1233
Baranya	69%	233,761	4%	5%	53	2%	1278
Heves	73%	187,892	3%	4%	52	3%	1235
Vas	80%	170,832	3%	4%	51	3%	1247
Somogy	61%	285,306	5%	6%	47	4%	1271
Békés	56%	259,071	4%	6%	46	3%	1266
Veszprém	77%	201,904	3%	5%	45	3%	1252
Budapest	219%	22,091	0%	1%	42	0%	1247
Zala	69%	146,585	2%	4%	39	1%	1261
Csongrád-Csanád	76%	160,833	3%	5%	38	1%	1281
Hajdú-Bihar	73%	174,230	3%	7%	28	3%	1248

7. Table Licensed capacity in each Hungarian county (NUTS3) and in Budapest, ordered by the density of the capacity (kW/km²). Solar irradiation value is calculated by the weighted average (based on area) of the municipalities of the given county.

4.1.3.Domestic and foreign ownership

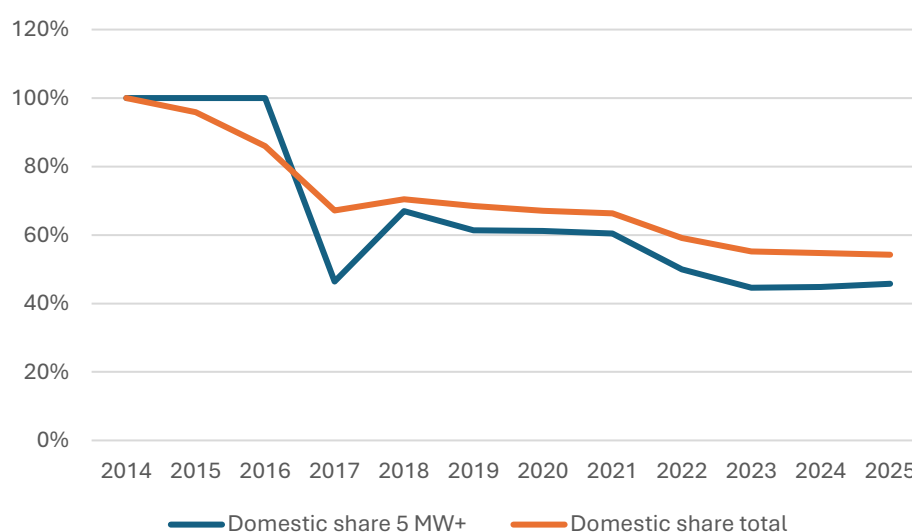
The first layer of local ownership designation is the distinction between domestic and foreign ownership. As 8. Table shows, 46% of the total licensed capacity is owned by natural persons or legal entities with official residence/registration outside Hungary. For projects licenced after 2020 (in the new FiP scheme, METÁR, which was first awarded in March 2020), i.e. projects with larger average capacity, the share of foreign ownership increases to 54%. The same shares are observed for projects with capacities above 5 MW (45-55%).

<i>All licensed projects</i>				
Owner	Total capacity (kW)	Share in total	Count	kW/owner
Domestic	3,178,686	54%	1,640	1,938
Foreign	2,681,834	46%	188	14,265

<i>Projects licenced between 2020-2025</i>				
Domestic	1,665,479	46%	400	4,163
Foreign	1,985,838	54%	112	17,730

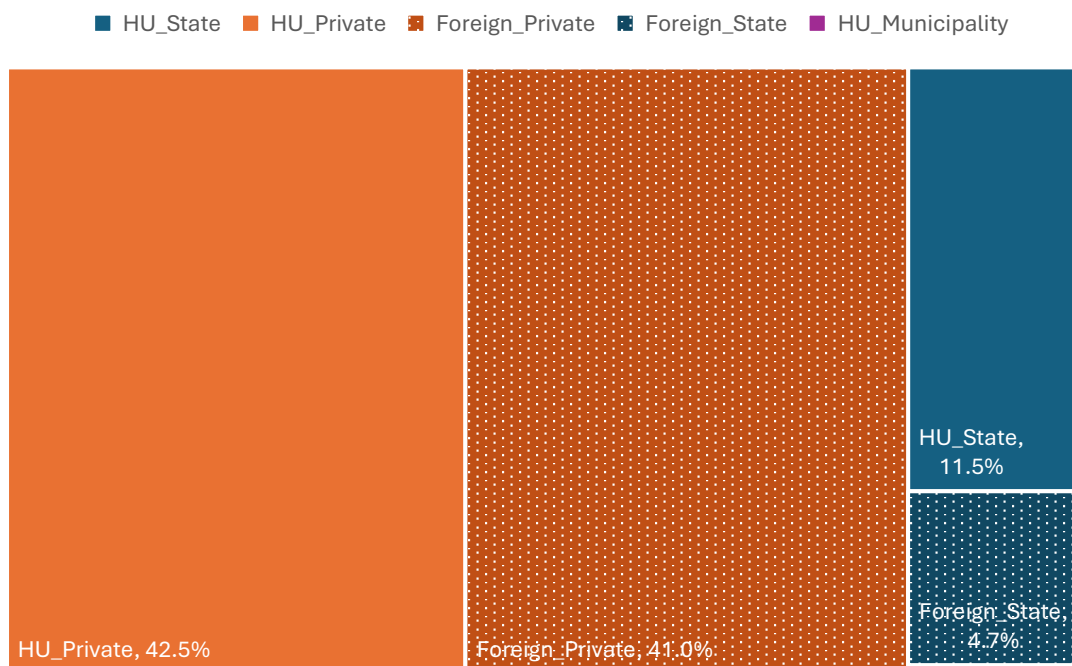
8. Table Share of the ownership of domestic (registered/resident in Hungary) and foreign natural persons and legal entities.

14. Figure shows the change in the share of domestic ownership in the incremental total licensed capacity and in projects above 5 MW, based on the date of the licence. The graph shows a relatively steady decline in domestic ownership over time, along with the entry of foreign investors into the Hungarian market, particularly in larger projects.

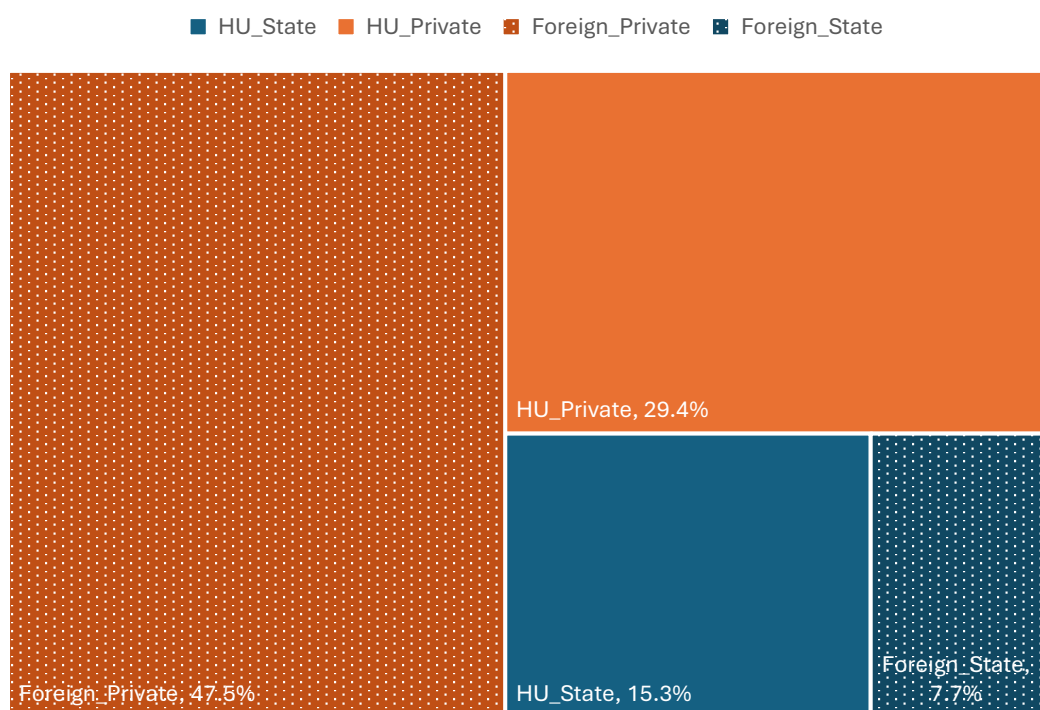


14. Figure Change in the share of domestic-owned licensed capacity over time, incrementally.

Both domestic and foreign ownership is dominated by private entities, although state ownership still makes up 16%, as seen in 15. Figure. This is noticeably different for projects above 5 MW capacity, illustrated in 16. Figure: the share of private domestic ownership decreases significantly, while Hungarian state ownership (almost exclusively through the 100% state-owned public utility company MVM Zrt.) increases, as well as foreign state and private ownership.



15. Figure Share of ownership for different entity types for the total licensed capacity.



16. Figure Share of ownership for different entity types for power plants above 5 MW capacity.

The noticeable market presence of the Hungarian state through MVM Zrt. is also apparent through its top position in the order of UBOs by total owned capacity – see 9. Table. Among the largest owners, many actual UBOs were not possible to identify,

or the UBOs are publicly traded companies. The German state is represented by Uniper, the Chinese state by several companies.

<u>Owner</u>	<u>Registered in</u>	<u>Capacity (kW)</u>	<u>No. of projects</u>
Hungarian State	HUN	681,028	236
People's Republic China	CHN	246,385	14
German State	DEU	223,995	6
MET Green Assets Holding AG	CHE	201,013	136
Central European Opportunity Private Eq. Fund	HUN	171,715	16
[Turkish citizen]	HUN	159,499	5
Voyager Private Eq. Fund	HUN	116,750	5
Enlight Renewable Energy Limited	ISR	116,625	5
[Swiss citizen]	CHE	110,390	8
[UK citizen]	GBR	110,390	8
Polat Energy Europe BV	NLD	99,750	2
EDP SA	PRT	94,907	3
KKR Group Co. Inc.	USA	94,900	2
[Hungarian citizen]	HUN	82,770	34
MOL Nyrt.	HUN	80,616	29
[Bulgarian citizen]	BGR	69,820	2
Nap Nyrt.	HUN	62,904	75
[Slovak citizen]	SVK	62,100	138
Antin Infrastructure Partners SA	FRA	48,000	1
[Hungarian citizen]	HUN	47,227	60

9. Table Top 20 UBOs of licensed power plants. The names of natural persons are replaced by their nationality.

Foreign ownership is mainly held by European entities based on the residence/official seat of the identified UBOs, as 10. Table shows. UBOs with EU residence/seat comprise 22.8 % of the total ownership, while the share of UBOs with residence/seat in Europe is 32.3% (37% if Turkey and Israel are included). The share of foreign UBOs of non-EU (and non-Hungarian) residents is 21.1%, almost as much as that of EU-resident UBOs. Although MET AG, with its 3.6% share, is somewhat distorting this data, as it is registered in Switzerland, but is suspected to be controlled by Hungarian entities. This shows that, in the Hungarian PV market, there was truly global investor interest, and it was not only incumbent actors in the EU who entered the market.

<u>Residence/Company seat</u>	<u>Capacity (kW)</u>	<u>Share of total</u>	<u>No. of projects</u>
Budapest (Hungary)	2,006,020	34.2%	1,784
Switzerland	348,015	5.9%	238
Germany	338,574	5.8%	199
PRC	290,865	5.0%	27

United Kingdom	181,092	3.1%	58
Turkey	166,185	2.8%	42
Spain	164,310	2.8%	44
Denmark	146,517	2.5%	1,094
Austria	134,316	2.3%	69
Israel	133,595	2.3%	35
France	119,281	2.0%	31
Netherlands	99,750	1.7%	2
USA	97,952	1.7%	8
Portugal	94,907	1.6%	3
Dad (Hungary)	84,831	1.4%	42
Czechia	75,139	1.3%	224
Szeged (Hungary)	74,012	1.3%	215
Slovakia	71,091	1.2%	169
Bulgaria	69,820	1.2%	2
Luxemburg	50,119	0.9%	10

10. Table Top 20 locations for residence/company seat locations - municipalities for Hungarian seats and countries for foreign registered entities.

4.1.4. Local ownership

The relatively significant share of foreign ownership and the high ratio of Budapest as the seat/residence of domestic UBOs (10. Table) suggests that there is only a relatively small room for local ownership on the municipal or even sub-regional level, especially for larger-scale projects.

There are 808 municipalities (out of 3155, excluding the districts of Budapest) that serve as sites for licensed commercial-scale PV projects. That is ca. 7 MW/settlement. However, only 334 municipalities serve as registered seats of the project companies. Budapest alone hosts more than 50% of the project companies, representing 69% of the total licensed capacity.

Domestic UBOs of the project owner companies are dispersed in 356 Hungarian municipalities. However, Budapest is also dominant in this regard, being the residence/seat of UBOs representing 63% of the total capacity, owned by domestic entities or natural persons. Excluding Budapest, the other 355 municipalities host UBOs that own an average 3.3 MW capacity. However, these owners can be considered residential owners only, as they do not necessarily share the exact location as the owned power plant (i.e. they might own a power plant in one municipality but reside hundreds of kilometres from it).

The average residential ownership capacity per capita in municipalities where at least one UBO is located is 0,99 kW/person, 1.15 kW/person in Budapest, and the top 10 highest numbers are shown in 11. Table. These municipalities represent 61% of the total population, 44% excluding Budapest.

Municipality	Share of capacity of residential ownership (from the total domestically owned)	Municipality	Per capita capacity owned by local UBOs (kW/capita)
Budapest	63.11%	Dad	86.9
Dad	2.67%	Sántos	37.4
Szeged	2.33%	Remeteszőlős	22.7
Hódmezővásárhely	1.16%	Kaszó	10.8
Bóly	1.06%	Palkonya	10.4
Székesfehérvár	1.04%	Hejce	9.1
Kaposvár	0.95%	Bóly	8.8
Hévíz	0.88%	Balatonhenye	7.8
Mátészalka	0.86%	Hévíz	6.2
Baja	0.84%	Kővágótöttös	5.7

11. Table Top 10 municipalities by the share of domestically owned capacity owned by UBOs resident in the given municipality [left]. Per capita value of domestically owned capacity under residential ownership (owned by UBOs resident in the given municipality, but not necessarily sharing the location of the power plants owned).

The list of top 10 municipalities by the share of the capacity owned by resident UBOs of the total domestically owned capacity shows a strong presence of major or mid-size towns apart from Budapest (Szeged, Hódmezővásárhely, Székesfehérvár, Kaposvár, Baja). In smaller settlements like Dad, and Hévíz, residential ownership is controlled by – as can be expected – a single individual or a family (e.g. 3 persons, likely one family in Dad). Bóly, a town with less than 4000 residents, is an interesting outlier: simply based on family names, 10 different families can be identified among the 18 distinct resident UBOs in the small town, 4 of them being relatively large owners (with at least 5% of the locally owned capacities). Mátészalka, a small- to mid-sized town of 15,000 inhabitants, also has 8, possibly separate, families, with one owning the majority (60%+) and 2 smaller families (7%) of the locally owned licensed capacities. These locations and concentrations of PV ownership can provide a good subject for case studies on local economic impacts and the emergence of local investors in such a globalised market.

There are only 148 municipalities where there is at least one local resident UBO who is an owner in a local PV plant, too, i.e. where truly local ownership can be found. There are altogether 331 projects with 176 MW such truly locally owned capacity, 3% of the total, 5.5% of the domestically owned capacity (little over 1189 kW/municipality or 0.96 kW/capita). In these municipalities, on average, 45% of the licensed capacity is owned by local UBOs. 12. Table shows the 10 municipalities with the largest nominal licensed truly locally owned capacity.

Municipality	Capacity (kW)	kW/capita	Share of locally owned PV capacity in the total licensed capacity in the municipality
Jászberény	9,771	0.37	65.2%
Kisvárd	8,208	0.54	78.7%
Győr	7,919	0.06	33.9%
Nyíregyháza	7,179	0.06	43.3%
Szeged	6,191	0.04	11.7%
Sántos	5,492	11.8	84.6%
Mátészalka	5,371	0.34	64.2%
Komló	4,487	0.20	24.4%
Baja	4,344	0.13	29.9%
Mosonmagyaróvár	4,295	0.13	17.0%

12. Table Top10 municipalities based on locally owned capacity; per capita value of that capacity, and its share in all capacity licensed in the same municipality.

There are only 17 projects with a capacity between 1 and 5 MW, and 2 projects with a capacity above 5 MW, in which at least one UBO is a local resident. The average capacity of locally owned projects is 657 kW (the total average of all licensed capacity is 1568 kW), and most of them (278) were licensed before 2020, i.e. most of them are KÁT recipients. The projects licensed after 2020 are – based on their project companies – mostly projects installing panels on or near commercial or industrial units (shopping malls, warehouses, production facilities), whose parent companies are partially locally owned.

There are 3 districts (LAU 1) from the total 174 (excluding Budapest) that have 0 licensed solar PV capacity in their territories. At the same time, there are 35 districts where no project company is seated. Of course, districts excluding Budapest host only 32% of the total capacity for project companies.

Excluding Budapest, 134 districts host at least one UBO, and these UBOs control 37% of the total domestically owned capacity, i.e. 636 MW, or 11,2% of the total licensed capacity. The rest of the UBOs are residents of Budapest.

5.2% (302 MW) of the total licensed capacity is owned by UBOs from the same district (Járás) where the capacity is located (i.e., truly local ownership). That is an increase by a factor of 1.7 compared to the municipal capacity. The average project size is also somewhat larger: 749 kW versus 657 kW, though still far from the national average of 1522 kW. There are 27 projects between 1-5 MW out of the total 522, and 5 projects are larger than 5 MW.

There are no counties (NUTS 3) that do not host either a licensed PV project or project company, or a domestic UBO. Truly local ownership increases to a total of 530 MW, a factor of 1,7 again, if the level of spatial analysis is at the county level. The constant growth factor is noticeable, as the rate of increase in average population is a factor of 18 from municipalities to districts and 8 from districts to counties.

13. Table shows the most important metrics on ownership on county level. Truly locally owned capacities account for more than 10% of total capacity in 8 counties, and it is hard to identify common socioeconomic or environmental factors across these counties. The share each county takes from the total of truly locally owned capacities, and the other metrics suggest that counties with lower GDP/capita values tend to have relatively more truly locally owned capacities (Szabolcs-Szatmár-Bereg especially, but also Borsod-Abaúj-Zemplén, Somogy, Baranya, and Somogy). This is less likely to be an explanatory factor, but it suggests that economically less developed countries can possibly receive more local economic impact through ownership than the average. However, per capita terms are low in either case: the maximum annual electricity production in a county from truly locally owned solar PV plants is 82 kWh, with a market value to the environment of 8-10 EUR/annum.

County (NUTS 3)	Share of the truly locally owned capacity in the total licensed capacity located in the county	Share of the county in the total truly locally owned capacity in Hungary	Licensed PV capacity located in the county/capita (kW)	Residential ownership /capita (kW)	Truly local ownership /capita (kW)
Bács-Kiskun	7.46%	6.29%	0.92	0.14	0.07
Baranya	17.53%	7.73%	0.67	0.26	0.12
Békés	4.11%	1.97%	0.83	0.05	0.03
Borsod-Abaúj-Zemplén	7.62%	13.24%	1.51	0.15	0.11
Budapest	9.41%	0.39%	0.01	1.19	0.00
Csongrád-Csanád	24.87%	7.54%	0.41	0.33	0.10
Fejér	9.03%	5.03%	0.71	0.11	0.06
Győr-Moson-Sopron	13.02%	5.48%	0.47	0.12	0.06
Hajdú-Bihar	16.90%	5.55%	0.33	0.09	0.06
Heves	11.91%	4.22%	0.67	0.09	0.08
Jász-Nagykun-Szolnok	2.88%	3.33%	1.76	0.09	0.05
Komárom-Esztergom	24.68%	7.48%	0.54	0.32	0.13
Nógrád	0.70%	0.24%	1.02	0.02	0.01
Pest	8.61%	6.01%	0.28	0.13	0.02
Somogy	6.64%	3.57%	0.98	0.23	0.07
Szabolcs-Szatmár-Bereg	12.70%	11.89%	0.95	0.17	0.12
Tolna	7.67%	4.51%	1.52	0.15	0.12
Vas	4.04%	1.30%	0.70	0.04	0.03
Veszprém	9.36%	3.56%	0.61	0.10	0.06
Zala	2.44%	0.67%	0.57	0.16	0.01

13. Table County-level data on local (in this case, spatially within the boundaries of the county) ownership. Every data point below the column average is marked in red, while every data point above the column average is marked in yellow.

4.2. Impact through taxes (commercial-scale)

4.2.1. Methodology

In Hungary, taxes are imposed either on the national or on the municipal level; administrative levels in between have no tax authority (except for four specially designated industrial parks between 2020 and 2024). Local taxes are regulated by law 1990/C.

There are three local taxes to which solar power plants can be subject in municipalities, one levied on business activity, and two on property:

- **Local Business Tax.** Each company is subject to the local business tax in the municipality it is either registered in, or has an official site of operation in. The tax level is set by the municipality, but the maximum is 2% of the tax base

(annual sales revenue of the company reduced by the cost of materials, the purchase value of goods sold, the costs of subcontractors, intermediary services, and basic research, applied research, and development) (Magnet Faktor 2024). The tax must be divided between all municipalities the company has its registration or has an operational site in. The rule of division is differentiated by the income level of the company. Under 100 million HUF tax base, it can choose to share between the municipalities either according to the asset value or the personal expenditure in each site. Above 100 million, it needs to use the combination of the two methods.

- Land Tax. Each empty lot (or the area of the lot without a building) within the administrative border of a municipality can be subject to the tax, with few specific exemptions: any parcel in agricultural use in the interior area of the municipality is exempt, while for lots on which building is prohibited 50% tax reduction is applied. The tax rate is set by the municipality adhering to a certain maximum level (changed each year along with the inflation rate).
- Building Tax. A third tax, the Building tax, could also apply if the solar power plants would be considered buildings. A decision by the Hungarian Constitutional Court from 2021 suggests that parts of a solar power plant can be considered buildings, hence local taxes on non-residential buildings may apply to them, although the tax level cannot be excessive (*Újszentiván Község Önkormányzat Képviselő-testületének a helyi adókról szóló 17/2015. (XI. 30.) önkormányzati rendelete 6. § (2) bekezdése, valamint a Szegedi Törvényszék 101.K.700.642/2020/5. számú ítélete elleni alkotmányjogi panasz (telekadó) 2021*). However, the legal situation is not clear. Nevertheless, the Land and Building Tax are mutually exclusive; a land plot can either be taxed as an empty land or as a building if it's built on. Therefore, both taxes cannot be applied for the same solar capacity.

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 tax data as of March 2025.

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 is not publicly available information. Therefore, a score is applied for each municipality

to help estimate the potential tax revenue. For each project, the capacity of the power plant is taken as a base, assuming that the size of the tax base is a linear function of the built-in capacity. For each project owner company that is registered in a different municipality than where the power plant is located, half of the capacity is assigned to each of the municipalities. Each project is calculated separately, regardless of how many municipalities the given company operates PV power plants in. Then the total capacity is summed and multiplied by the tax rate to acquire the 'Business Tax score of the municipality. 14. Table below is an illustrative calculation of the Business Tax score. The Business Tax Score is measured in MW capacity (that is taxable locally).

Project owner company	Company is registered to	PV is located in	Capacity
First Solar	Town A	Town A	10 MW
Second Solar	Town B	Town A	7 MW
Third Solar	Town C	Town B	5 MW
Third Solar	Town C	Town D	1 MW

Company/Capacity	Town A	Town B	Town C	Town D
First Solar	10 MW	0	0	0
Second Solar	$7/2=3,5$ MW	$7/2=3,5$ MW	0	0
Third Solar	0	$5/2=2,5$ MW	$5/2+1/2=3$ MW	$1/2=0,5$ MW
Total capacity	13,5	6	3	0,5
Tax rate	2%	1,5%	2%	1%
'Business Tax score	0,27	0,09	0,06	0,005

14. Table An illustrative example of the calculation of the Business Tax Score for four projects owned by three project companies in four different municipalities.

This method can only provide an indicative estimation of the potential of local tax income from the Business Tax, and only for the 2025 fiscal year. However, it can enable comparisons between municipalities.

Concerning Land and Building Tax, Municipalities have a high degree of freedom in determining whether legal entities and/or natural persons are tax subjects, whether certain buildings or locations are exempt from the tax, or whether they set different tax rates for different building/land types. Therefore, providing an exact tax income value for each municipality would require processing the relevant local tax decrees individually.

This analysis focuses only on Land Tax and disregards the local Building Tax. The current legal situation is uncertain as to whether solar power plants can be considered buildings, and the Land Tax rate per m² is lower in every municipality than the Building Tax rate (as of 2025). Therefore, calculating the potential Land Tax for each municipality can provide a better baseline approximation for local tax income for 2025 than assuming that Building Tax is applied.

The TZ-SAM database (used for the land-use impact analysis, see subchapter 5.1) provides a 56 W/m² power density value for the Hungarian commercial PV plants (after excluding 14 outliers or 1% of the total observations). Using that value, for each municipality, the total area of the licensed power plants is calculated based on their total capacity.

Power plants located on the rooftops of industrial buildings or areas covered artificially cannot be considered as land, so it is most likely not a tax subject in most or all municipalities. From the TZ-SAM database for each municipality, the share of existing commercial-scale PV plants on the following surfaces was calculated:

- Urban fabric
- Industrial, commercial and transport units

Then, the share of this non-taxable PV capacity was applied to municipal-level data on licensed power plants, assuming that the same ratio would approximate the land-use ratio of all local commercial-scale licensed power plants. For the tax base calculation, the total capacity not assumed to be built on the aforementioned artificial sites was taken as a base. For municipalities with no TZ-SAM data available (ca. 17%), the average ratio across all municipalities was used (9,8% artificial coverage and 90.2% land coverage).

For tax rate, the current official data is used for each municipality (MÁK 2025). For Budapest, the average of the district-level tax rate is used.

4.2.2. Business tax (HIPA)

There are 887 municipalities that could theoretically receive local business tax (helyi iparűzési adó, HIPA) from the operator/owner companies of the licenced large-scale solar capacities in Hungary. However, in 17 of them, the tax rate is 0%, including Újlengyel, with a total taxable capacity of 32.9 MW out of the total untaxed 56.6 MW

(according to the model used in this analysis. Újlengyel has the 20th largest modelled taxable capacity of all locations).

The vast majority, 4,762 MW of the total 5,860 MW (81%) is taxed in municipalities with the maximum allowed 2% tax rate. This is partly explained by the fact that Budapest, with a 2% tax rate, hosts 34% of the total taxable capacity (1,947 MW). Excluding Budapest somewhat decreases the average tax rate: while the capacity-weighted average tax rate for total capacity is 1.93%, without Budapest it is reduced to 1.89%.

15. Table shows that the licensed PV plants (based on the capacity, not the number of projects) are taxed on average with a higher HIPA rate than the national average, i.e. PV capacities and their license-owner project companies are located in municipalities that have on average higher tax rate, than the national average. This suggests that the local HIPA rate is not a decisive factor in the location of either the PV plants or the project companies. If looking into the location of the project companies only, the capacity-weighted average of the HIPA rate decreases from 1.95% to 1.85%. The same value for the capacity-weighted average HIPA rate for municipalities physically hosting the licensed power plants is 1.9%, whether Budapest is included or not. This could suggest some level of tax optimisation, but even the 1.85% is above the weighted average national HIPA rate of 1.76%.

HIPA tax rate	Incremental occurrence in the total population	Incremental occurrence for the total PV capacity	Incremental occurrence for the total PV capacity excluding Budapest
0-0.5%	1%	1%	2%
0-1%	9%	1%	2%
0- 1.25%	11%	1%	2%
0-1.5%	27%	7%	11%
0-1.7%	34%	11%	16%
0- 1.95%	42%	16%	24%
2%	100%	100%	100%

15. Table Comparison of the HIPA tax rate for licensed solar capacities and the national average. The tax rate brackets are incremental, Each bracket shows the share of the municipalities (for the total population) or the share of capacity that is taxed either at or below the maximum value of the bracket. For example, while only 1% of all the Hungarian municipalities use a HIPA rate at or below 0,5%, 27% use 1,5% or less, and 58% use 2% (there is no intermediate step from 1,95% to 2%).

The distribution of the potential HIPA income is somewhat uneven throughout the country, as shown by 16. Table. Budapest is the seat of so many project companies that almost 70% of the taxable capacity on behalf of the project companies is in the capital. At the same time, the 34% share is roughly equal to the share of Budapest from the total national GDP.

Municipality	Taxable capacity (kW)	Business Tax Score	Share in total	2022 HIPA/capita income compared to the national average
Budapest	1,946,708	38,934	35.7%	434.1%
Kazincbarcika	133,190	2,664	2.4%	616.8%
Mezőcsát	117,247	2,345	2.2%	32.8%
Szolnok	75,193	1,504	1.4%	196.9%
Szeged	73,989	1,480	1.4%	148.1%
Tiszaújváros	84,985	1,275	1.2%	1154.2%
Szombathely	61,992	1,240	1.1%	245.7%
Kaposvár	51,750	1,035	1.0%	147.2%
Inárcs	50,336	1,007	0.9%	62.7%
Sajószöged	48,000	960	0.9%	137.2%

16. Table Top 10 municipalities by the Business Tax Score (taxable capacity times the local tax rate) that captures the local business tax (HIPA) potential for each municipality.

The top 10 municipalities based on the HIPA score are mostly cities with relatively large HIPA/capita income (only Mezőcsát and Inárcs are under the national average). The largest share of potential HIPA income from solar capacity goes to municipalities with already high levels of HIPA income.

Out of the 887 municipalities with potentially taxable capacity, 411 were below the national average of the personal tax (SZJA) base per capita in 2022 (an estimate for the income level, hence the affluence of the municipality); their average was 82%. 8 of these (out of the total 17) have 0 HIPA rate, while they are on average at 74% of the average national per capita personal tax base level. The average per-capita tax base value across the 887 municipalities is 105% of the national average. However, only 17.6% of the total Business tax Score is in these 411 municipalities (even after excluding Budapest the share of these municipalities increases only to 27%). These figures suggest that licensed capacities are more likely to be located in relatively wealthier municipalities, limiting the local impact in reducing inequalities, including for municipal administrations.

The interviews with the municipalities provided examples for smaller (under 1000 population) settlements, where the local HIPA income is dominated by the income from the PV project company. This was a significant budget boost for these municipalities (if they were allowed to keep the extra income, since in recent years extra HIPA income has often been collected by the central government). However, this also poses a risk, as these municipalities become exposed to the timely payment of the company. There was at least one municipality that, when selling its land to the project developer, included it in the contract that, in case the company is not obliged to pay local business tax (e.g. due to legal changes), it still must pay the same amount in some other form into the municipality's budget.

4.2.3.Land tax

Land tax is potentially relevant only for the 807 municipalities providing the territory for the licenced power plants. However, Land tax is only introduced in 177 municipalities out of the 807. The total potentially taxable capacity in the municipalities actually introducing Land tax is 1760 MW, 33% of the total potentially taxable capacity in Hungary.

There are 12 municipalities, listed in 17. Table, with a Land tax potential above 10,000 HUF/capita. The average value for all 177 settlements is 3556 HUF/capita. 54 of 177 municipalities are below the national average for the per capita personal income tax base level and can therefore be considered relatively poorer. Their average is 85% of the national average. These municipalities host 330 MW capacity, 18% of the 1760 MW, significantly less than their numerical share.

Municipality	Land tax/capita (HUF)	Ratio of the personal tax base to the national average
Sajószöged	206,740	151%
Szuhakálló	89,414	103%
Zalaszentiván	69,474	113%
Gyöngyöshalász	59,547	126%
Buzsák	51,835	81%
Berente	35,340	126%
Szőc	27,942	59%
Mátraverebély	25,452	68%
Sajókaza	22,144	66%
Ballószög	21,182	142%

Kaposvár	13,692	118%
Und	10,371	87%

17. Table Municipalities above 10000 HUF/capita Land tax potential.

There are 5 settlements where the potential local Land tax would comprise more than 10% of the total municipal budget revenue of 2022 - 18. Table. For an additional 29, the value is between 1-10%. The average for the 177 municipalities is 1.6%.

Municipality	Ratio of the potential Land tax revenue in the total 2022 budget	Ratio of the personal tax base to the national average
Sajószöged	70.0%	151%
Szuhakálló	31.6%	103%
Zalaszentiván	27.9%	113%
Gyöngyöshalász	24.2%	126%
Szőc	16.8%	59%
Ballószög	7.7%	142%
Mátraverebély	7.1%	68%
Und	7.0%	87%
Sajókaza	6.5%	66%
Baracska	5.1%	94%

18. Table Top 10 municipalities by the share of the potential Land tax in their 2022 budget.

The Land tax potential estimate shows that most municipalities do not utilize the potential of this income for most of the licensed capacity. Relatively poorer municipalities are somewhat underrepresented in terms of taxable capacity compared to municipalities with higher-than-average per capita income. Introducing a 126 HUF/m² (the current average of the 177 municipalities with Land tax in place) Land tax for all municipalities with licensed PV capacities would triple the total annual income from close to 4 bn HUF to over 12 bn HUF a year.

Out of the 9 interviewed municipalities, 6 had commercial-scale PV capacities in their territories. All 7 reported that their only tax income from these plants is the local business tax, and no land or building tax is levied upon them.

4.3. Impact through cost-reduction (residential)

4.3.1. Methodology

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 generalized modelling or examining single case studies (M. 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.

To calculate the income effect from the operation of the household projects (HMKE) on the municipal level, the following methods and inputs were used:

1. The variation of solar irradiation was approximated by the differences in the municipal average irradiation rate. The data was derived from the 'long-term yearly average of potential photovoltaic electricity production' metric of the SolarGIS spatial database (World Bank 2019). The average value for the territory of the municipality was calculated, and then for every municipality, a general 1150 kWh/kW/year capacity utilization value was multiplied by the deviation of the solar irradiation output value of the municipality's territory from the national average. The resulting municipal utilization rates, adjusted for the differences in solar irradiation, range from 1070 to 1196 kWh/kW/year.
2. The data for the number of households with residential solar panels in each municipality is derived from the 2022 National Census. As only the number of installations is provided, the capacity is estimated. The estimate is done using a lower and an upper bound. The national average capacity of HMKE projects in 2022 was 8,7 kW (MEKH 2024b). However, in 2021, Horváth, Tamás, and Éva (2021) found that the mode of the capacity of the HMKEs owned by natural persons is 5 kW⁴. A 5 kW unit produces roughly 5.2-6 MWh a year (depending

⁴ The number of non-household HMKEs, i.e. HMKE-sized units operated by SMEs and public institutions (schools, hospitals, etc.) is likely small, in 2022, roughly 6000 (in 2022, there were 171.589 HMKEs installed, and the national census lists 165.298 households with solar panels). However, 6000 HMKE with 50 kW capacity each (the upper capacity limit) can provide 20% of the total installed HMKE capacity, distorting the average.

on the location and orientation). That is double the national average annual electricity consumption per household (see point 5. below). However, it can be assumed that residential PV is installed mostly by households with larger consumption (either because of higher affluence or more household members), and that PV systems are often oversized, as the previous support scheme and investment grants did not incentivise such optimisation⁵. This oversizing is confirmed by Gergely et al. (2025), who find in their survey that among the respondents, the PV unit has an average 14% higher capacity than the annual household electricity demand.

3. The legal framework governing the settlement and the potential income from HMKE operation changed in 2022, effective in 2024 (see Chapter 1.5), introducing the gross accounting framework and replacing the net metering (annual netting) scheme. However, for 2022 data, the original net metering framework should be used.
4. The net metering (balance settlement) framework simply nets the annual PV production from the annual consumption of the household, and the household needs to pay the electricity fee for its consumption above its yearly total production.
5. For electricity consumption in the households, a 2,913 kWh/year/household value was used. The value was derived by dividing the total amount of household electricity supplied in 2022 by the number of households in 2022. This is far below the estimated yearly average production of 5,350-5,981 kWh. Therefore, all HMKE-operating households are assumed to be net producers of the grid.
6. For the price level, the changes in the residential pricing introduced in Summer 2022 are applied: 36 HUF/kWh under a monthly 210 kWh cap and 70.1 HUF/kWh above 210 kWh, while 4.92 HUF/kWh revenue for electricity supplied to the grid.
7. To calculate the savings from HMKEs in each municipality, the following calculation was used:

⁵ The most recent EU-funded grant available for natural persons had a maximum 5 kW limit on supported projects, which, under the net metering scheme still available for some of the recipients of that grant, could be a rational investment choice.

$$MC = N_{hh} * (D_{rp} * P_r + D_{mp} * P_m + Q_{pv} * P_g)$$

where

MC: total cost effect in municipal aggregation (HUF)

N_{hh} : number of households in the municipality with PV HMKE

D_{hh} : annual electricity consumption of an average household=2913 kWh

D_{rp} : annual demand served with the limited residential price=2523 kWh

D_{mp} : annual demand served with the market-based price = $D_{hh}-D_{rp}$

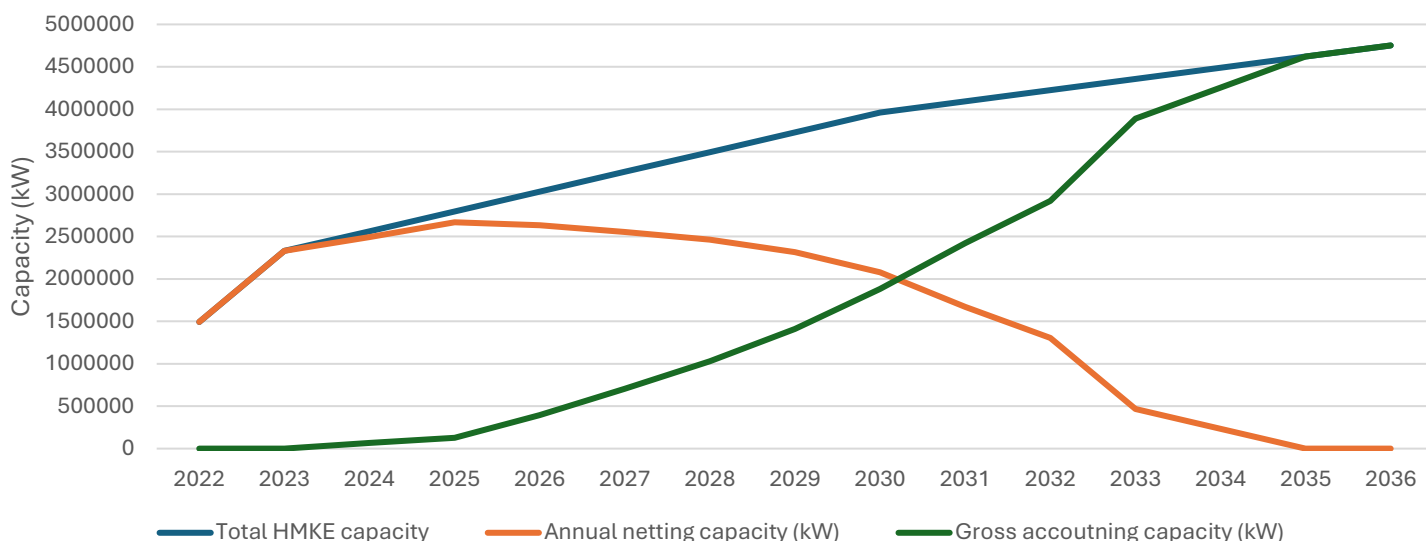
Q_{pv} : HMKE production above the average household annual demand

P_r : limited residential price, 36 HUF/kWh

P_m : market-based electricity price for the consumption above 2523 kWh, 70,1 HUF/kWh

P_g : price paid to the prosumer for the electricity provided for the grid, 4,92 HUF/kWh.

8. For illustrative purposes, the potential income is also calculated with the newly introduced gross accounting framework too, which applies to all HMKE units which are either older than 10 years or whose license for installation was requested before September 2023 and are installed by 2026. As the modelling in 17. Figure shows, by 2035, 100% of the built-in HMKE capacity will use gross accounting, but the share of net metering might remain above 50% until 2030. For gross accounting, the electricity service provider pays for the HMKE-produced electricity (currently 4,92 HUF/kWh on the national average), while the household pays for the electricity it consumes from the grid. There is no netting whatsoever. Therefore, HMKE owners are strongly incentivised to use their own production behind the meter (and possibly install storage units too). In general, if an average user described above (5 kW HMKE, 2913 kW annual consumption, 1150 kWh/kW utilisation rate) can use 50% of its self-production to offset electricity bought from the service provider, they can see similar savings as the users in the net metering framework, assuming the same price levels.



17. Figure A modelled increase in the HMKE capacity and the capacity under net metering and gross accounting.

The model in 17. Figure starts from 2023 data and extrapolates based on the 2030 and 2050 national solar capacity targets of 12 GW and 20 GW, respectively – although the latter is not an official policy target, just an assumption in the most up-to-date national strategic document, the National Energy and Climate Plan (Energiaügyi Minisztérium 2024). The model assumes that the roughly 33% share of HMKE capacity in the total built-in solar capacity that was valid between 2016-2023 will remain the case in the future too, therefore assuming 3.96 GW HMKE capacity by 2030 and 6.6 GW by 2050. Between these dates, the increment is assumed to be linear (blue line). The model assumes a 25-year lifespan for PV modules, and since the capacity installed before 2010 is negligible, no reduction in HMKE capacity due to the end of the useful lifespan should occur prior to 2035.

4.3.2. Results

The local value addition from the ownership of household solar panels (HMKEs) is approximated by the local income effect of these units for the households owning them. These values are aggregated on the municipal level.

Based on the model used in this analysis, the average income effect from the operation of a 5 kW rooftop panel in Hungary in 2022 was 133,136 HUF/household or 22 billion HUF in total. This result is heavily dependent on what the starting assumptions are on the capacity of the individual residential units and the annual household level consumption. The values above (5 kW and 2,913 kWh) are the best available, non-

biased estimates from the literature and public datasets. But to account for the sensitivity, in 19. Several scenarios are calculated based on different capacities (2.5 – 3.5 – 5 kW) and demand (2523 – 2913 – 4000 – 5000) values, to cover cases with higher consumption (4 and 4+ family homes) and smaller PV capacities, optimised for covering self-consumption. These scenarios show a range of 70-200% relative to the baseline estimate of the annual household income effect of HUF 133,136.

ANNUAL HOUSEHOLD INCOME EFFECT FROM RESIDENTIAL PV, HUF (NATIONAL AVERAGE)

		Annual household consumption (kWh)			
		2523	2913	4000	5000
Average residential capacity (kW)	2,5	93,570	119,206	195,375	265,475
	3,5	99,228	124,649	195,594	265,475
	5	107,716	133,136	203,987	269,167

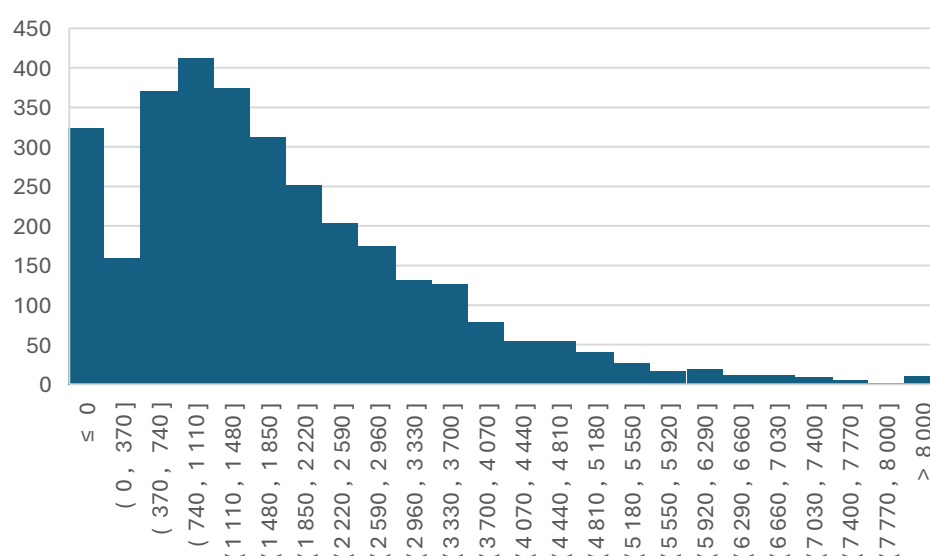
19. Table Annual household income effect from the operation of a residential PV plant under net metering schemes in different capacity and consumption scenarios.

Continuing with the original assumptions on 5 kW/unit capacity and an annual 2913 kWh/household consumption, residential PV plants' estimated production covered on average 6% of the household electricity consumption in all municipalities, 6.7% excluding municipalities with 0 installations. The top 10 municipalities have an average value of 35%. The top 10 districts (LAU 1, including the Districts of Budapest) are shown in 20. Table. Many of these are suburban areas in and around Budapest, showing that solar panels are not only favoured by the suburban lifestyle. Their sudden concentration, however, leads to significant grid issues in areas where the grid and transformation infrastructure were sized for a smaller population and next-to-no prosumers.

District (LAU1)	Share of the estimated household solar production in the total household consumption, 2022
Budakeszi	22.3%
Pilisvörösvári	17.4%
Dunakeszi	17.0%
Budapest XX.	15.0%
Veszprémi	14.8%
Győri	14.4%
Érdi	14.3%
Budapest III.	14.2%
Gárdonyi	13.6%
Gödöllői	13.6%

20. Table Top 20 districts by the share of the estimated production by household solar panels in the total electricity supplied for households.

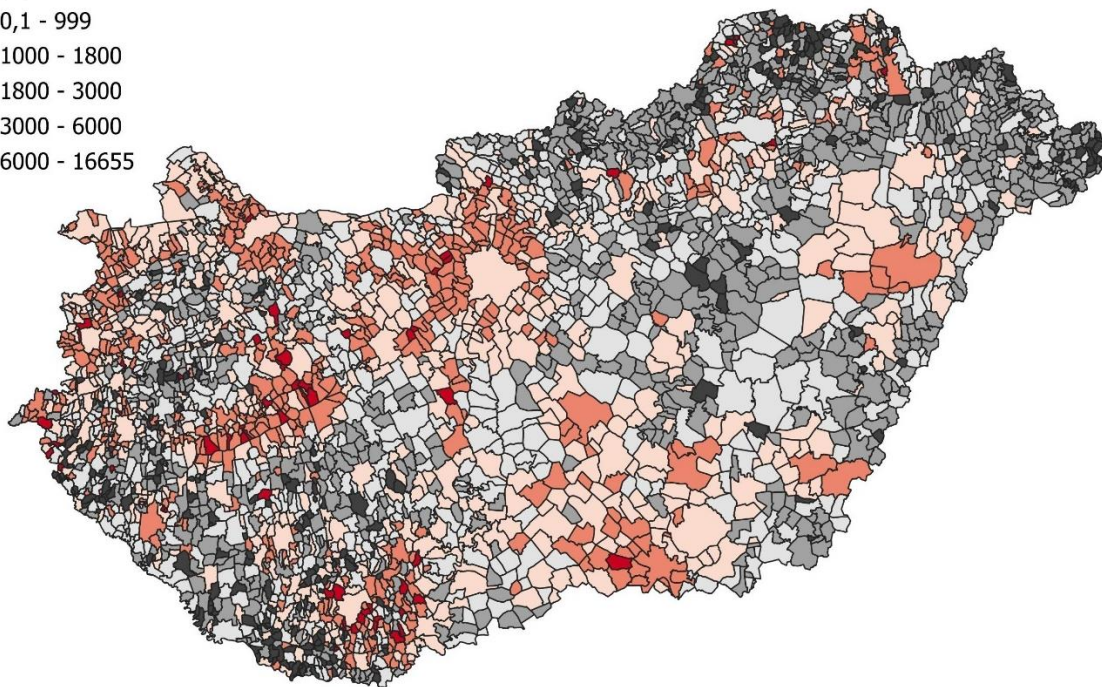
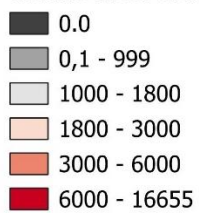
For municipalities with at least one household PV installed (89,8% of all municipalities) the average per capita income effect is 1,786 HUF per year. For the top 10% of municipalities in terms of income per capita, the value is 5,164 HUF/capita/year on average, and 0.26% of the tax base. The distribution curve of the per capita income effect values on 18. Figure shows a positively skewed distribution, suggesting that there are relatively few municipalities with relatively extremely high levels of income effect (i.e. high levels of per capita residential PV units).



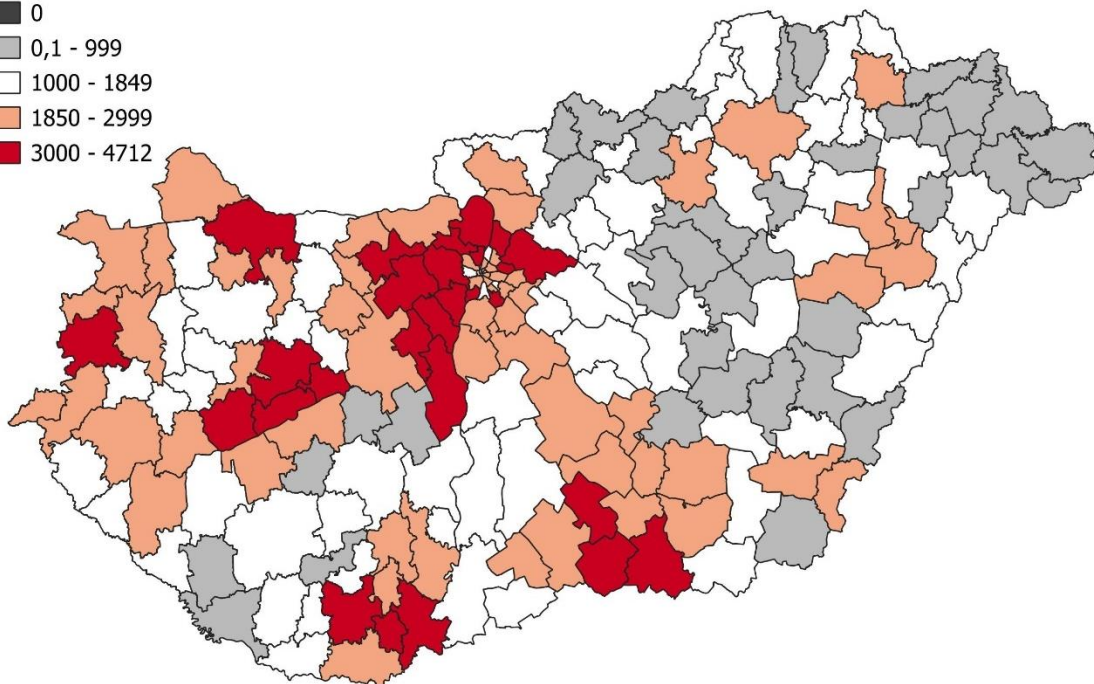
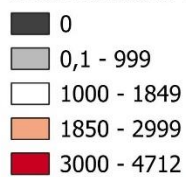
18. Figure Distribution of municipalities by income effect/capita.

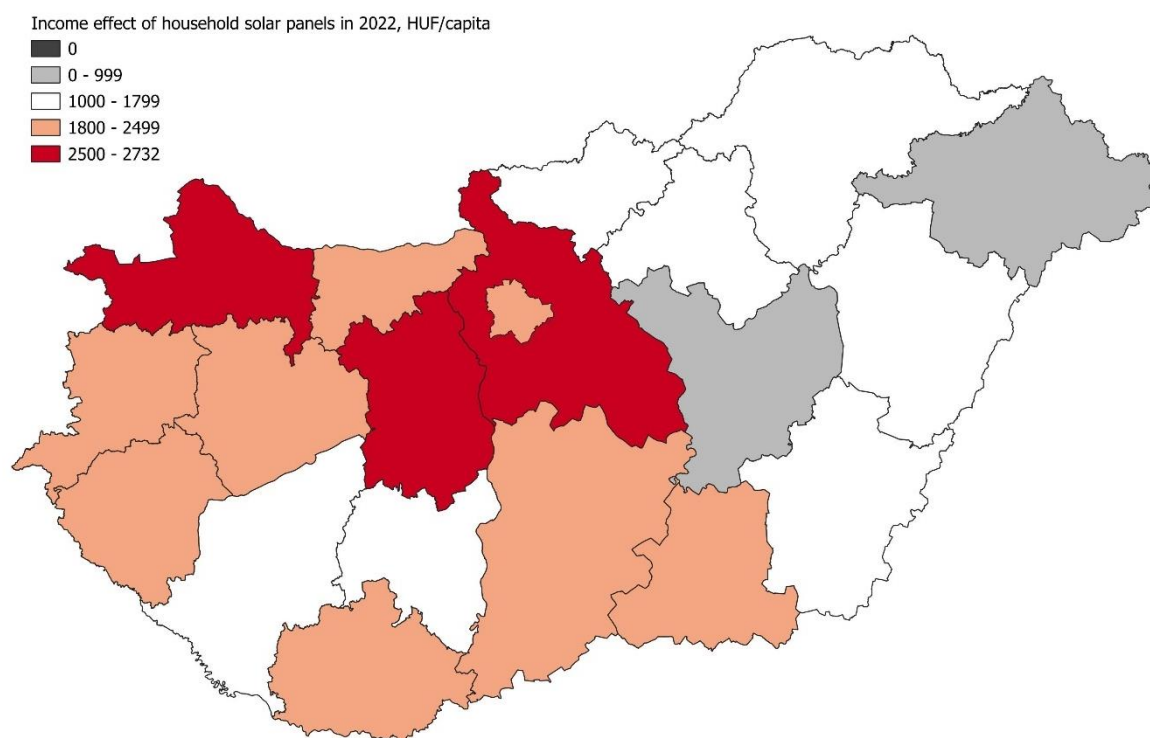
Maps 1-3. show the geographical distribution of the estimated per capita income effect on three different administrative levels (Municipal, District and County). The values for Districts and Counties are the averages of the municipalities within their boundaries. The maps show that – as expected – the distribution of solar panel-equipped homes defines the distribution of the estimated income effect, too. Mostly regions with higher socio-economic status and especially regions favoured by households leaving Budapest to its agglomeration or the vicinity of Lake Balaton, as well as the agglomerations of major cities like Szeged, Pécs, Győr, Veszprém, Székesfehérvár, and Szombathely stand out, Debrecen and Miskolc (major centres in the Eastern part of the country) to a lesser degree.

Income effect of household solar panels in 2022, HUF/capita



Income effect of household solar panels in 2022, HUF/capita





1. Maps The average of the estimated municipal income effect of household solar panels on Municipal (LAU2), District (LAU1) and county (NUTS 3) levels.

Comparing the income effect to the total local income (measured by the total personal tax [SZJA] base in the municipality), the average of the municipalities is slightly less than 0.1%. There is one single outlier case well above 1% (Felsőszenterzsébet, a small village of 16 inhabitants with a high share of PV but a low-income level). Even the second highest is only 0.68%; the top 10 has an average of 0,56%, and the top decile 0.26% (excluding municipalities with no HMKE).

In general, the introduction of the gross accounting scheme drastically reduces the potential income effect for households that cannot utilise their own production behind the meter. For a typical household, described earlier, the annual average income is only 28,200 HUF if no electricity consumption is avoided. To be on par with the net metering model, 100% of the electricity produced should be utilised behind the meter, assuming no other income, or the off-take price should increase from 5 to 23 HUF, assuming no avoided cost. Therefore, if regulation or pricing doesn't change and household-level electricity storage does not catch up rapidly, the local income effect of

residential PV units presented above will quickly diminish by 2035, when all the capacities will be under the gross accounting scheme.

The actual reduction in expected residential income is approximated by the following model.

$$MC_g = Q_{bm} * P_r + (Q_{bm} - 2523) * P_m + Q_g * P_g$$

where

MC_g: total cost effect on household level in gross accounting (HUF)

Q_{bm}: annual HMKE power production consumed behind the meter (i.e. avoided consumption from the grid)

*Q_{bm}=HMKE capacity (kW)*Annual irradiation (kWh/kW)*share of behind the meter consumption (%)*

Q_{bm} is maximised at 2523 (quantity limit of residential price)

if Q_{bm}-2523<0, then the second term (Q_{bm}-2523)=0

Q_g: annual HMKE power production supplied to the grid

Q_g=Total annual household consumption-Q_{bm}

if Q_{bm}-2523 is < annual household demand, then Q_g=0

P_r: limited residential price, 36 HUF/kWh

P_m: market-based electricity price for the consumption above 2523 kWh, 70,1 HUF/kWh

P_g: price paid to the prosumer for the electricity provided for the grid, 4,92 HUF/kWh.

Based on that limited model, several scenarios are calculated using the same values, as earlier for the sensitivity analysis of income from the net metering scheme (2.5 – 3.5 – 5 kW unit capacity and 2523 – 2913 – 4000 – 5000 kWh/a household consumption). These scenarios are differentiated using three values for the share of the behind-the-meter consumption: 30% (no electricity storage, just pure self-consumption), 50% (small battery or Electric Vehicle with limited home charging),

100% (assuming a large, 10+ kWh battery or full and day-to-day home charging of an EV).

30% self-consumption

ANNUAL HOUSEHOLD INCOME EFFECT FROM RESIDENTIAL PV, HUF (NATIONAL AVERAGE)					
		Annual household consumption (kWh)			
		<i>2523</i>	<i>2913</i>	<i>4000</i>	<i>5000</i>
Average residential capacity (kW)	<i>2.5</i>	43,810	45,729	51,077	55,997
	<i>3.5</i>	56,369	58,288	63,636	68,556
	<i>5</i>	75,208	77,127	82,475	87,395

50% self-consumption

ANNUAL HOUSEHOLD INCOME EFFECT FROM RESIDENTIAL PV, HUF (NATIONAL AVERAGE)					
		Annual household consumption (kWh)			
		<i>2523</i>	<i>2913</i>	<i>4000</i>	<i>5000</i>
Average residential capacity (kW)	<i>2.5</i>	64,742	66,661	72,009	76,929
	<i>3.5</i>	85,674	87,592	92,940	97,860
	<i>5</i>	127,208	129,126	134,474	139,394

100% self-consumption

ANNUAL HOUSEHOLD INCOME EFFECT FROM RESIDENTIAL PV, HUF (NATIONAL AVERAGE)					
		Annual household consumption (kWh)			
		<i>2523</i>	<i>2913</i>	<i>4000</i>	<i>5000</i>
Average residential capacity (kW)	<i>2.5</i>	127,208	129,126	134,474	139,394
	<i>3.5</i>	202,170	204,089	209,437	214,357
	<i>5</i>	318,080	318,080	321,881	326,801

21. Table Annual household income effect from the operation of a residential PV plant under gross accounting scheme in different capacity, consumption and self-consumption scenarios.

21. Table shows that the introduction of gross accounting schemes significantly reduces the expected income from residential PV systems – roughly halves it - unless the household can increase its self-consumption share significantly above 50%, either through demand optimisation or with batteries. While achieving 100% self-consumption from spring to autumn can be feasible by short-term storage solutions (batteries), covering 100% of winter electricity demand, especially heat pumps, likely requires extra investments and vastly oversized PV and/or battery capacities.

4.4. Impact on local businesses and employment

4.4.1. Methodology

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.

The exact datasets used:

- Household PV: number of households with solar panels installed in each municipality according to the 2022 National Census (2022).
- Commercial PV: the incremental capacity of commercial-scale PV plants having a licence in a given year in each municipality (2014-2023) derived from the dataset used for the UBO analysis in chapter 5.1.
- Municipal level data on the number of registered companies and entrepreneurs with the registered activity code 4321'25 'Electricity Engineering' listed (source: Opten company database, years 2014-2024). After consulting the registered contractor list of the Hungarian Solar Cell Association (<https://www.mnnsz.hu/regisztralt-kivitelezok/>), that activity code was the only one shared among all companies.
- District level data between 2014-2023 on the employment and gross profit data of companies with registered seat in the District that have the registered activity code TEÁOR'08 3511 (Electricity Production) and 4321 (Electricity Engineering) combined. This data is provided by the Hungarian Central Statistical Office (*Központi Statisztikai Hivatal - KSH*) upon specific request (*Központi Statisztikai Hivatal 2025*).

Due to the limits of data availability, a panel regression can be used only to assess the effect of commercial PV deployment on the number of relevant businesses over time. For residential units, only a simple OLS regression on 2022 data can be used.

The following variables were defined for the analyses:

- Dependent variable:
 - Panel regression:
 - Municipal level:
 - number of registered new enterprises for each year.
 - District level:
 - Number of registered new enterprises for each year.
 - Annual employment in the companies between 2014 and 2022.
 - Annual gross profit in the companies between 2014 and 2022.
 - OLS: total number of new companies between 2014 and 2022.
- Explanatory variable:
 - Panel regression: incremental capacity of commercial-scale PV plants having a licence in a given year in each municipality (2014-2023).
 - OLS regression:
 - number of households with solar panels installed in each municipality according to the 2022 National Census (2022).
 - total capacity of commercial-scale power plants licensed until 2022.
- Control variables (annual 2014-2023 values for panel and 2022 values for OLS):
 - Fixed effect (District for Municipal level analysis and County for District level analysis).
 - Population of the municipality
 - Number of job seekers
 - Number of total registered business entities

For the panel data analysis, time lags of 1-3 years are also included.

A significant constraint is that the commercial-scale PV database lists only the initial registration of the license, not the actual date of commercial operation.

The same models are also run not only on municipal-level data but also aggregated to the district level (LAU 1 – “járás”). The local economy of most municipalities in

Hungary might be just too small to really incorporate the PV industry, and it is reasonable to assume that for many companies, the smallest viable market is on the LAU1 scale and, hence, will likely be located in the micro-regional economic-administrative centres.

4.4.2.Results

Panel regression

The results of the panel data regression (using fixed effects and robust errors) on the municipal level are shown in 19. Figure suggest that one year after receiving a license, the commercial-scale PV projects have a significant, though very small, effect on forming local businesses in the electricity sector: one MW additional capacity leads, on average, to the registration of 0.01 companies.

Fixed-effects (within) regression		Number of obs	=	22078		
Group variable: municipality		Number of groups	=	3154		
R-sq: within	= 0.2335	Obs per group: min	=	7		
between	= 0.0000	avg	=	7.0		
overall	= 0.0005	max	=	7		
		F(7,3153)	=	30.98		
corr(u_i, Xb)	= -0.5814	Prob > F	=	0.0000		
(Std. Err. adjusted for 3154 clusters in municipality)						
newbusiness	Coef.	Robust Std. Err.	t	P> t	[95% Conf. Interval]	
compvttotal_loc						
--.	-.0000131	5.84e-06	-2.24	0.025	-.0000245	-1.62e-06
L1.	.000016	7.13e-06	2.24	0.025	2.01e-06	.00003
L2.	-1.14e-07	.0000118	-0.01	0.992	-.0000233	.0000231
L3.	6.44e-06	9.34e-06	0.69	0.491	-.0000119	.0000248
reg_busentities	.0112297	.0012221	9.19	0.000	.0088334	.0136259
jobseekers	-.0005359	.0017642	-0.30	0.761	-.0039951	.0029233
population	-.0020549	.0002944	-6.98	0.000	-.0026322	-.0014776
_cons	1.399278	.5248826	2.67	0.008	.3701324	2.428425
sigma_u	5.1640803					
sigma_e	1.2233598					
rho	.94686154	(fraction of variance due to u_i)				

19. Figure Output table for the panel regression on the municipal level with time lags (year 1-3).

For District-level data, the same analysis on municipal-level impact on new business formation returns the output listed in 20. Figure. The effects are significant only at the three-year lag, while the one-year lag, although close, is insignificant, though the effect is somewhat larger than at the municipal level. The result suggests that for each 10 MW of additional capacity, 0.8 new businesses with a profile in electrical engineering are registered in a District.

```
Fixed-effects (within) regression          Number of obs   =      1225
Group variable: district_c~e              Number of groups =      175

R-sq:  within  = 0.1906                   Obs per group: min =       7
        between = 0.0363                               avg  =      7.0
        overall  = 0.0335                               max  =       7

                                           F(7,174)         =      5.33
corr(u_i, Xb)  = -0.9902                  Prob> F          =      0.0000
```

(Std. Err. adjusted for 175 clusters in district_code)

newbusiness	Coef.	Robust Std. Err.	t	P> t	[95% Conf. Interval]	
commpv_total						
--.	.0000101	.0000157	0.64	0.521	-.0000209	.0000411
L1.	.0000438	.0000258	1.70	0.091	-7.07e-06	.0000947
L2.	.0000461	.0000336	1.37	0.172	-.0000202	.0001123
L3.	.0000843	.000033	2.55	0.012	.0000191	.0001494
population	.0005803	.0002525	2.30	0.023	.0000819	.0010787
jobseekers	-.0021194	.0019974	-1.06	0.290	-.0060617	.0018229
regbusinesses	.0027629	.0012054	2.29	0.023	.0003839	.005142
_cons	-39.30061	17.19061	-2.29	0.023	-73.22957	-5.371652
sigma_u	157.59961					
sigma_e	7.4563874					
rho	.99776655	(fraction of variance due to u_i)				

20. Figure Output table for the panel regression on the district level with time lags (year 1-3).

Using Employment data for relevant firms at the District level, with time lags of 1-3 years, yields stronger results (with high explanatory power). Even after controlling for population change and an approximate local business dynamic (using unemployment and the number of local registered businesses), the increase in new licensed commercial PV capacity explains some of the increase in local employment in the relevant sectors, especially 3 years after the license is issued. This effect is, however,

rather small: 10 MW average increase in licensed production creates, on average, 2 new jobs in the District in firms active in electrical engineering or renewable energy production. Both the small impact and the time lag suggest that local employment is likely confined to supervisory or caretaker activities, but not involvement in the actual investment procedure. Assuming that all 5.8 GW licensed commercial projects are built, this would – according to this model – create ca. 1000 jobs.

```
Fixed-effects (within) regression      Number of obs      =      1225
Group variable: district_c~e          Number of groups    =      175

R-sq:  within  = 0.8112                Obs per group: min =      7
      between  = 0.2332                      avg  =      7.0
      overall  = 0.1695                      max  =      7

                                         F(7,174)           =    6076.43
corr(u_i, Xb)  = -0.7460                Prob > F            =     0.0000
```

(Std. Err. adjusted for 175 clusters in district_code)

regloc_e~4321	Coef.	Robust Std. Err.	t	P> t	[95% Conf. Interval]	
commpv_total	.0000725	.0001032	0.70	0.483	-.0001312	.0002763
commpv_total						
--.	0	(omitted)				
L1.	-.000073	.0000707	-1.03	0.303	-.0002125	.0000666
L2.	.0002606	.0001862	1.40	0.163	-.0001068	.000628
L3.	.0002256	.0001072	2.10	0.037	.0000139	.0004372
regbusinesses	.0947122	.0093031	10.18	0.000	.0763508	.1130736
jobseekers	-.0279463	.0065725	-4.25	0.000	-.0409184	-.0149743
population	-.0239618	.00515	-4.65	0.000	-.0341264	-.0137973
_cons	613.3225	385.3358	1.59	0.113	-147.2115	1373.856
sigma_u	910.31476					
sigma_e	57.429611					
rho	.99603573	(fraction of variance due to u_i)				

21. Figure Panel regression on District level with local employment in the electricity sector as the dependent variable and local commercial capacity increase as the explanatory variable.

Running the same model, but with the gross profit of the firms registered within the district active in the electricity and renewables sector, provides no significant results - 22. Figure. The explanatory power of the model is low, and the capacity increase is not significant at any time lag (including 4-, 5-, and 6-year lags). This can be interpreted in light of earlier findings that profits from the operation of these power plants rarely stay within the area.

Fixed-effects (within) regression	Number of obs	=	1225
Group variable: district_c~e	Number of groups	=	175
R-sq: within = 0.3332	Obs per group: min	=	7
between = 0.6823	avg	=	7.0
overall = 0.5027	max	=	7
	F(7,174)	=	830.93
corr(u i, Xb) = -0.9969	Prob >F	=	0.0000

(Std. Err. adjusted for 175 clusters in district code)

regloc_gr~432	Coef.	Robust Std. Err.	t	P> t	[95% Conf. Interval]	
commpv_total	3.052128	6.577347	0.46	0.643	-9.929525	16.03378
commpv_total						
--.	0	(omitted)				
L1.	-10.62393	9.954261	-1.07	0.287	-30.27057	9.022709
L2.	3.566032	12.59643	0.28	0.777	-21.29543	28.42749
L3.	11.45278	12.6162	0.91	0.365	-13.44771	36.35326
regbusinesses	2127.405	501.3332	4.24	0.000	1137.928	3116.882
jobseekers	179.3551	387.6778	0.46	0.644	-585.8013	944.5115
population	-1130.511	331.1414	-3.41	0.001	-1784.082	-476.9403
_cons	4.23e+07	2.38e+07	1.78	0.077	-4623776	8.91e+07
sigma_u	90736722					
sigma_e	5285907.7					
rho	.99661778	(fraction of variance due to u_i)				

22. Figure Panel regression on District level with the gross profit of the firms active in the electricity sector as the dependent variable and local commercial capacity increase as the explanatory variable.

OLS

The OLS regression results (23. Figure - 24. Figure) with the commercial-scale and small-scale (HMKE) capacities both included as explanatory variables show that, contrary to the suggestions of the panel regressions, commercial-scale PV plants' impact on businesses, at least for 2022 data, is insignificant both on the municipal as well as the district level. On the other hand, small-scale units (HMKE) do seem to have a significant influence on the number of businesses in the electricity sector, even after controlling for regional effects, general economic activity, and population.

Linear regression

Number of obs = 3155
 F(5, 174) = 91.89
 Prob > F = 0.0000
 R-squared = 0.7205
 Root MSE = 17.42

(Std. Err. adjusted for 175 clusters in jrs)

electrbusiness_20142~w	Coef.	Robust Std. Err.	t	P> t	[95% Conf. Interval]	
ResidentialPV_number	.2237527	.0258226	8.66	0.000	.1727868	.2747186
commlicenscap_20142022	2.96e-06	.000063	0.05	0.963	-.0001215	.0001274
jobseekers	.0253228	.0193831	1.31	0.193	-.0129335	.0635791
reg_busentities	-.0311792	.004574	-6.82	0.000	-.0402068	-.0221516
population	.0037003	.0016187	2.29	0.023	.0005054	.0068952
_cons	1.731522	.5035991	3.44	0.001	.7375733	2.725472

23. Figure Output table for the OLS regression on the municipal level (fixed effect District).

Linear regression

Number of obs = 175
 F(5, 19) = 83.41
 Prob > F = 0.0000
 R-squared = 0.5412
 Root MSE = 119.7

(Std. Err. adjusted for 20 clusters in county)

sumofelectrbusiness_20142~w	Coef.	Robust Std. Err.	t	P> t	[95% Conf. Interval]	
ResidentialPV_number	.2980577	.0534992	5.57	0.000	.1860826	.4100329
sumofcommlicenscap_20142022	.0004793	.0002698	1.78	0.092	-.0000854	.001044
jobseekers	.0697096	.0199376	3.50	0.002	.0279796	.1114395
regbusinesses	.032497	.0237599	1.37	0.187	-.0172331	.0822271
sumofpopulation	-.037996	.0227478	-1.67	0.111	-.0856077	.0096157
_cons	69.19817	33.38948	2.07	0.052	-.6868054	139.0831

24. Figure Output table for the OLS regression on the municipal level (fixed effect County).

Interviews

These results are in line with those from the municipal interviews. In Inárcs, Királyegyháza, and Töttös, local employment at the commercial PV plants is limited to 1-2 seasonal, low-added-value jobs, and in Oroszlány, the situation is similar. Only in the case of Szászberek was it reported that even this kind of employment is outsourced to a firm with a national service area, providing no local employment opportunity. In Bóly, where both commercial and residential capacities have a prevalence far above average, there are multiple local firms active in the sector. Similarly, in Oroszlány, there are roughly 20 enterprises active across the PV value chain. However, both are economic and administrative centres of their neighbourhood

with industrial capacity and tradition. Employment in companies active in the electricity and renewables sector has increased by 424% in the Dabas (Inárcs) and 381% in the Bóly District (Bóly), comparing the 2014-2016 average to the 2022-2023 average. One of the highest results in the country. In Oroszlány, however, the opposite is true: a drastic reduction in employment, most likely due to the 2016 closure of the local coal-fired power plant.

Where there is a local firm that provides installation and maintenance services for residential PV units, according to the interviews, those firms become almost monopolistic actors in the local market: in the case of Bóly and Kardoskút, a local firm, while in the case of Inárcs, an enterprise from the neighbouring district was entrusted with 90+% of the local residential installations and maintenance. In the case of Budajenő and Töttös, the two municipalities with the highest residential PV installation rates among the 9, no similar reports were made, likely due to their extreme proximity to Budapest (and hence the availability of more companies).

According to the officials interviewed, this concentration is simply due to the spread of information within the community: local residents usually acquire information before their investment decision or grant application from neighbours with existing units, who, along with the know-how, usually suggest the company they worked with too, and this suggestion is mostly trusted.

5. ENVIRONMENTAL IMPACTS

This chapter, as indicated earlier, deals only with the downstream segment of the PV value chain. As PV-panel production and its transportation happen basically completely outside of Hungary and therefore outside the municipal boundaries, only the investment and the operation are of concern in this case. End-of-life waste management is also disregarded as it is currently (and likely for the next decade) not relevant, especially not for the average local community. Municipal interviews confirmed that the construction of the commercial-sized power plants had no significant local environmental or public opinion impact (muddy roads from construction vehicles were mentioned in one case).

5.1. Land-use change by commercial-scale PV plants

While the Thesis's geographical focus is Hungary, the current chapter deals extensively with the situation within the EU. This is to provide a base for comparison of the Hungarian data, which is almost completely missing from the literature, as opposed to the other topics, where at least some relevant international references can be made on the international context.

5.1.1. Methodology

Solar power plant data

For the land-cover analysis, a dataset is needed not just of the location but also of the area coverage of the power plants. Transition Zero's Solar Asset Mapper database is based on satellite data and uses algorithms to detect commercial solar facilities globally. The quarterly-updated dataset for 2026 Q2 identifies more than 35,000 km² of solar power plant surface area across 194 countries, with a combined estimated capacity of 1,383 GW across 109,000 projects. The dataset contains three main data points for each identified project:

1. A solar facility polygon covering the estimated total area of the power plant (plants smaller than 1,000 m², or ca. 0.3 MW, are excluded from the sample, as the margin of error for false detection is too high). The polygon includes the territory between the rows, not only the surface area of the panels.
2. An estimate for the capacity of each observed power plant.
3. An upper limit for the construction period. (Phillpott et al. 2024)

The dataset has, however, three main limitations (Phillpott et al. 2024):

1. The 2026 Q2 release of the TZ-SAM database covers 1,383 GW of capacities globally. IRENA (2026a) lists 2,455 GW total built-in solar capacity for 2025 for all PV technologies and sizes.
2. The data is processed algorithmically, and the complete dataset is not manually curated. However, based on a representative sample, its false-positive rate is under 0.5%.
3. The capacity data is estimated only and is sensitive to large variations in the density of solar panels in the area.

Despite its limitations, the TZ-SAM database is currently the most advanced publicly available dataset on the spatial data of solar PV panels. The alternative Global Solar Power Tracker covers a marginally larger set of projects, but it uses point geometry and has no area coverage.

COUNTRY	TZ-SAM PV CAPACITY (2026, MW)	NO. OF PROJECTS (TZ-SAM 2026)	EUROSTAT 30 KW+ CAPACITY (2024 MW)	RATIO OF TZ-SAM TO EUROSTAT >30 kW CAPACITY (%)
AUSTRIA	1,217	328	1,039	117%
BELGIUM	1,041	322	3,247	32%
BULGARIA	4,603	596	4,434	104%
CROATIA	611	111	715	85%
CYPRUS	395	115	397	100%
CZECHIA	3,089	872	2,297	134%
DENMARK	3,386	243	2,965	114%
ESTONIA	1,312	262	824	159%
FINLAND	514	57	495	104%
FRANCE	14,224	2,006	21,013	68%
GERMANY	38,772	6,654	54,722	71%
GREECE	9,829	3,345	8,161	120%
HUNGARY	5,634	1,108	5,053	111%
IRELAND	1,590	87	870	183%
ITALY	21,639	5,961	25,364	85%
LATVIA	1,354	133	475	285%
LITHUANIA	1,322	191	97	1363%
LUXEMBOURG	50	25	296	17%
MALTA	23	10	117	20%
NETHERLANDS	7,486	788	12,639	59%
POLAND	10,893	2,625	9,162	119%
PORTUGAL	5,195	426	4,888	106%
ROMANIA	5,369	615	4,257	126%
SLOVAKIA	961	253	713	135%
SLOVENIA	104	61	665	16%
SPAIN	47,951	3,253	30,214	159%
SWEDEN	826	155	1,770	47%
TOTAL	189,389	30,602	196,891	(avg) 150%

22. Table Coverage of TZ-SAM 2026 Q2 data in comparison with Eurostat data from 2024 (latest available) on total installed solar photovoltaic capacity with at least 30 kW capacity (Eurostat 2026a).

The general threshold for TZ-SAM data inclusion is a total facility area of at least 1,000 m², that has an approximate 0.3 MW capacity. Therefore, a large share of small-scale autoproducing units (including almost all residential units) is not included. The TZ-SAM database covered 189 GW of total installed capacity in the EU as of 2026, while

Eurostat data shows 197 GW installed PV with capacity above 0.3 MW two years earlier (Eurostat 2026a). This means that the analysis can cover 96% of the total installed capacity in the EU as of 2024. In the case of Hungary, 5,634 MW is covered out of the total 5,053 MW (above 30 kW) reported by Eurostat.

The TZ-SAM dataset was modified to help the analysis. The originally multipart polygons, where TZ-SAM originally clustered PV installations in close proximity that were not touching each other, were split up into individual polygons using QGIS software (version 3.44.12) 'Multipart to Singleparts' algorithm. Otherwise, QGIS would have calculated not the land cover of the actual polygons of the power plants, but the total larger area of the smallest rectangle containing all parts the cluster covers. For the separated polygons, the original total capacity estimate of the cluster was divided proportionally to the areas of the newly formed polygons and that new capacity value was used as an approximation. After this modification, for the EU27 territory, a total of 32,668 observations were available, up from the original 30,602 before breaking up the clusters. Of these observations, 1,149 are located in Hungary, compared with 1,055 before splitting the multipart polygons. However, during the analysis, 32 observations with a total capacity of 99 MW were dropped because they were located in overseas EU territories not covered by CLC mapping. Therefore, the final number of observed PV polygons on EU territory was 32,636, with an aggregated, approximate capacity of 189,290 MW.

Land cover data

To enable the comparison of Hungarian and other EU Member State data, an EU-level dataset was used. EU land-cover data was obtained from the CORINE Land Cover Database (CLC) 2012 (EEA 2019). The database comprises 44 land-cover classes, with a 25-hectare minimum mapping unit (MMU) and 100-meter minimum mapping width (resolution). The data is derived from a combination of satellite observations and national topological maps and datasets.

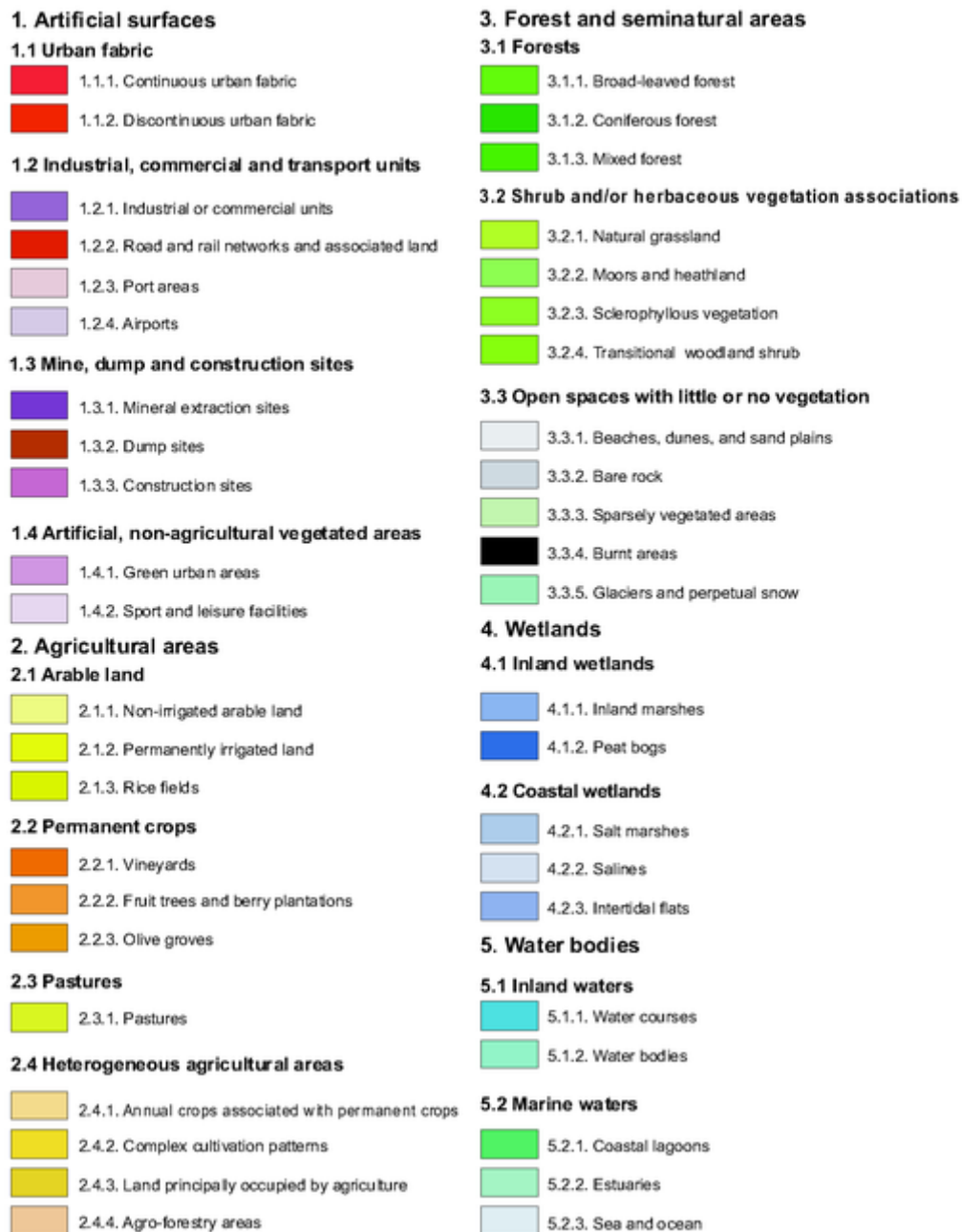
The 2012 CLC data is not the most up-to-date, since CLC is updated every six years. The 2018 updated dataset is also available, as is the CLC Backbone dataset with 10m resolution, which started in 2018 and was updated in 2021. However, for the purposes of the current analysis, baseline land-cover data were needed to show conditions prior to the PV installations. In 2012, the total built-in solar capacity larger than 30 kW in the

EU-27 was only 21 GW, 10.7% of the built-in capacity in 2024 (Eurostat 2026a). For 2006 the same value is 0.1%, as solar power plants (apart from some rooftop installations) were basically non-existent at that time. However, it can be assumed that between 2006 and the PV installations, so many land-use changes have happened that using 2006 data would distort the findings. This is especially true in Hungary and across most CEE countries, where in 2012 the installed solar capacity was negligible. A significant share of PV capacity was already available by 2012 in only Belgium (39%), France (25%), Germany (18%), Italy (18%), and Spain (16%). Future research that focuses on comparisons between EU countries might consider using 2006 data for those countries and 2012 data for the rest. However, that might raise comparability issues.

For the land-cover data on the total area of countries, the same data source was used, (the alternative Eurostat land-cover data uses the LUCAS [Land Use and Cover Area frame Survey] and not the CLC classification, and that would lead to distortions in the data analysis). This leads to a small margin of error in the total national territory calculated from the CLC data, due to the relatively low spatial resolution: the measured total area of EU members varies between 97% and 103% of the official area.

The three tiers of the CLC nomenclature were derived from (Weiss and Banko 2018). This allows the grouping of the original 44 classes into 15 mid-tier and 5 high-tier classes (see 25. Figure).

Corine land cover classes



25. Figure CLC (Corine Land Cover) nomenclature classes in three tiers. (EEA 2017)

For Hungary, a separate National Ecosystem Map (NÖSZTÉP) is available, produced by the Agricultural Ministry in 2019 using mostly 2015-2016 data (Agrárminisztérium 2019a). The map has a higher resolution, 20m x 20m and combines satellite imagery with numerous national land-use datasets (Agrárminisztérium 2019b). However, the classification used differs from the CLC and was designed specifically for the

Hungarian land use characteristics. While CLC uses 44 low and 15 mid-level classes, NÖSZTÉP divides the land use into 56 low and 22 mid-level categories; therefore, it is more granulated. The top third level contains the five classes for CLC and six for NÖSZTÉP, as the Hungarian system puts grasslands into a different main category than forests. Therefore, by extracting 3.2 “Shrub and/or herbaceous vegetation associations” from the 3. CLC main category and creating a new top class, on the top tier, the two systems become seemingly comparable. However, the large differences between the total areas covered by each main class make it clear that the underlying definitions differ too much to enable real comparability (see 23. Table). Hence, the current analysis uses CLC data for the EU-level analysis, and both CLC and NÖSZTÉP data for Hungary – the former makes EU-level comparison available, while the latter provides more detailed results.

Corine classes	Total area (km²)	NÖSZTÉP classes	Total area (km²)
Artificial surfaces	5,948	Urban	9,468
Agricultural areas	60,689	Croplands	45,109
3.2 Shrub and/or herbaceous vegetation associations	6,447	Grasslands and other herbaceous vegetation	9,224
Forest and semi natural areas (excl. 3.2 shrublands)	17,500	Forests and woodlands	24,116
Wetlands	867	Wetlands	3,559
Water bodies	1,776	Rivers and lakes	1,527

23. Table Incomparability of the top-tier Corine and NÖSZTÉP classification.

For the Natura 2000 spatial data the EEA datafile was used (EEA 2025a).

Analytical steps

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.

The low resolution of the CLC dataset still leaves some room for error, even with the introduction of the buffer zone. However, that error is negligible: the difference between the total PV land-cover area calculated by the process outlined above and the total PV area from the TZ-SAM dataset was 0.00013%.

For the analysis of Natura 2000 sites, a similar approach was used, with no need to polygonise the basemap.

The analysis uses the so-called Representativity index to show whether the PV cover for a specific land-cover class is over- or underrepresented relative to the share of PV installations in that class's area. A value of 100% means that PV power plants occupy land in a given class in the same rate, as the class occupies in the total area of the spatial unit (EU/country/municipality). It is equivalent to randomly selecting site locations across the entire territory. This way the Representativity index works as a Location Quotient for the land cover of commercial-scale PV installations.

$$RI = \frac{\text{PV area in CLC class /total PV area}}{\text{CLC area in class/total study area}}$$

5.1.2.EU results

In the EU, according to the TZ-SAM dataset, a total of 3,929 km², 0.096% of the EU's total area, is covered by solar power plants as of Q2 2026. Based on 2024 data, the same ratio is only 0.069%, which shows a rapid increase. The highest land-cover share is in the Netherlands at 0.27%, while Finland's land area covered by commercial-scale PV is less than 0.004%. Hungary is above the EU average, with an almost 0.13% land-cover share.

Country	PV area (km ²)	Share of land covered by PV (%) 2026	Share of land covered by PV (%) 2024	Share of Built-up area
Austria	22.9	0.028%	0.018%	1.4%
Belgium	19.6	0.064%	0.046%	5.2%
Bulgaria	94.1	0.086%	0.061%	0.7%
Croatia	11.8	0.021%	0.012%	1.0%
Cyprus	7.3	0.079%	0.071%	1.8%
Czechia	58.5	0.076%	0.070%	1.9%

Denmark	69.9	0.167%	0.118%	1.9%
Estonia	25.1	0.058%	0.035%	0.2%
Finland	10.3	0.003%	0.001%	0.3%
France	263.1	0.041%	0.035%	1.5%
Germany	709.3	0.201%	0.159%	2.5%
Greece	194.1	0.149%	0.115%	0.9%
Hungary	115.6	0.127%	0.096%	1.3%
Ireland	32.4	0.047%	0.020%	1.2%
Italy	422.7	0.142%	0.111%	2.2%
Latvia	27.9	0.045%	0.007%	0.3%
Lithuania	25.7	0.041%	0.022%	0.5%
Luxembourg	0.9	0.033%	0.026%	2.5%
Malta	0.4	0.127%	0.111%	14.6%
Netherlands	90.5	0.266%	0.201%	4.2%
Poland	204.3	0.067%	0.045%	1.3%
Portugal	110.7	0.122%	0.092%	1.8%
Romania	110.6	0.047%	0.025%	0.9%
Slovakia	18.3	0.038%	0.035%	1.1%
Slovenia	1.8	0.009%	0.009%	1.0%
Spain	1265.3	0.252%	0.179%	0.9%
Sweden	15.7	0.004%	0.001%	0.4%
EU27	3928.7	0.096%	0.069%	1.3%

24. Table Total land area covered by commercial-scale PV in 2026 and the share of land covered by commercial-scale PV in 2024 and 2026. Share of total built-up area per country is provided for reference. Total land area and total built-up area are taken from Eurostat (Eurostat 2013, 2025c).

24. Table shows the total land area and PV cover by 2nd level CLC classes. It is apparent that, while urban territories are less favoured, brownfield territories such as industrial, commercial, and transport units, mines, dumps, and construction sites were far more often chosen as locations for commercial-scale PV than their rate of occurrence would suggest. From the perspective of potential ecological impact, this can be considered a positive characteristic.

Similarly, the total potential ecological impact of commercial-scale PV in the EU is likely limited, as forests, a land-use type with relatively high ecological potential, are among the most underrepresented land-use types.

Agricultural land is more often used for commercial-scale PV siting than the general occurrence rate. However, arable and permanent croplands are more favoured than pastures, and the literature presented above suggests that the latter has a higher ecological value, and a land-use change from intensive agriculture to PV parks can often yield ecological benefits.

Land cover of commercial-scale PV on water bodies (a total of 6.3 km²) is likely a combination of floating PV farms and inaccuracies in the CLC data, arising primarily from its low resolution.

The 2.9% share of (previously) forested area is smaller than the estimate of Zhang (2024), who, based on 2018 data, estimated that 4.9% of the total global solar capacity at that time was built on previously forested areas.

CLC 1st class	CLC 2nd class	Share of PV cover in total class area	Share of class in total PV coverage	Share of class area in total area	Representativity index
Artificial surfaces	Urban fabric	0.04%	1.6%	3.5%	45.3%
	Industrial, commercial and transport units	1.63%	13.1%	0.8%	1,716.2%
	Mine, dump and construction sites	1.17%	2.4%	0.2%	1,226.2%
	Artificial, non-agricultural vegetated areas	0.10%	0.3%	0.3%	109.9%
Agricultural areas	Arable land	0.20%	53.2%	25.1%	212.3%
	Permanent crops	0.17%	4.9%	2.7%	177.8%
	Pastures	0.10%	8.7%	7.9%	109.6%
	Heterogeneous agricultural areas	0.06%	5.9%	9.2%	64.2%
Forest and semi-natural areas	Forests	0.01%	2.9%	33.3%	8.9%
	Shrub and/or herbaceous vegetation associations	0.05%	6.1%	10.7%	56.6%
	Open spaces with little or no vegetation	0.03%	0.4%	1.5%	30.2%
Wetlands	Inland wetlands	0.01%	0.3%	1.8%	14.5%
	Maritime wetlands	0.02%	0.0%	0.1%	20.2%
Water bodies	Inland waters	0.01%	0.2%	2.6%	9.0%
	Marine waters	0.00%	0.0%	0.4%	0.4%

25. Table. Land-use class-based differentiation between commercial-scale PV units' land-use characteristics in the EU total.

25. Table shows the share of the land-use of PV capacities among the five main CLC land-cover classes within a single Member State. As PV area and capacity are highly correlated, this approximately matches the share of the capacity. 26. Table shows that most of the capacity is located in agricultural areas in most Member States, while artificial surface and, in a few Member States, forested areas also host a significant share of the capacity. However, this does not consider differences in total land cover, which likely explain the differences to some extent.

	Artificial surface s	Agricultural areas	Forest and semi-natural areas	Wetlands	Water bodies
Austria	16.6%	78.6%	4.0%	0.0%	0.7%
Belgium	67.5%	24.7%	5.8%	0.3%	1.7%
Bulgaria	25.9%	62.9%	10.0%	0.8%	0.4%
Croatia	9.5%	40.3%	50.3%	0.0%	0.0%
Cyprus	2.6%	78.7%	18.6%	0.0%	0.0%
Czechia	35.0%	60.7%	4.2%	0.0%	0.0%
Denmark	6.8%	91.7%	1.5%	0.0%	0.0%
Estonia	9.9%	71.5%	14.2%	4.4%	0.0%
Finland	8.8%	14.4%	53.1%	23.7%	0.0%
France	25.7%	41.0%	31.8%	0.0%	1.4%
Germany	30.5%	64.8%	4.6%	0.0%	0.1%
Greece	9.4%	72.4%	17.9%	0.3%	0.0%
Hungary	9.7%	84.5%	5.1%	0.4%	0.4%
Ireland	1.2%	87.3%	1.8%	9.6%	0.0%
Italy	15.5%	83.1%	1.4%	0.0%	0.0%
Latvia	2.1%	88.9%	8.9%	0.1%	0.0%
Lithuania	4.3%	93.6%	1.6%	0.0%	0.4%
Luxembourg	59.4%	33.5%	7.1%	0.0%	0.0%
Malta	22.6%	71.0%	6.4%	0.0%	0.0%
Netherlands	19.5%	75.9%	1.8%	0.0%	2.7%
Poland	4.2%	93.8%	1.9%	0.0%	0.0%
Portugal	7.2%	43.9%	48.9%	0.0%	0.1%
Romania	5.7%	91.4%	0.9%	1.6%	0.4%
Slovakia	21.8%	76.6%	1.6%	0.0%	0.1%
Slovenia	44.9%	47.1%	8.0%	0.0%	0.0%
Spain	14.0%	77.3%	8.6%	0.0%	0.0%
Sweden	18.9%	53.2%	27.5%	0.0%	0.3%

26. Table. The share of land area occupied by PV parks in Member States by different land cover types of the 1st level CLC classification.

27. Table shows the land-use Representativity index for each EU member in the 15 2nd-level CLC classifications. From the data, several conclusions can be drawn:

- Repurposing non-urban artificial surfaces for PV parks is common in almost all EU Members.
- France, Luxembourg and Belgium are the only EU Members in which arable land is underrepresented relative to its share of national land cover. These countries (and Croatia), however, 'overutilize' the Shrub and/or herbaceous vegetation associations land type (e.g. grasslands and moors).
- Ireland, with a low share of arable land in the total area, extensively repurposes arable land for PV production, while it underuses most artificial land-use types compared to other Member States. To a lesser degree, but Lithuania, Latvia and Cyprus share a similar characteristic.
- PV parks are most frequently located in forests in Portugal, followed by Finland and France. Portugal and France both have a smaller share of tree cover than the EU average.
- In Sweden, PV parks are disproportionately located on agricultural lands (arable land and pastures mostly).

There are significant differences among Member States, as shown with the observations above. Despite these differences, a broadly consistent land-use profile emerges across member States: artificial surfaces are relatively overused in most countries, as are agricultural areas (mostly arable land and pastures), but forests, shrubs, and other less cultivated areas are mostly underutilised.

Country	Urban fabric	Industrial, commercial and transport units	Mine, dump and construction sites	Artificial, non-agricultural vegetated areas	Arable land	Permanent crops	Pastures	Heterogeneous agricultural areas	Forests	Shrub and/or herbaceous vegetation associations	Open spaces with little or no vegetation	Inland wetlands	Maritime wetlands	Inland waters	Marine waters
Austria	89.3%	1777.6%	2130.8%	87.6%	376.6%	94.2%	109.8%	145.5%	6.8%	10.3%	0.0%	0.0%	N/A	79.2%	N/A
Belgium	43.4%	1854.7%	3511.1%	39.2%	63.0%	20.6%	21.0%	35.9%	4.8%	416.1%	0.0%	98.5%	14.9%	328.0%	0.0%
Bulgaria	70.1%	2624.5%	644.0%	466.8%	101.6%	233.1%	314.6%	105.6%	6.1%	76.5%	12.0%	623.6%	0.0%	38.4%	0.0%
Croatia	78.8%	1231.9%	302.5%	40.8%	157.3%	0.9%	215.9%	51.8%	2.8%	225.3%	1207.2%	0.0%	0.0%	0.0%	0.0%
Cyprus	1.3%	76.6%	76.9%	77.8%	199.6%	108.6%	0.0%	118.4%	9.8%	57.0%	155.7%	0.0%	0.0%	0.0%	0.0%
Czechia	179.1%	2550.6%	366.2%	60.6%	125.3%	80.6%	82.9%	63.3%	8.5%	54.6%	0.0%	23.3%	N/A	6.6%	N/A
Denmark	15.5%	551.1%	29.5%	2.7%	144.0%	16.5%	14.6%	26.6%	5.5%	22.4%	0.0%	0.8%	0.0%	0.0%	0.0%
Estonia	111.4%	1395.4%	675.3%	36.4%	164.6%	266.4%	481.4%	152.6%	24.9%	28.0%	0.0%	97.4%	0.0%	0.0%	0.0%
Finland	82.4%	2006.3%	3729.3%	3.7%	229.8%	0.0%	0.0%	99.4%	74.0%	64.1%	0.0%	365.6%	0.0%	0.2%	5.9%
France	29.3%	2035.7%	3528.0%	417.2%	60.8%	185.4%	48.6%	91.6%	54.5%	285.8%	20.1%	11.7%	12.5%	219.5%	0.3%
Germany	66.4%	1412.3%	894.1%	58.3%	129.6%	21.7%	83.0%	91.1%	11.2%	88.6%	44.5%	14.3%	0.0%	5.3%	0.0%
Greece	4.1%	445.6%	1902.5%	32.5%	348.9%	37.4%	429.5%	69.3%	1.5%	40.5%	174.5%	19.2%	114.9%	1.2%	0.1%
Hungary	31.3%	298.2%	2618.6%	123.6%	121.9%	145.1%	199.0%	99.5%	12.8%	38.4%	0.0%	41.4%	N/A	22.2%	N/A
Ireland	10.5%	63.2%	26.3%	247.2%	669.1%	0.0%	95.9%	34.6%	16.3%	14.2%	0.0%	68.2%	0.0%	0.0%	0.0%
Italy	29.9%	1148.0%	529.3%	59.7%	222.9%	113.4%	89.2%	77.6%	1.7%	6.1%	6.4%	27.3%	20.0%	1.8%	0.0%
Latvia	13.3%	392.1%	44.0%	39.1%	236.7%	0.0%	332.9%	100.2%	17.6%	14.2%	0.0%	4.8%	N/A	1.1%	0.0%
Lithuania	22.3%	501.1%	333.6%	124.8%	174.4%	0.0%	326.6%	55.8%	4.6%	4.7%	0.0%	0.0%	N/A	22.9%	0.0%
Luxembourg	140.6%	2443.5%	1564.9%	0.0%	46.4%	0.0%	116.7%	35.1%	19.8%	0.0%	N/A	0.0%	N/A	0.0%	N/A
Malta	5.5%	63.8%	1559.9%	0.0%	108.2%	0.0%	N/A	147.5%	0.0%	51.7%	0.0%	N/A	0.0%	N/A	0.0%
Netherlands	14.5%	344.0%	1246.4%	143.9%	162.2%	162.3%	100.8%	93.8%	16.4%	16.9%	11.8%	3.5%	0.4%	33.3%	0.0%
Poland	14.6%	239.3%	748.4%	74.0%	183.6%	215.3%	131.0%	34.8%	4.0%	36.4%	0.0%	1.8%	N/A	3.2%	0.0%
Portugal	15.3%	942.8%	281.6%	85.6%	209.1%	60.9%	246.8%	34.4%	78.8%	129.2%	65.7%	0.0%	4.8%	6.2%	0.0%
Romania	28.1%	672.8%	435.9%	80.5%	186.1%	96.8%	159.3%	52.2%	1.6%	7.0%	65.9%	135.3%	0.0%	29.5%	0.0%
Slovakia	76.0%	2009.6%	1671.7%	0.0%	197.1%	15.6%	63.8%	100.3%	3.6%	2.6%	0.0%	0.0%	N/A	8.8%	N/A
Slovenia	547.8%	2554.3%	11318.0%	0.0%	189.2%	0.0%	116.8%	143.6%	8.3%	79.1%	0.0%	0.0%	0.0%	0.0%	0.0%
Spain	12.1%	1851.2%	687.3%	17.3%	239.7%	107.2%	152.1%	34.9%	2.6%	31.5%	16.2%	0.1%	6.7%	3.0%	0.0%
Sweden	105.4%	7690.3%	600.9%	709.6%	727.4%	0.0%	363.0%	166.4%	43.4%	16.3%	0.0%	0.7%	0.0%	0.0%	88.9%

27. Table Representativity of the land-use of commercial-scale PV power plants in each EU country. Blue shading marks values above 100% (i.e. overrepresented), while red shading highlights values below 100% (i.e. underrepresented). N/A refers to land cover classes non-existent in the given country.

A different approach for approximating whether commercial-scale PV installations have *in situ* ecological impact potential through land-use change is to assess whether they are in environmentally protected areas. Natura 2000 is an EU-level regulatory framework for a network of protected natural areas, covering 18.6% of the European Union land area (EEA 2025b). There are two major types of Natura 2000 sites: Special Protection Areas focusing on rare and migratory birds and Special Areas of Conservation (SAC) protecting a wide range of other vulnerable plants, animals, and natural habitats (EEA 2025b). Being located on Natura 2000-designated territory does not necessarily mean increased (negative) ecological impacts for a PV park, but it likely increases the potential for such impacts.

Country	Share of PV capacity on Natura 2000	Share of PV capacity on SAC	Share of Natura 2000 area in total national territory	Representativity index for Natura 2000	Representativity index for SAC
Austria	3.9%	3.0%	15.4%	25.4%	42.0%
Belgium	5.2%	0.0%	12.7%	41.2%	0.0%
Bulgaria	13.8%	6.9%	34.9%	39.7%	40.8%
Croatia	9.3%	4.5%	36.7%	25.4%	17.6%
Cyprus	1.2%	0.3%	18.3%	6.4%	10.5%
Czechia	1.4%	0.3%	14.1%	10.0%	1.9%
Denmark	0.2%	0.2%	8.3%	2.2%	3.3%
Estonia	0.1%	0.0%	17.9%	0.4%	0.3%
Finland	0.0%	0.0%	12.6%	0.0%	0.0%
France	5.1%	2.2%	13.0%	39.3%	22.5%
Germany	1.6%	0.4%	15.4%	10.1%	3.2%
Greece	10.7%	1.5%	27.3%	39.0%	10.1%
Hungary	0.5%	0.2%	21.4%	2.3%	0.7%
Ireland	0.1%	0.1%	13.2%	0.4%	0.7%
Italy	0.7%	0.4%	19.1%	3.5%	3.4%
Latvia	2.7%	2.7%	11.5%	23.4%	27.2%
Lithuania	0.1%	0.0%	13.8%	0.5%	0.0%
Luxembourg	12.7%	0.6%	27.1%	47.0%	2.5%
Malta	1.2%	0.9%	13.3%	9.3%	7.5%
Netherlands	0.2%	0.1%	14.7%	1.5%	0.4%
Poland	5.5%	1.1%	19.6%	28.1%	10.3%
Portugal	5.3%	0.9%	20.6%	25.6%	4.3%
Romania	5.6%	1.8%	22.7%	24.7%	11.0%
Slovakia	7.2%	0.2%	30.0%	23.9%	1.2%
Slovenia	2.4%	0.7%	37.9%	6.4%	2.5%
Spain	3.5%	1.8%	27.3%	12.7%	9.8%

Sweden	0.0%	0.0%	12.8%	0.2%	0.8%
EU27	3.4%	1.2%	18.6%	18.1%	10.3%

28. Table Share of the PV capacity within the total covered by the TZ-SAM dataset that is located in Natura 2000 area in general, or specifically in Special Areas of Conservation. The source for Natura 2000 data is the EEA (EEA 2025a).

Table 6 shows that the capacity of commercial-scale PV on Natura 2000 sites is lower than their share of the total national territory; i.e., these protected sites are underrepresented as PV locations, especially Special Areas of Conservation that host diverse habitats. However, the significant differences between Member States merit attention, as countries like Austria, Bulgaria and France tend to host PV capacity on Natura 2000 territory more frequently, whereas in many Member States Natura 2000 areas are almost completely free of large-scale PV installations.

5.1.3. Hungary

National level

In Hungary, commercial-scale PV locations are dominated by sites classified by CLC 2012 as arable land (62%) and pastures (15%), as shown in 29. Table. Altogether, 85% of the PV land cover is on (former) agricultural land. The 5.6% of the capacity located on dump sites is likely built mostly on recultivated mining areas (e.g., the neighbourhood of Komló and PV facilities near the Mátra Power Plant). The relative prevalence of industrial sites and urban fabric is likely partially explained by the spread of captive power plants for some industrial sites (MAVIR 2026c).

Arable land is utilised more than what random selection would explain, although the difference is relatively small (122% compared to the baseline 100%). Pastures see a much larger overutilization rate (almost 200%). Industrial units (likely rooftops and manufacturing sites) are utilised frequently; however, they have relatively small capacity, as do other artificial sites.

2nd level CLC class	Share of class in total PV coverage	Representativity index
Discontinuous urban fabric	1.5%	31.4%
Industrial or commercial units	2.0%	269.8%
Road and rail networks and associated land	0.1%	50.7%
Airports	0.7%	923.3%
Mineral extraction sites	0.0%	49.3%

Dump sites	4.8%	8,861.6%
Green urban areas	0.2%	253.4%
Sport and leisure facilities	0.4%	102.5%
Non-irrigated arable land	61.9%	122.1%
Vineyards	0.2%	20.8%
Fruit trees and berry plantations	2.5%	310.2%
Pastures	14.9%	199.0%
Complex cultivation patterns	2.8%	98.1%
Land principally occupied by agriculture, with significant areas of natural vegetation	2.1%	101.5%
Broad-leaved forest	2.1%	13.3%
Coniferous forest	0.1%	10.5%
Mixed forest	0.2%	9.6%
Natural grasslands	0.3%	13.7%
Transitional woodland-shrub	2.3%	52.0%
Inland marshes	0.4%	46.2%
Water bodies	0.4%	28.9%

29. Table Land-use share of Hungarian commercial-scale PV by CLC 3rd-level classification, where there is at least 0.1 km² coverage.

30. Table suggests that larger PV parks tend to be located more frequently on agricultural land and areas with more ecological potential, like forests and shrubland, while also mines and dumps (likely recultivation areas). Yet even the larger PV parks are far from reflecting the natural occurrence rates of forest and shrub areas in Hungary, which are 19% and 7%, respectively.

2nd level CLC class	Below 0.5 MW	0.5-4.9 MW	5MW or larger
Urban fabric	4.0%	5.5%	0.3%
Industrial, commercial and transport units	25.2%	4.6%	2.1%
Mine, dump and construction sites	0.0%	0.4%	6.3%
Artificial, non-agricultural vegetated areas	5.1%	0.7%	0.5%
Arable land	33.7%	53.0%	64.8%
Permanent crops	2.6%	2.1%	3.0%
Pastures	17.4%	15.2%	14.7%
Heterogeneous agricultural areas	12.1%	13.5%	2.2%
Forests	0.0%	2.1%	2.5%
Shrub and/or herbaceous vegetation associations	0.0%	2.6%	2.7%
Inland wetlands	0.0%	0.0%	0.0%
Marine waters	0.0%	0.2%	0.5%

30. Table Land cover of PV projects in the given capacity category, by land-cover class.

Municipal level

To focus on local, municipal-level land-use characteristics, each commercial-scale PV installation in the TZ-SAM database was assigned to the municipality where it is located. In cases where the plant was located on the territory of more than one municipality, the PV plant area and capacity were shared between the settlements accordingly.

The main problem in this analysis is whether any Hungarian municipalities are disproportionately affected by commercial-scale PV installations through land-cover change. There are 66 settlements in Hungary with larger PV coverage on their territory than the national average of 0.127%. Their total population is above 362,000, with 9 municipalities with populations above 10,000 (including Kaposvár and Szolnok, county administrative centres). The largest share of land is occupied by PV in Szuhakálló, a small village with a population under 1,000, where 21% of the land is covered by solar parks. However, there are only 9 municipalities with PV coverage above 5%, while there are 738 municipalities with at least one commercial-sized PV power plant. The ten municipalities with the largest share of land cover are shown in 31. Table.

Municipality	Share of PV coverage in total area	Population (2022)
Szuhakálló	20.71%	973
Sárfimizdó	9.92%	87
Szihalom	9.23%	1,982
Bocfölde	7.56%	1,178
Inárcs	7.32%	4,680
Galgaguta	7.11%	624
Gersekarát	5.83%	646
Berente	5.30%	967
Szügy	5.05%	1,400
Sényő	4.59%	1,330

31. Table The ten Hungarian municipalities with the highest ratio of land covered by commercial-size PV.

Regarding land-use extremes among Hungarian municipalities, 32. Table shows the top 10 settlements in the main 1st-level CLC categories by the area of commercial-scale PV within their territories. Values show the share of area covered by PV parks within the total area of the same land-use type.

Artificial surfaces		Agricultural areas		Forest and semi-natural	
<u>Municipality</u>	<u>PV share</u>	<u>Municipality</u>	<u>PV share</u>	<u>Municipality</u>	<u>PV share</u>
Mánfa	34.8%	Szuhakálló	22.4%	Inárcs	9.4%

Zalaszentiván	20.6%	Sárfimizdó	16.8%	Sényő	5.3%
Kaba	16.0%	Bocfölde	12.0%	Bodroghalom	4.7%
Sajószentpéter	13.7%	Szihalom	10.1%	Pellérd	3.6%
Abaújalpár	13.6%	Galgaguta	9.6%	Sárfimizdó	3.6%
Királyegyháza	13.3%	Gersekarát	9.5%	Kulcs	3.5%
Kakucs	10.9%	Szügy	9.4%	Egyházasharaszti	3.2%
Kaposújlak	9.7%	Berente	7.6%	Gyál	2.9%
Markaz	8.3%	Inárcs	7.5%	Kaposszekcső	2.5%
Tiszaújváros	7.1%	Mezőcsát	7.1%	Keszü	1.8%

32. Table The ten Hungarian municipalities in three 1st-level CLC categories. Wetlands and Water bodies are omitted due to the low rate of occurrence. Values show the ratio of the territory with the specific land-use type in the column covered by commercial-scale PV within the settlements' boundaries.

Most importantly, there is no Hungarian municipality in which the forest and semi-natural areas would have been turned into PV farms in great numbers. Inárcs is the municipality losing most of its forest and semi-natural areas, but only less than 10%, and the share quickly drops in the top 10.

A total of 41 settlements, where the Representativity index calculated for forest and semi-natural areas land cover is above 100%, i.e. PV parks occupy such area types more frequently than they occur within the boundaries of the settlement naturally. A total of 317 MW capacity is located on these settlements, 5.6% of the total capacity covered by the database in Hungary. 12 municipalities host projects above 5 MW. This indicates that while overutilisation is not common among municipalities, it happens slightly more often with large-scale projects, as their share among the total would suggest (29% vs 20%).

While ecological value is hard to assess solely from the land-use type in question, the agricultural quality of the lands used for PV parks could be approximated. In Hungary, agricultural lands are evaluated in the Aranykorona-system, which is a land quality index taking into account the fertility, location, and cultivability. For this brief analysis, the Aranykorona-values were provided by the Hungarian Central Statistical Office (KSH) upon request. Aranykorona data is from 2000.

There is no available Aranykorona (land quality) data on the parcel level, or any sub-settlement level. Therefore, the subsequent analysis uses average municipality-level land quality data and cannot control for the difference between particular parcels.

33. Table suggests that municipalities that host commercial-scale PV capacity have, on average, agriculturally somewhat more valuable lands than the national average,

even when using different weights. However, the difference is rather small (the standard deviation of the total sample is above 7).

	Aranykorona-value/ha
Average of all municipalities	17.8
Average of all municipalities weighted by total area	19.2
Average of municipalities with commercial PV	19.2
Average of municipalities with commercial PV weighted by total area	20.5
Average of municipalities with commercial PV weighted by PV capacity	18.8

33. Table Difference in the land quality index (Aranykorona value) of Hungarian municipalities with or without commercial-scale PV.

In Hungary, 62 municipalities host commercial-scale PV installations that are at least partially located on Natura 2000 sites. The total capacity of the plants is 514 MW, ca. 10% of the total; however, out of that total capacity, only 32 MW is located in actual Natura 2000 areas. There is only one settlement, namely Keszü, where a PV installation occupies more than 1% (3.81%) of the municipality's total Natura 2000 area.

5.2. Residential PV and local emissions

The link between residential solar PV adoption and change in heating patterns is not obvious, and is rather hypothesized at this point, as international literature is also scarce on the issue (see Subchapter 2.2.2).

Residential PV adoption and the installation of heat pumps and/or ACs to cover home heating partially or fully have a strong reinforcing effect on each other: available cheap electricity from the rooftop PV unit makes such investment more likely, while existing heat pump systems incentivise PV adoption to lower expensive electricity consumption from the grid. In Hungary, as it was argued in Subchapter 4.3, rooftop PV units are typically oversized, leaving room for the extra demand by heat pump systems, possibly installed later.

According to the National Census data from 2022, the share of inhabited dwellings with heat pumps installed was 1.2% on average in Hungary – PV adoption rate was 3.7%, so significantly higher. However, a simple linear regression shows that PV adoption rate significantly increases heat pump adoption ($R^2=0.22$, coefficient: 0.25,

significant at 99.9%). Heat pump adoption rate in municipalities with 0 rooftop PV system is only 0.7%, while in municipalities with at least 1 household with PV 1.3%. These numbers suggest that the hypothesized connection between PV and heat pump adoption indeed exists.

While in Hungary solar PV production would likely not be sufficient to produce the electricity required for heating during the winter – and certainly not during the night, without batteries – the net metering scheme in force in Hungary until 2023 made that rather irrelevant for adopters. As net metering offered annual netting, the excess solar production of the household in the summer could be ‘stored’ in the grid for the winter, at least from an accounting perspective.

If solar PV adoption could indeed increase heat pump (and electricity based heating) adoption, it also helped switching from likely more polluting heating sources to (locally certainly) clean electricity.

5.2.1. Methodology

To measure the effect of PV installation on local non-GHG emission, local pollution data should be used. In Hungary, however, there are only 34 automated metering stations for measuring local air pollution, most of them located in the largest cities (9 in Budapest). Therefore, there is no access to proper air pollution data on the municipal (or even regional) level, and satellite services offer data only in very low resolution (on the scale of 40x40km).

Since in Hungary, household heating is responsible for the largest share of local pollution and produces almost exclusively all particulate matter emissions, analysing household heating practices and dynamics can approximate the pollution level.

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). PV adoption was not a question in the 2011 survey, but according to regulatory data, there were only 629 residential solar installations in Hungary in 2011 (MEKH 2019). That is negligible compared to the more than 170.000 households with rooftop PV in 2022. Therefore, the 2011 level can be assumed to be zero in all municipalities.

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 listed in 34. Table were also added to a second OLS model to control for the typical socioeconomic effects behind the change of heating modes.

The regression model uses the following variables for each municipality (n=3176):

- *Dependent variable*
 - [heat_woodexcldiff20112022]: difference in the share of all dwellings using wood exclusively for heating in 2022 and in 2011.
 - [heat_wooddiff20112022]: difference in the share of all dwellings using wood for heating either exclusively or in combination with other fuels, in 2022 and in 2011
 - [heat_elecotherdiff2011_2022]: difference in the share of all dwellings using electricity and wood for heating in 2022 and in 2011
- *Explanatory variable* [pvoccupapart]: the share of households with small-scale solar PV units in the total number of dwellings.
- Control variables, as summarized in 34. Table.

Theme	Variable name	Description	Value type	Source
Age	age_60plusshare	Share of residents over 60 years of age in the total population of the municipality	%	(KSH 2022)
Education	edu_universityshare	Share of the population with a university degree	%	(KSH 2022)
Employment	employedintotalpopshare	Share of employed in the total population	%	(KSH 2022)

Personal Income	revenuepercap	Total personal income subject to personal income tax	HUF/cap	(Lechner Tudásközpont 2025)
Population density	popdens	Population density (calculated for the interior area of the municipality)	person/km ²	(Lechner Tudásközpont 2025)
Centrality	distance50thminute	Distance to the closest city with a population of 50 thousand	minutes	(Lechner Tudásközpont 2025)
Municipal income	localmunipincome_thhufpercap	Total income of the municipality budget per capita	1000 HUF/cap	(Lechner Tudásközpont 2025)
Housing	newdetached20112022_share	Ratio of new detached houses built between 2011-2022 to all houses	%	(Lechner Tudásközpont 2025)
Disadvantaged municipality	fetedummy	Whether the municipality is among the ~300 settlements officially designated as the least developed	y/n	Government decree 1404/2019
Energy investments	euprojectfinpercentage_huf	Total EU funding for (non-residential) entities in the municipality for energy efficiency and renewable energy 2013-2020	1000 HUF/cap	palyazat.gov.hu

34. Table Control variable used to control for the most common socio-economic attributes of the municipalities and inhabitants.

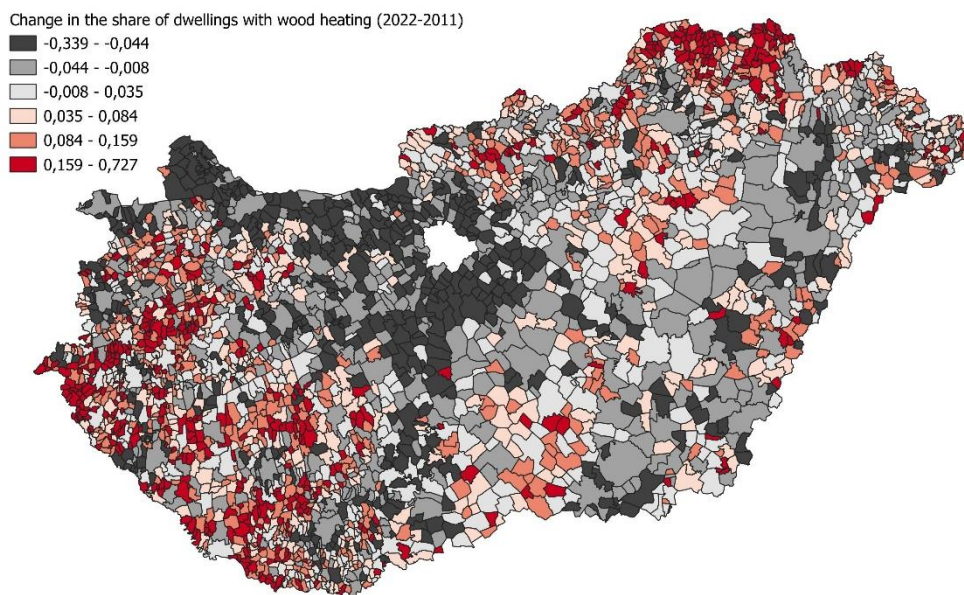
5.2.2. Results

In 2011 in Hungary, 37% of the dwellings used wood for heating, but only 18% used wood exclusively; the rest of the apartments were heated with a combination of wood and natural gas, electricity or other fuels. Coal (hard coal and lignite) use was less widespread; only 4% of the households were heated with coal (not exclusively, but mostly as a secondary option) (KSH 2011). By 2022, the rates had dropped: only 32% of dwellings were heated with wood, and only 15,5% used wood exclusively. Coal use almost disappeared (1% co-heating) (KSH 2022).

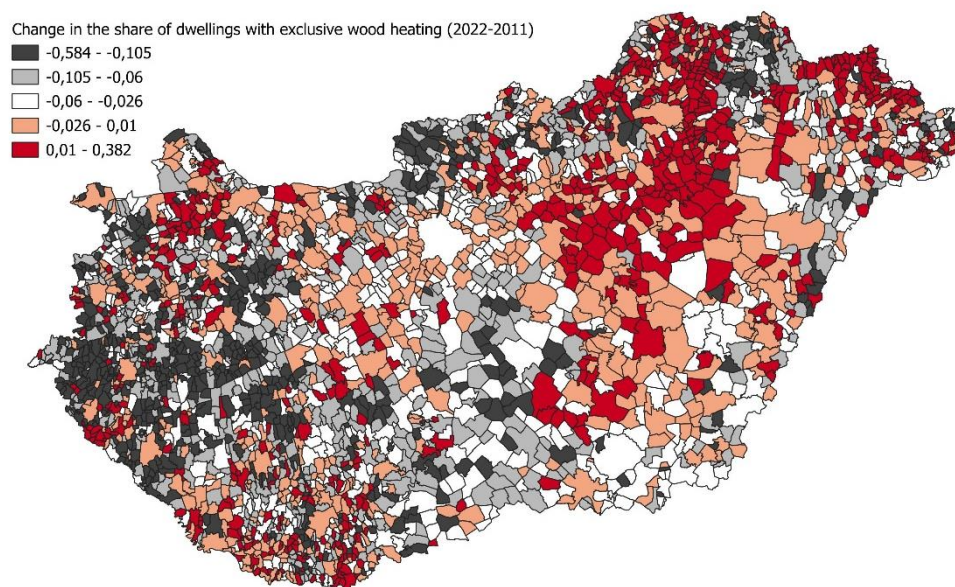
In 2022, there were 399 municipalities where at least 90% of the dwellings were fully or partially heated with wood, with a total population of 117,518. In 186 municipalities, a total population of 52,038 relied exclusively on wood heating for at least 90% of the dwellings. There were 1136 settlements (more than a third of the total) where exclusive wood heating was used in at least half of the households, while only 592 735 inhabitants lived in these municipalities, only 6% of the total population of Hungary.

In 757 municipalities (total inhabitants 1,175,526), the share of exclusive wood heating increased from 2011 to 2022. This includes 14 towns with a population above 10,000,

where both the increase (1% average) and the base (11.7%) were relatively small, yet it shows that the phenomenon is not confined to small settlements. In comparison, while the total number of homes using wood for heating non-exclusively decreased, in 1994 settlements, two-thirds of the total (with 1,825,789 inhabitants total) the share of wood use potentially combined with other sources has increased, with 11 settlements having population over 10,000 (including two county administrative centres, Zalaegerszeg and Szekszárd). In 591 settlements, including 4 towns with populations above 10,000.



2. Map Change in the share of households using wood for heating, possibly combined with other sources from 2011 to 2022. Grey areas show a decrease in the share, while red indicates municipalities where the share increased.



3. Map Change in the share of households using wood exclusively for heating from 2011 to 2022. Grey areas show a decrease in the share, while red colour indicates municipalities where the share increased.

The maps indicate that the more peripheral, economically less developed areas see an increase in the share of solid fuel use, especially for using wood exclusively. Latter is more prevalent in areas, where combined solid fuel use actually decreased (e.g. Hungarian Great Plain area, especially its Northern part, plus the vicinity of Győr). This suggests that in these areas households changed from combined heating to wood exclusive heating,

By 2022 178,992 households had residential rooftop solar panel systems installed according to the national census data, i.e. 4% of the total households (KSH 2022; MEKH 2024b). Therefore, currently, almost 10 times more households use wood, at least partially for heating, than as many have rooftop PV installed. Also, the built-in capacity of these solar power plants was 1,492 MW in 2022, producing roughly 1,500 GWh of energy (assuming a lower bound 1,050 hour/year load factor) – ca. 10% of the total household biomass use (53 PJ, or ca. 14,700 GWh). Therefore, while biomass heating cannot be directly substituted by electricity, it is apparent that, on paper, at least, there are no scale differences, and an average, household PV systems can produce enough electricity to limit or replace solid fossil fuel consumption on annual average. The main constraint is of course that solar PV production drops significantly during winter and is zero at nights, when heating is mostly used.

To estimate nevertheless, to what extent a switch from wood heating to electric (PV heating) happened, first, a simple linear (OLS) regression model was used with the share of homes with PV as an explanatory variable to the change in the share of apartments using wood exclusively or potentially combined with other fuels for heating, with robust errors and fixed effect control (Districts) but without control variables. 35. Table and 36. Table summarise the results.

Linear regression				Number of obs = 3177		
				F(1, 196) = 41.61		
				Prob > F = 0.0000		
				R-squared = 0.0533		
				Root MSE = .07815		
(Std. Err. adjusted for 197 clusters in district)						
heat_woodexcl~2	Coef.	Robust Std. Err.	t	P> t	[95% Conf. Interval]	
dep_pvoccupapart	-.5375113	.0833325	-6.45	0.000	-.7018547	-.373168
_cons	-.026281	.0051773	-5.08	0.000	-.0364913	-.0160707

35. Table Regression output table for the change in the number of households using wood exclusively for heating. Fixed effect model without control variables.

Linear regression

Number of obs = 3176

F(1, 196) = 129.21

Prob > F = 0.0000

R-squared = 0.0905

Root MSE = .1122

(Std. Err. adjusted for 197 clusters in district)

heat_wooddiff2~2	Coef.	Robust Std. Err.	t	P> t	[95% Conf. Interval]	
dep_pvttotalapart	-1.275574	.1122179	-11.37	0.000	-1.496883	-1.054264
_cons	.097916	.0065959	14.84	0.000	.0849079	.1109241

36. Table Regression output table for the change in the number of households using wood for heating either exclusively or in combination with other fuels. Fixed effect model without control variables.

The results indicate that there is a statistically significant relationship between the dependent and the independent variables. The coefficient for the share of households with rooftop solar installations is -0.5375. This negative coefficient implies that for each percentage point increase in the share of households with rooftop solar, there's an

associated decrease of approximately 0.5375 percentage points in the share of households heating with wood exclusively from 2011 to 2022. While the relationship is statistically significant, and the indicated effect aligns with the expected results, the total explanatory power (R-sq) of the independent variable is rather low (5.3% of the total variance).

Running the same model with the change in the share of households using *wood non-exclusively* for heating delivers similar but stronger results: the explanatory power (R-sq) of the share of PV installations increases to 9%, and while the relationship is still significant at the $p < 0.0001$ level, the coefficient is -1.2755. This suggests that the replacement effect (if such exists at all) is more substantial for 'non-necessary' wood use, and households which rely exclusively on fuel wood for heating and likely have a lower general socio-economic status are less likely to invest in PV.

The model with the control variables does not aim to explain the causes behind the reduction in the share of wood used exclusively for heating. It merely puts the PV-effect into context and identifies that its effect can actually be significant, and it is not just confounded, at least not by the most common and likely causes.

Linear regression

Number of obs = 3177

F(11, 196) = 13.73

Prob > F = 0.0000

R-squared = 0.1125

Root MSE = .07578

(Std. Err. adjusted for 197 clusters in district)

heat_woodexcldiff20112022	Coef.	Robust Std. Err.	t	P> t	[95% Conf. Interval]	
dep_pvoccupapart	-.378456	.1066262	-3.55	0.000	-.588738	-.168174
age_60plusshare	-.2662361	.064671	-4.12	0.000	-.3937764	-.1386957
edu_universityshare	-.1262311	.0537575	-2.35	0.020	-.2322485	-.0202137
employedintotalpopshare	-.2198704	.0575317	-3.82	0.000	-.333331	-.1064098
popdens	8.60e-06	3.31e-06	2.60	0.010	2.08e-06	.0000151
revenuepercap	2.54e-08	8.69e-09	2.92	0.004	8.27e-09	4.26e-08
distance50thminute	-.000267	.0001517	-1.76	0.080	-.0005662	.0000323
newdetached20112022_share	-.1253567	.0969226	-1.29	0.197	-.3165018	.0657884
localmunipincome_thhufpercap	9.87e-07	4.38e-06	0.23	0.822	-7.64e-06	9.62e-06
fetedummy	.0233523	.0084891	2.75	0.007	.0066106	.0400941
euprojectfinpercapthhuf	.0000192	1.00e-05	1.92	0.056	-4.84e-07	.000039
_cons	.077288	.023994	3.22	0.001	.0299684	.1246076

37. Table Regression output table for the change in the number of households using wood exclusively for heating. Fixed effect model with control variables. VIF score <2.

Linear regression

Number of obs = 3176
 F(11, 196) = 49.82
 Prob > F = 0.0000
 R-squared = 0.2461
 Root MSE = .10231

(Std. Err. adjusted for 197 clusters in district)

heat_wooddiff20112022	Coef.	Robust Std. Err.	t	P> t	[95% Conf. Interval]	
dep_pvttotalapart	-.3342005	.1542972	-2.17	0.032	-.6384963	-.0299047
age_60plusshare	.4387505	.0915905	4.79	0.000	.2581211	.61938
edu_universityshare	.1311252	.0888001	1.48	0.141	-.0440011	.3062516
employedintotalpopshare	-.09574	.0915222	-1.05	0.297	-.2762348	.0847548
popdens	-.0000125	7.28e-06	-1.71	0.088	-.0000268	1.88e-06
revenuepercap	-4.53e-08	1.56e-08	-2.90	0.004	-7.62e-08	-1.44e-08
distance50thminute	.0004657	.0002078	2.24	0.026	.0000558	.0008755
newdetached20112022_share	-.5906934	.1203039	-4.91	0.000	-.8279497	-.3534371
localmunipincome_thhufpercap	.0000543	.0000171	3.18	0.002	.0000206	.0000881
fetedummy	-.0131209	.0106991	-1.23	0.222	-.0342209	.0079792
euprojectfinpercapthhuf	-.0000472	.0000154	-3.07	0.002	-.0000775	-.0000168
_cons	.0974286	.0343405	2.84	0.005	.0297043	.1651529

38. Table Regression output table for the change in the number of households using wood for heating, either exclusively or in combination with other fuels. Fixed effect model with control variables. VIF score <2.

The control variables add explanatory power to the model both in the case of exclusive wood heating and wood heating in general; however, the increase is rather modest. The significance of the independent variable is weaker, although still remains below the $p > 0.05$ level in both cases. Its effect also weakens, but in the controlled models, a 1% increase in PV penetration still explains a -0.3% decrease in wood use.

The same analysis was conducted but not for wood heating directly, but for the share of dwellings using electricity and some other form of heating but not gas being the dependent variable (statistical data is not available on the share of dwellings using electricity+wood heating, but as central heating and natural gas use could be excluded, other forms of heating, apart from wood are negligible). This is to assess the impact of PV installation on the rate of households switching to electric+wood heating. The main question is whether those households have switched from wood-exclusive heating or introduced wood besides electricity as a replacement for natural gas heating.

The number of dwellings using electricity+nongas heating combination increased from 14,981 in 2011 to 66,200 by 2022. The rate of increase is significant; however, the share of such households is low; they make up only 1.6% of the total inhabited homes.

Linear regression

Number of obs = 3177
 F(2, 196) = 66.36
 Prob > F = 0.0000
 R-squared = 0.2013
 Root MSE = .02394

(Std. Err. adjusted for 197 clusters in district)

heat_elecotherdiff20~2022	Coef.	Robust Std. Err.	t	P> t	[95% Conf. Interval]	
dep_pvttotalapart	.2632371	.0285663	9.21	0.000	.2069004	.3195739
heat_woodexcldiff20112022	-.1040794	.0145155	-7.17	0.000	-.132706	-.0754529
_cons	.010089	.0009462	10.66	0.000	.008223	.011955

39. Table Regression output table for the change in the number of households using electricity and wood for heating. Fixed effect model controlling for the change in exclusive wood heating use.

Linear regression

Number of obs = 3177
 F(11, 196) = .
 Prob > F = .
 R-squared = 0.2240
 Root MSE = .02364

(Std. Err. adjusted for 197 clusters in district)

heat_elecotherdiff2011_2022	Coef.	Robust Std. Err.	t	P> t	[95% Conf. Interval]	
dep_pvttotalapart	.2577814	.044303	5.82	0.000	.1704095	.3451532
heat_woodexcldiff20112022	-.0964451	.0143944	-6.70	0.000	-.1248328	-.0680574
age_60plusshare	.0006184	.0226211	0.03	0.978	-.0439936	.0452304
edu_universityshare	.0668646	.0269602	2.48	0.014	.0136952	.1200339
employedintotalpopshare	.0046053	.0187399	0.25	0.806	-.0323525	.0415631
popdens	-4.34e-06	1.72e-06	-2.53	0.012	-7.73e-06	-9.60e-07
revenuepercap	-1.87e-09	4.24e-09	-0.44	0.660	-1.02e-08	6.49e-09
distance50thminute	.0000469	.0000422	1.11	0.268	-.0000363	.0001301
newdetached20112022_share	-.0874477	.0364539	-2.40	0.017	-.1593399	-.0155555
localmunipincome_thhufpercap	1.11e-06	2.28e-06	0.49	0.628	-3.39e-06	5.60e-06
fetedummy	-.0029351	.0022933	-1.28	0.202	-.0074578	.0015875
euprojectfinpercapthhuf	-7.06e-06	2.48e-06	-2.84	0.005	-.000012	-2.16e-06
_cons	.0055119	.0086685	0.64	0.526	-.0115835	.0226074

40. Table Regression output table for the change in the number of households using electricity and wood for heating. Fixed effect model with control variables. VIF score <2.

The results in 39. Table and 40. Table show that solar adoption has a statistically significant positive effect on the switching rate for electric+wood heating, even after controlling for the effect of the change in exclusive wood use (which is expectedly negative and significant). This suggests that electric+wood heating is not only replacing wood-exclusive heating but for some households, wood is newly introduced to combine with the electric heating supplied by the solar unit (indirectly). That partially

offsets the potential positive local emission effect of solar power installation in several municipalities.

6. SOCIAL NEXUS

The following analysis provides a more detailed understanding of the social profile of Hungarian residential PV adopters and their potential motivations for adoption. The analysis cannot provide an actual impact assessment of the social impacts of residential PV adoption, but it helps delimit the potential impacts. It enables a deeper understanding of the likely socio-economic drivers of PV adoption (to measure the impact of affluence, age, social status, education, etc.), while also accounting for the potential impacts of the local environment (municipal status, spatial spillover from neighbouring PV investments). Having insight into the social nexus in which PV adoptions occur also fosters understanding of the potential impact of these investments: whether they are driven by affluence, education, neighbours' influence, or age, they have different potential impacts. If rooftop panels are predominantly owned by wealthy and informed households concentrated around the Capitol, then their potential impact on energy equity is rather limited. If adopters are predominantly young families in rural Hungary with lower affluence but renovated homes, who are influenced by their neighbours, this suggests that the spread of residential PV can be more widespread, and that wider social strata can reap its benefits.

6.1. Methodology

Following the literature, the analysis of the adopters of residential PV in Hungary uses descriptive statistics first 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, presented in 42. Table, 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. 41. Table provides an overview of the units of analysis. 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 socio-economic status (SES) measure for capturing the economic and social resources (Sommerfeld et al. 2017).

Paper	Study area total population	Number of observed units	Avg. population of the unit of obs.
Sommerfeld et al. (2017)	1,920,205	117	16,412
Dharshing (2017)	81,000,000	402	201,493
Sunter et al. (2019)	316,100,000	73,057	4,327
Graziano et al. (2019)	268,000	4	67,000
Thormeyer et al. (2020)	8,373,000	2,222	3,768
Müller and Trutnevyte (2020)	8,373,000	143	58,552
Balta-Ozkan et al. (2021)	61,500,000	378	162,698
Lan et al. (2021)	25,000,000	2,658	9,406
Collier et al. (2023)	56,000,000	34,753	1,611
Zhang et al. (2023b)	17,060,860	13,205	1,292
Baranyai et al. (2021); Szép and Tóth (2025)	9,603,000	174 (197)*	55,190 (48,746)*
Horváth et al. (2021)	9,603,000	3,178	3,022
<i>Thesis</i>	9,603,000	3,178	3,022

41. Table: Granularity of the units of spatial observation of the studies reviewed. The units of the studies are often not compatible with the standardised EU classification of administrative units (NUTS-LAU). Therefore, the total and average population are used to provide comparability. *Including the Districts of Budapest.

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 (Magyar Energetikai és Közműszabályozási Hivatal), while the 2022 data is from the National Census. A further difference is that the time-series dataset by MEKH includes all HMKE projects with a capacity under 50kW, not all of which are residential; a particular share is installed by businesses and public institutions to cover self-consumption. Including these in the analysis can distort results. National Census data provide information exclusively on household units, although not even an aggregated capacity value is provided in that dataset. 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.

The Census asked the following question related to the dwelling:

13. Which of the following devices are available [as of 1 October 2022]?

- fixed internet connection (wired connection, WiFi, router, antenna)
- air conditioning
- heat pump
- solar panels (to generate electricity)
- solar collector, solar heating (to generate heat)
- none of the above

The data collection refers to dwellings, which is, according to the definition of Eurostat (which the Hungarian Central Statistical Office, KSH adheres to): “a room or suite of rooms - including its accessories, lobbies and corridors - in a permanent building or a structurally separated part of a building which, by the way it has been built, rebuilt or converted, is designed for habitation by one private household all year round” (Eurostat 2022).

According to the National Census 2022 Figures, the number of households and the number of inhabited dwellings (including inhabited resorts) are practically equivalent at the municipal level. There are ca. 5,000 households, 1,3% of the total, sharing a dwelling with other households. There are only 65 municipalities where this share is above 10%, with a total population of 4,600. Therefore, this can be considered negligible.

For privacy concerns, for all census statistics, values of 1 and 2 on the municipal level are not published but indicated by “...”. Therefore, for municipalities with 1 or 2 solar PV installed, there is no published official information. These values (1 or 2) were recreated using a random number generator (497 cases).

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 (TelR – Területi Információs Rendszer). The few exceptions are noted in 42. Table.

The models use the number of dwellings with rooftop PV installed in 2022 per all inhabited dwellings in the municipality as the dependent variable [dep_pvoccupapart].

42. Table provides an overview of the explanatory variables used in the regression analysis, including the rationale for inclusion.

Variable Name	Description	Data type	Expected effect	Theme	Generalised variable	Mention in the literature	Comment
PVout_mean	Annual average solar radiation (average for the municipality area)	kWh/year	+	Local environment	PV potential	5 - Szép and Tóth (2025); Thormeyer et al. (2020); Müller and Trutnevyte (2020); Ruokamo et al. (2023); Du et al. (2024)	Standard variable in the literature. The higher solar potential likely leads to a higher investment rate.
AGE_2039Share	Share of the population aged 20-39 years.	%	+	Social	Age	12 - Dharshing (2017); Sommerfeld et al. (2017); Sunter et al. (2019); Graziano et al. (2019); Thormeyer et al. (2020); Balta-Ozkan et al. (2021); Lan et al. (2021); Ruokamo et al. (2023); Collier et al. (2023); Zhang et al. (2023); Zhang et al. (2023b); Du et al. (2024)	Standard variable in the literature. Young families are more likely to consume more electricity as well as find the financial means for an investment. In Hungary, young families are targeted with subsidy programs for buying/renovating houses, which likely increase PV adoption likelihood.
AGE_60plusShare	Share of the population above 60.	%	-	Social	Age	12 - Dharshing (2017); Sommerfeld et al. (2017); Sunter et al. (2019); Graziano et al. (2019); Thormeyer et al. (2020); Balta-Ozkan et al. (2021); Lan et al. (2021); Ruokamo et al. (2023); Collier et al. (2023); Zhang et al. (2023); Zhang et al. (2023b); Du et al. (2024)	Standard variable in the literature. Pensioners are less likely to have the financial means, as well as the rate of electricity consumption, to enable or incentivise the investment.
MaleShare	Share of the male population.	%	+	Social	Share of Males	1 - Collier et al. (2023)	At least in one paper, males are assumed to be more open to technological innovations.
EDU_University Share	Share of the population with a university degree.	%	+	Social	Education	9 - Szép and Tóth (2025); Dharshing (2017); Sommerfeld et al. (2017); Müller and Trutnevyte (2020); Balta-Ozkan et al. (2021); Lan et al. (2021); Ruokamo et al. (2023); Collier et al. (2023); Zhang et al. (2023b)	Standard variable in the literature. Higher education likely signals more access to information, openness to green aspects and also more affluence.
EmployedinTotalpopShare	Share of employed in the total population.	%	+	Economic	(Un)Employment	4 - Baranyai et al. (2021); Dharshing (2017); Zhang et al. (2023); Graziano et al. (2019)	Standard variable in the literature. Approximating the local economic situation and potential affluence.
RevenuePercap	Total tax base of the personal income tax.	HUF/capita	+	Economic	Household wealth/affluence	10 - Szép and Tóth (2025); Dharshing (2017); Sommerfeld et al. (2017); Sunter et al. (2019); Thormeyer et al. (2020); Müller and Trutnevyte (2020); Balta-Ozkan et al. (2021); Ruokamo et al. (2023); Zhang et al. (2023); Zhang et al. (2023b)	Standard variable in the literature. This is the best available measure to approximate household-level income, which is among the most influential factors in the literature. This metric provides the average income in the municipality from employment, dividends, rental, but not pension.

DIGI_LowNoShare	Share of the population with no or low digital activity level.	%	-	Social	Information	0	Novel variable. Approximating access to information on the potential benefits of solar systems as well as the funding opportunities.
LMPVoteShare	Share of votes for LMP [Hungary's prominent green party] at the 2019 European Parliament elections.	%	+	Social	Green (political) attitude	4 - Dharshing (2017); Sunter et al. (2019); Graziano et al. (2019); Thormeyer et al. (2020)	Approximating green (political) attitudes. It needs to be noted that LMP in 2019 was indeed the only party with predominantly green messaging, but its support was low, 5% only; also, European Parliamentary elections in Hungary have a low turnout. On the municipal level, there is no other measure available for approximating green attitudes.
ApAGE_19601980Share	Share of dwellings built between 1960-1980.	%	-	Dwelling	Date of building	5 - Baranyai et al. (2021); Szép and Tóth (2025); Lan et al. (2021); Zhang et al. (2023); Zhang et al. (2023b)	Standard variable in the literature. Older houses are less likely to be fitted with rooftop panels (owners are less affluent, roof might require renovation before installation). The thresholds are defined by the original dataset.
ApAGE_19802000Share	Share of dwellings built between 1980-2000.	%	-	Dwelling	Date of building	5 - Baranyai et al. (2021); Szép and Tóth (2025); Lan et al. (2021); Zhang et al. (2023); Zhang et al. (2023b)	Standard variable in the literature. Older houses are less likely to be fitted with rooftop panels (owners are less affluent, roof might require renovation before installation). The thresholds are defined by the original dataset.
ApAGE_2000plusShare	Share of dwellings built between 2000-2022.	%	+	Dwelling	Date of building	5 - Baranyai et al. (2021); Szép and Tóth (2025); Lan et al. (2021); Zhang et al. (2023); Zhang et al. (2023b)	Standard variable in the literature. New houses are more likely to be fitted with rooftop panels (owners are more affluent, and no additional investments are required; also, net zero building regulations were expected to come in place in the late 2010s already). The thresholds are defined by the original dataset.
ApSize_Under60Share	Share of dwellings under 60 m ² .	%	-	Dwelling	Size of dwelling	5 - Szép and Tóth (2025); Sunter et al. (2019); Lan et al. (2021); Ruokamo et al. (2023); Zhang et al. (2023b)	Standard variable in the literature. Small dwellings are likely home to smaller, less affluent households and are more likely to be in block houses. The thresholds are defined by the original dataset.
ApSize_60_100Share	Share of dwellings between 60-100 m ²	%	+	Dwelling	Size of dwelling	5 - Szép and Tóth (2025); Sunter et al. (2019); Lan et al. (2021); Ruokamo et al. (2023); Zhang et al. (2023b)	Standard variable in the literature. Medium-sized dwellings are likely home to larger, more affluent households and are also less likely to be situated in

							blockhouses. The thresholds are defined by the original dataset.
DetachedHouse Share	The share of detached houses in the total number of inhabited dwellings [the number is derived by totalling the number of detached houses available in 2011 and the total number of detached houses built in 2011-2022]	%	+	Dwelling	Detached house	9 - Dharshing (2017); Sommerfeld et al. (2017); Graziano et al. (2019); Balta-Ozkan et al. (2021); Lan et al. (2021); Zhang et al. (2023); Zhang et al. (2023b); Tao (2024)	Standard variables in the literature - Detached homes can host rooftop panels; the regulation in Hungary basically prohibits installing rooftop panels for dwellings with more than one apartment.
Newdetached20112022_share	The share of detached houses built between 2011-2022 among all dwellings.	%	+	Dwelling	Detached house	9 - Dharshing (2017); Sommerfeld et al. (2017); Graziano et al. (2019); Balta-Ozkan et al. (2021); Lan et al. (2021); Zhang et al. (2023); Zhang et al. (2023b); Tao (2024)	As the building stock is relatively old in Hungary, new investments are likely to see rooftop PV. Also filters out apartments in blocks of houses built since 2000 from the variable "ApAGE_2000plusShare"
HousingDensity	Housing density (dwellings per ha of residential territory)	number/ha	-	Local environment	Housing density	4 - Szép and Tóth (2025); Sunter et al. (2019); Ruokamo et al. (2023); Du et al. (2024)	Standard variable in the literature. High density is likely to reduce the adoption rate, as in cities, the ratio of detached houses is small.
PopChange	Population change from 2011 to 2022 (2022pop/2011pop)	%	+	Social	Population change	0	Novel variable. With declining demographic trends in Hungary, the increased population from 2011 to 2022 is only characteristic of municipalities that are highly popular among internal migrants (mostly in agglomerations).
Distance50thMinute	Distance to the closest municipality with 50 thousand inhabitants	minutes	-	Local environment	Periphery	0	Novel variable. Measures the centrality-periphery of the municipality. Peripheral municipalities are less likely to have a favourable socio-economic status for a large share of PV adoption.
LocalMunicipalIncome_thHUFpercentage	Total budget income of the municipality	1000 HUF/capita	+	Economic	Municipal income	1 - Baranyai et al. (2021)	Approximating the local economic situation and potential affluence.
FETEDummy	Is among the list of most disadvantaged municipalities (FETE)	dummy	-	Economic	Disadvantaged municipalities	0	Novel variable. A complex metric for the most disadvantaged municipalities, where adoption rate is likely low.
BenefDummy	Is among the list of beneficiary municipalities	dummy	-	Economic	Disadvantaged municipalities	0	Novel variable. A complex metric for the most disadvantaged municipalities, where adoption rate is likely low.

(similar to FETE but three time as many settlements)						
ElecProvidperCap_2011	Total electricity provided for households in 2011.	kWh/cap	+	Economic	Electricity consumption	7 - Baranyai et al. (2021); Szép and Tóth (2025); Thormeyer et al. (2020); Müller and Trutnevyte (2020); Ruokamo et al. (2023); Zhang et al. (2023b); Du et al. (2024) Standard variable in the literature. Higher consumption leads to a greater likelihood of PV adoption, to offset costs. Measures the initial level of consumption (as cause).
ElecProvidAvgperCap_2011_2023	2011-2023 average of electricity provided for households.	kWh/cap	+	Economic	Electricity consumption	7 - Baranyai et al. (2021); Szép and Tóth (2025); Thormeyer et al. (2020); Müller and Trutnevyte (2020); Ruokamo et al. (2023); Zhang et al. (2023b); Du et al. (2024) Standard variable in the literature. Higher consumption leads more likely to PV adoption, to offset costs.
EUProjectFinPerCap	Total EU funding received between 2007-2020 for energy efficiency and renewable energy projects (non-residential, only SME's and public institutions).	1000 HUF/capita	+	Local environment	Neighbourhood effect	0 Novel variable. Local renewable energy investments in public buildings and businesses (not households) supported by EU funds can likely exert some neighbourhood effect and increase local know-how.
Neigh_CommPVMMunip	Total commercial capacity licensed before 2022.	kW	+	Local environment	Neighbourhood effect	0
Neigh_CommPVNeighMunip	Total commercial capacity licensed before 2022 in the neighbouring municipalities.	kW	+	Local environment	Neighbourhood effect	0
Neigh_HHPVNeighMunip	Number of residential solar PV units in the neighbouring municipalities.	pcs	+	Local environment	Neighbourhood effect	1 - Sunter et al. (2019)

42. Table Explanatory variables used in the regression analysis.

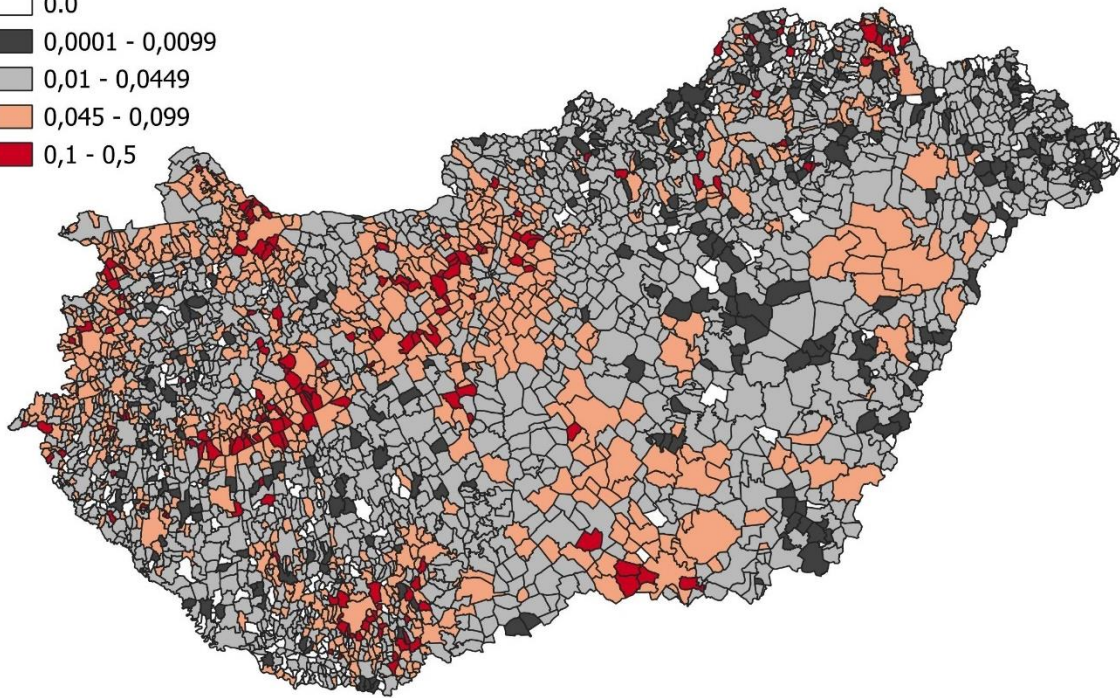
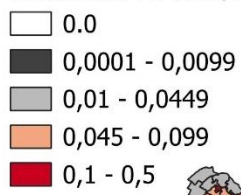
6.2. Descriptive statistics

According to the 2022 National Census, 178,992 dwellings had solar PV installed (in comparison, only 30,000 had solar heating units). That is almost 4,5% of all the inhabited apartments in Hungary (while less than 4% of all the apartments). There are almost 1000 municipalities with a local share above 4.5%, with a total population of 4.4 million, while 2200 municipalities below the 4.5% share with a total population of 5.2 million, suggesting a relative concentration of residential solar power plants compared to the distribution of the population.

281 municipalities, ca. 9% of the total, had 0 residential PV units installed, with an average population of 286 (Szemere, with 2,001 inhabitants, is the largest such municipality).

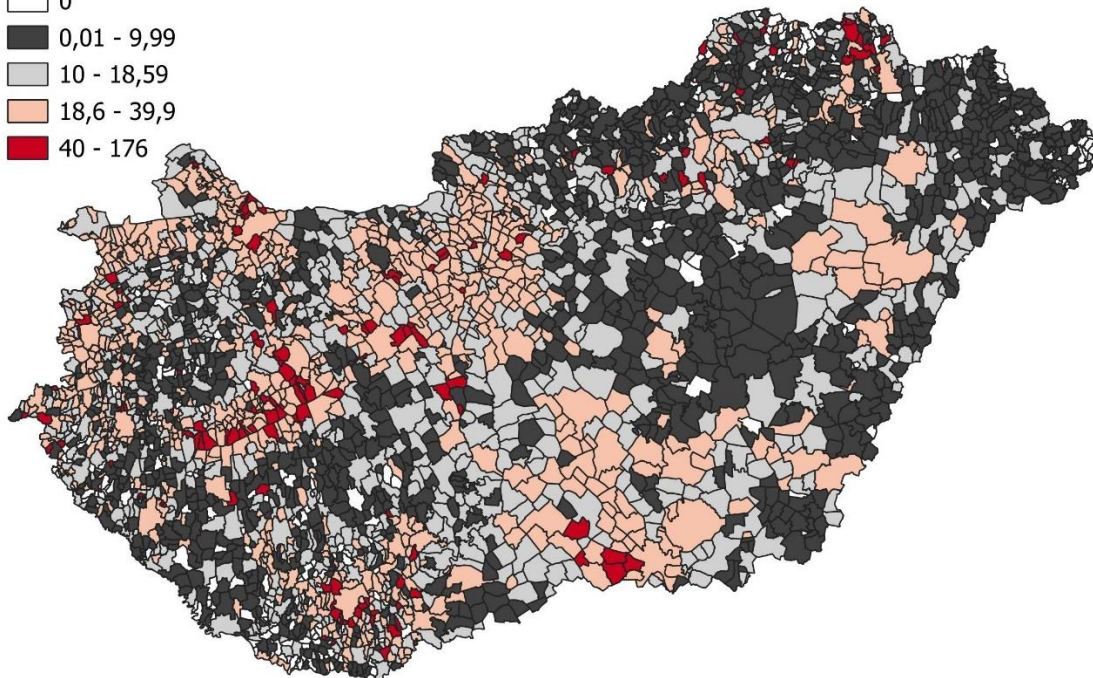
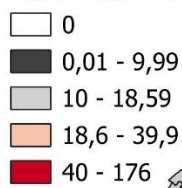
4. Map, 5. Map, and 6. Map show the spatial distribution of residential PV units. The results show, similar to earlier findings, above-average PV penetration around Lake Balaton and Lake Velence, in the vicinity of Szeged and Pécs, and in the agglomeration of Budapest. A peculiar concentration of municipalities with above-average PV penetration is located in the region of Zemplén, in the vicinity of Sátoraljaújhely, which is unlikely to be explained by either solar radiation values or affluence.

Residential PV units/inhabited dwellings



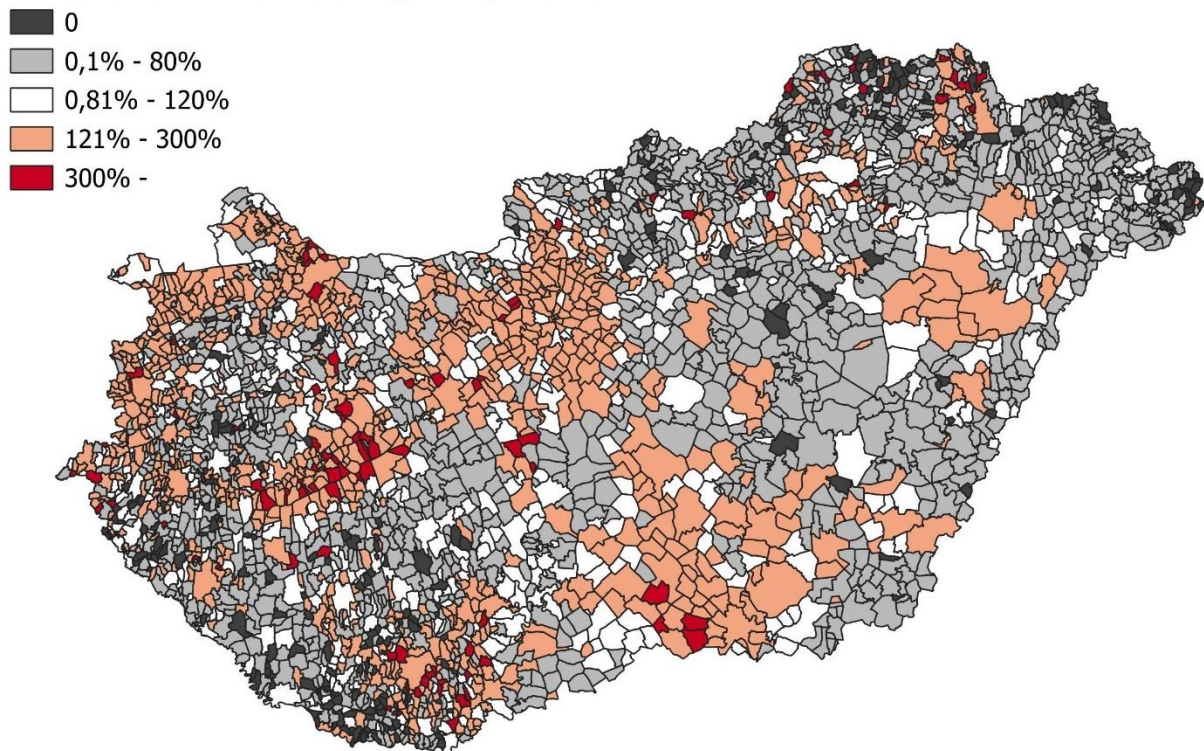
4. Map Residential PV units/inhabited dwellings (~households) for each municipality

Residential PV units/1000 inhabitants



5. Map Residential PV units/1000 people for each municipality

Difference from the national average of PV/1000 inhabitant



6. Map Difference of the local PV unit/1000 inhabitants value from the national average.

The average values of the per capita and per dwelling PV penetration for municipal types in Hungary in 43. Table show that with the increase in size, the adoption rate increases, except for the capital, likely due to the low share of detached houses.

Municipal type	Rooftop PV/1000 pop	Rooftop PV/inhabited dwelling
Village	15.8	4.13%
Budapest (capital)	20.6	4.33%
Town	18.1	4.49%
Major city*	22.1	4.99%
National average	18.6	4.47%

43. Table Average rate of PV-adoption in different types of municipalities. *Cities with county-rights.

6.3. Regression models

First, an Ordinary Least Squares regression was used using robust errors with the following variables and results. The VIF-score of the model is 2.41, with no variable

having an individual VIF-score higher than 5.03, suggesting that multicollinearity is not strongly present in the model. The explanatory power of the model (R^2) is 0.525, meaning that the model explains slightly more than 50% of the variance of the explanatory variable (residential PV/inhabited dwellings).

Linear regression

Number of obs = 3176
 F(27, 3147) = .
 Prob > F = .
 R-squared = 0.5251
 Root MSE = .02387

dep_pvoccupapart	Coef.	Robust Std. Err.	t	P> t	[95% Conf. Interval]	
pvout_mean	.0000741	.0000265	2.80	0.005	.0000221	.0001261
age_2039share	-.1069643	.0307847	-3.47	0.001	-.1673243	-.0466042
age_60plusshare	-.0667776	.0315239	-2.12	0.034	-.1285871	-.0049681
maleshare	-.0136827	.0452762	-0.30	0.763	-.1024567	.0750912
edu_universityshare	.1228161	.0258514	4.75	0.000	.0721288	.1735034
employedintotalpopshare	-.0042512	.0189455	-0.22	0.822	-.041398	.0328956
revenuepercap	4.75e-09	5.03e-09	0.95	0.345	-5.11e-09	1.46e-08
digi_lownoshare	-.0509606	.0154599	-3.30	0.001	-.0812731	-.020648
lmpvotesshare	.1048418	.0732498	1.43	0.152	-.0387804	.2484641
apage_19601980share	-.0213034	.0052106	-4.09	0.000	-.03152	-.0110868
apage_19802000share	.0073272	.0074303	0.99	0.324	-.0072415	.0218959
apage_2000plusshare	.0582423	.0169596	3.43	0.001	.0249893	.0914953
apsize_under60share	-.044765	.0109911	-4.07	0.000	-.0663153	-.0232146
apsize_60100share	-.038256	.008259	-4.63	0.000	-.0544495	-.0220625
detachedhousesshare	.0044988	.0091302	0.49	0.622	-.013403	.0224006
newdetached20112022_share	.0974763	.0461634	2.11	0.035	.0069628	.1879897
housingdensity	-4.84e-06	1.71e-06	-2.83	0.005	-8.19e-06	-1.49e-06
popchange	-.0013256	.0108206	-0.12	0.903	-.0225417	.0198905
distance50thminute	-.0001185	.0000225	-5.28	0.000	-.0001626	-.0000745
localmunipincome_thhufpercap	1.19e-06	1.99e-06	0.60	0.551	-2.71e-06	5.08e-06
fetedummy	.000342	.0015728	0.22	0.828	-.0027418	.0034259
benefdummy	.0014534	.002244	0.65	0.517	-.0029465	.0058534
elecprovidpercap_2011	2.35e-06	6.72e-06	0.35	0.727	-.0000108	.0000155
elecprovidavgpercap_20112023	.0000158	5.90e-06	2.67	0.008	4.20e-06	.0000273
euprojectfinpercapthhuf	2.54e-07	2.24e-06	0.11	0.909	-4.13e-06	4.64e-06
neigh_commpvmunip	2.32e-08	3.31e-08	0.70	0.484	-4.18e-08	8.82e-08
neigh_commpvneighmunip	8.65e-09	1.30e-08	0.66	0.507	-1.69e-08	3.42e-08
neigh_hhpvneighmunip	-2.73e-07	4.94e-07	-0.55	0.580	-1.24e-06	6.95e-07
_cons	-.0042564	.0461726	-0.09	0.927	-.0947879	.0862751

44. Table Regression output for the simple OLS model.

However, because regional differences are likely to have a significant impact on municipal differences, the districts in which the municipalities are located were included to control for regional fixed effects. The resulting model has greater explanatory power ($R^2=0.591$) and captures some local differences as well. However,

many of the explanatory variables have lost their significance. Using counties instead of districts resulted in no increase of R^2 .

Linear regression

Number of obs = 3176
 F(201, 2951) = .
 Prob > F = .
 R-squared = 0.5910
 Root MSE = .02288

dep_pvoccupapart	Coef.	Robust Std. Err.	t	P> t	[95% Conf. Interval]	
pvout_mean	-.0001297	.0000878	-1.48	0.140	-.0003019	.0000425
age_2039share	-.082111	.0314932	-2.61	0.009	-.1438619	-.0203602
age_60plussshare	-.0696497	.0349557	-1.99	0.046	-.1381898	-.0011097
maleshare	-.0314434	.0496688	-0.63	0.527	-.1288325	.0659457
edu_universityshare	.124155	.0316406	3.92	0.000	.0621151	.1861949
employedintotalpopshare	-.006076	.0230431	-0.26	0.792	-.0512581	.039106
revenuepercap	8.62e-09	7.03e-09	1.23	0.220	-5.17e-09	2.24e-08
digi_lownosshare	-.0544528	.0170691	-3.19	0.001	-.0879214	-.0209842
lmpvotesshare	.0872341	.0687532	1.27	0.205	-.047575	.2220432
apage_19601980share	-.0111343	.0073268	-1.52	0.129	-.0255006	.0032319
apage_19802000share	-.0019817	.0104936	-0.19	0.850	-.0225572	.0185937
apage_2000plussshare	.0801469	.0194931	4.11	0.000	.0419254	.1183683
apsize_under60share	-.0473189	.0127045	-3.72	0.000	-.0722295	-.0224084
apsize_60100share	-.0322324	.0104996	-3.07	0.002	-.0528197	-.0116452
detachedhousesshare	-.004053	.0105434	-0.38	0.701	-.0247262	.0166202
newdetached20112022_share	.0860656	.0493817	1.74	0.081	-.0107605	.1828916
housingdensity	-8.19e-06	4.19e-06	-1.95	0.051	-.0000164	3.19e-08
popchange	.0051167	.0123995	0.41	0.680	-.0191959	.0294293
distance50thminute	-4.51e-06	.0000654	-0.07	0.945	-.0001327	.0001237
localmunipincome_thhufpercap	-1.53e-07	2.73e-06	-0.06	0.955	-5.51e-06	5.20e-06
fetedummy	.0000576	.0016633	0.03	0.972	-.0032037	.003319
benefdummy	.0023245	.0020014	1.16	0.246	-.0015997	.0062488
elecprovidpercap_2011	6.91e-06	7.32e-06	0.94	0.345	-7.45e-06	.0000213
elecprovidavgpercap_20112023	.0000102	7.01e-06	1.46	0.145	-3.53e-06	.000024
euprojectfinpercapthhuf	-5.52e-07	2.28e-06	-0.24	0.808	-5.02e-06	3.91e-06
neigh_commpvmunip	1.06e-08	3.51e-08	0.30	0.762	-5.83e-08	7.95e-08
neigh_commpvneighmunip	-3.07e-09	1.51e-08	-0.20	0.839	-3.26e-08	2.65e-08
neigh_hhvpvneighmunip	6.99e-07	5.84e-07	1.20	0.231	-4.46e-07	1.84e-06
_cons	.2436808	.1134402	2.15	0.032	.0212509	.4661107

45. Table Regression outputs for the fixed effect model (regional dummies are not represented in the table).

Interpretation of the results

For the interpretation, statistical significance is understood as $p < 0.05$. The following interpretation is based on the second model with fixed effects included unless specified otherwise.

The share of the population under 40 is statistically significant, although, the effect is rather weak (0.082) and contrary to the initial expectation negative. This might be explained by the relatively lower affluence (spending power) of young people/families, even despite some government subsidy programs. Including the share of people aged 40-59 does not produce a statistically significant effect. The share of the population above 60 is also below the defined significance threshold, and its effect is negative as expected, even though the effect is relatively small. This is also in contrast with the reports from the interviewed municipalities, where young (often newly moved in) families were highlighted in most cases as a group with a high rate of PV adoption. The result is also unexpected, as there are numerous state subsidy programs available for young families buying or renovating houses, on which PV installation is considered more likely. The result suggests that these programs are not able to counteract the lower affluence level of young families.

Higher education is statistically significant and delivers a relatively strong influence on PV adoption, in line with some of the literature.

A lower level of digital literacy also has an expectedly negative, significant effect, suggesting that PV adoption is also a matter of available information on the potential benefits, especially the available subsidies and funding programs.

Apartment size under 100 m² collectively has a significantly negative, although relatively weak effect on PV adoption rate, suggesting that not only small but even medium-sized apartments are less likely to have rooftop PV installed.

New apartments (built since 2000) are statistically significantly more likely to have rooftop panels installed, as originally expected, and the share of newly built detached houses also has an expectedly positive, although slightly above significance level effect. The total share of detached homes is insignificant, further suggesting that old (unrefurbished) houses are not likely to receive rooftop installation; however, housing density is practically at the significance threshold with a small negative effect, likely thanks to the low share of PV in heavily urbanised municipalities, where blocks of houses are dominant (on which rooftop PV installation is currently legally almost impossible).

Variables considered to account for household affluence (per capita personal income tax base, employment rate, municipal income) do not show a statistically significant

impact in the OLS or fixed-effects model. This can be either because the variables do not grasp household affluence properly (focus more and imprecisely on income, while wealth and assets are more critical), or the impact of direct affluence is less relevant. It is also noteworthy that belonging to either of the official lists of settlements with low socio-economic status does not significantly affect the rate of adoption. The interviews consistently indicated that wealth was the most important adoption factor across the municipalities.

Neighbourhood effects also turn out to be highly insignificant in these models, although these results should be interpreted with caution, as spatial spillovers can be measured only with time-series data.

7. DISCUSSION AND CONCLUSION

The main ambition of the current Thesis was to provide insight into the local impacts of the energy transition, especially of the spread of solar PV panels in Hungary. The impacts of the shift in the energy system to modern renewables are rather well understood globally, whether direct or indirect, desired or externality-like. The nature, severity and effects of these impacts on the local level are less explored except for some aspects (like the literature's focus on community-based renewable energy frameworks). Due to the spatially decentralised nature of renewable energy sources, especially solar PV, the investments underway will directly affect many, if not most, communities in Hungary, across Europe, and globally.

In Hungary, 4% of households already have residential solar panels installed – a figure likely to increase to 10-20% in the coming years if the current policy goals are met. There are only a few municipalities with a residential PV adoption rate of zero. Large-scale solar power parks are an everyday sight for most people travelling roads and highways in rural Hungary.

Hungary, as a case, offers an interesting insight into the later-stage developments in the national adoption cycle of solar PV. The share of built-in PV capacity already makes Hungary unique in Europe and stands out in global comparison, and the current policy targets are equally ambitious. At the same time, Hungary is practically not participating in the global solar value chain, only as a customer – a role taken up by

more and more countries as the economic value chain in recent years has concentrated mostly in China.

The Thesis aimed to provide a comprehensive overview of the potential impacts in Hungary at the lowest possible local administrative level. It was a deliberate choice not to focus on and deep-dive into a single aspect, but to provide a spatially granular overview of all potentially relevant aspects. The goal is not to provide a detailed and refined understanding of a single, narrow aspect but to give a well-established approximation of all relevant aspects. This not only delivers policy-relevant conclusions on the general impacts of Hungarian renewable energy policies but also helps navigate future research by highlighting relevant and less relevant aspects and identifying gaps in data and understanding.

The lack of data hinders analysis in many respects, yet, for the most part, available national data can be used to address the most relevant and interesting issues. Collecting detailed information from the field on all Hungarian municipalities, or even on a representative subset, is infeasible. However, the Thesis sought to demonstrate that the best available public data is sufficient to provide at least an indicative conclusion on the identified impacts, their relevance, and importance.

The Thesis first identified through an extensive literature review the theoretically relevant impacts and then refined them to impacts that are assumed to be relevant in the case of Hungary. These impacts were classified under the three aspects of sustainability: economic, environmental and social. This division guided the formulation of questions and hypotheses, as well as the subsequent empirical research. The main results of these investigations are also presented in the same grouping.

7.1. 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 lower-than-average GDP per capita, suggesting that 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 across the country; their spatial horizon is not confined to their immediate neighbourhood.

Truly local ownership, in general, is 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 in the Hungarian solar sector, whereas foreign private and state-owned actors captured most of the Hungarian market, especially for truly large-scale projects.

At the same time, the Hungarian solar market is highly competitive rather than oligopolistic, according to HHI calculations. Therefore, the entry barrier is not legal or stemming from the market structure, but likely from the lack of capital and/or know-how concentration for domestic private actors. Nevertheless, the Hungarian case shows that without explicit policy support for local actors, in small and open economies coming relatively late to the renewable boom, the renewable sector becomes dominated by mostly non-local, and 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 the project companies from these local taxes. However, there are only a handful of municipalities in which, according to the model used in the analysis, potential land tax income would represent more than 5% of total municipal income. Land and Building Tax, as a local source of income from commercial PV plants, is highly underutilised by municipalities, thereby limiting 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 selection for investors; therefore, marginally increasing their tax burden is unlikely to trigger 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, at the municipal level it is not a significant source of local added value, as the residential POV penetration rate is low in most settlements and adopters are relatively well dispersed across the country.

The research could partially confirm 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 from commercial-scale investments, it is apparent that the Hungarian solar PV boom likely did not provide a significant economic development opportunity for most 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).

7.2. 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. 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. 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.

At the same time, substantial differences exist among EU Member States. Some countries rely predominantly on agricultural land, while others make greater use of industrial, mining, or forested areas. These differences likely reflect variations in land-use structure, planning regulations, topography, and the timing of national solar deployment.

The Hungarian case broadly follows the overall European trend but also exhibits several distinctive features. Commercial-scale PV installations are overwhelmingly located on agricultural land, particularly arable land and pastures. The analysis provides little evidence that solar development has disproportionately affected ecologically or agriculturally valuable land. 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. The analysis also doesn't provide evidence that commercial-scale PV in Hungary would concentrate systematically in municipalities with unusually low or high agricultural land quality.

The municipal-level analysis further demonstrates that land-use impacts are unevenly distributed. While the national share of land occupied by commercial-scale PV remains low, certain municipalities experience considerably higher levels of land occupation. In several settlements, more than 5% of the municipal territory is covered by commercial-scale PV facilities, while in one case the proportion exceeds 20%. These findings highlight the importance of examining renewable energy development at multiple spatial scales. National averages may suggest limited land-use impacts, whereas local communities may experience much more substantial changes in landscape character and land-use structure.

The results also reveal an important temporal and structural tendency in the Hungarian case. As project size increases, solar developments become progressively less frequent on artificial and built-up surfaces and increasingly common on agricultural and semi-natural land. While this trend does not currently imply extensive forest or shrub conversion, it suggests that future growth may increasingly intensify competition for land resources unless alternative deployment strategies become more widespread. 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 declined from 23% in the first tender to 12% in the third (in terms of capacity). Greater utilisation of rooftops, industrial sites, brownfields, agrivoltaic systems, and other dual-use approaches could reduce potential conflicts between energy generation and other land-use functions.

The findings also have relevance for the emerging EU framework on Renewables Acceleration Areas established under the revised Renewable Energy Directive (RED

III). The Directive requires Member States to designate areas where renewable energy deployment is not expected to have significant environmental impacts, while prioritising artificial and built surfaces, as well as degraded land unsuitable for agriculture. At the same time, the framework calls for the exclusion or careful consideration of Natura 2000 sites and other environmentally sensitive areas. The land-cover analysis presented here does not constitute an assessment of Renewable Acceleration Areas. However, by documenting the land-cover types on which commercial-scale PV has actually been deployed in the EU and in Hungary, this analysis provides an empirical baseline against which the land-use implications of future spatial planning can be assessed. The analysis also suggests that such – conscious or unconscious - prioritisation of artificial surfaces and agricultural land over areas with more ecological potential (including Natura 2000 sites) is the current general reality in the EU. However, this is not to dismiss the potential negative ecological impacts, especially if the tendency observed in Hungary, i.e. larger capacity tends to be located on more sensitive areas, is true for other Member States as well.

Several limitations of the study should be acknowledged. The analysis relies on the best available satellite dataset, yet it still accounts for only 4/5 of the total capacity in Hungary and even less in the EU. Furthermore, municipal-level agricultural quality indicators provide only an approximate measure of the quality of specific parcels occupied by PV installations. Future research could benefit from parcel-level land-quality data, higher-resolution land-cover information, and longitudinal analyses of land-use change before and after PV deployment. However, the likely most important future research direction the current analysis points toward is the need for a thorough case-by-case analysis of different investment projects and their actual environmental impact, depending on location, pre-existing vegetation, and construction and operational methods.

As solar capacity continues to expand rapidly, land-use considerations will become increasingly important. The challenge for policymakers is not whether solar energy should continue to grow, but how to manage this growth spatially to minimise environmental conflicts while supporting both climate objectives and sustainable territorial development – most likely by implementing design and planning frameworks for agrivoltaic and ecovoltaic power plants.

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 using wood as fuel (coal use has 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 happened from wood, then residential solar units could reduce local air pollution.

The OLS regressions used to measure this effect suggest that the appearance of rooftop solar installations in Hungarian municipalities has significantly contributed to the decrease in the use of solid fuel, especially wood, for heating both exclusively and as a supplementary source. Therefore, it also contributed to a possible decrease but at least 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 on either the actual emission levels at the municipal level or the consumption of fuelwood (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 experiencing an increase in the share of solid fuel heating are in the

“Felzárkozó Települések” (catch-up settlements) program, which targets the most disadvantaged settlements in Hungary and covers only 9% of all 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.

7.3. Social nexus

Social impacts of solar PV investments are the hardest to identify, operationalise and measure. The analysis conducted in Chapter 7. 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

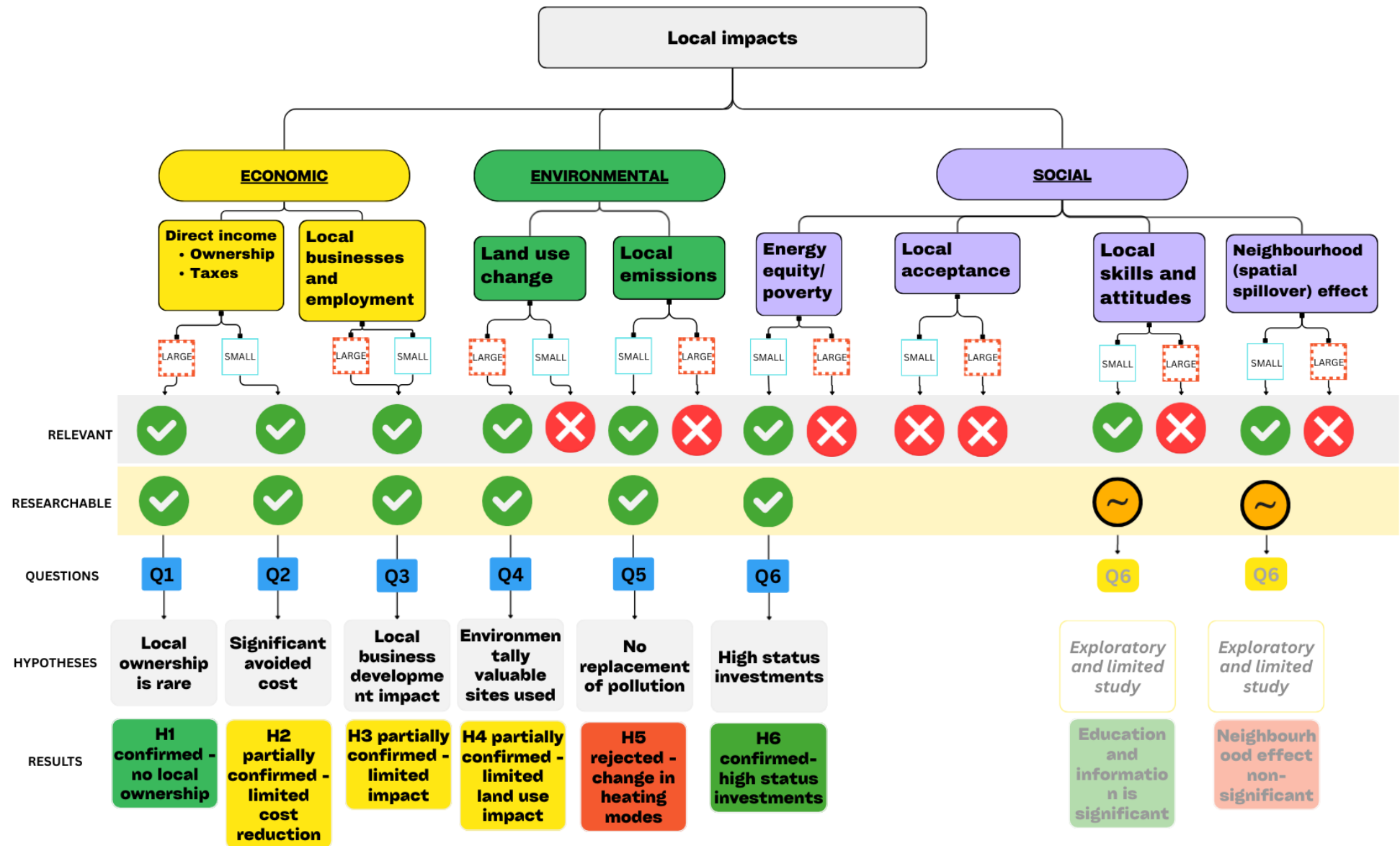
municipal level data), or in the Hungarian case, affluence is not as important as was assumed.

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 turned out to be 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.



26. 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.

7.4. 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.

7.5. Outlook

The current analysis has substantial room for improvement and also highlights promising directions for future research.

While some interviews were conducted during the latest stage of the research, extensive case studies would be required to assess whether and to what extent ownership of commercial capacities actually translates into localised money streams (use cases). Some Hungarian municipalities (e.g., Bóly) offer unique insights into how a local (partly municipality-driven) energy sector can be developed in the absence of central government support, and how such communities can be transformed into major

renewable energy hubs. Case studies could also be expanded to include entrepreneurs identified during the UBO analysis who became relevant players in the Hungarian solar sector, either nationally or locally. Only a handful of Hungarian businesses, especially locally owned ones, remained active players during the Hungarian PV boom. If localisation of PV revenues ever becomes a policy target, it will be vital to better understand what predicaments and features enabled that success.

It would be important to monetise both the potential local effects of owning commercial-scale PV capacity and the local tax potential of the Business Tax to approximate the actual rural development potential of commercial PV investments.

Acquiring time-series data on the municipal level for household solar adoption rates would help tremendously in refining the regression analysis on adopter profiling, particularly in analysing potential spatial spill-over (neighbourhood) effects. This would also enable the approximation of the actual local social impacts of residential solar PV installations.

Expanding the dataset to include commercial-scale capacities, along with the date of (planned) entry into operation, would largely remove the uncertainty stemming from the fact that, currently, the dataset contains licensed but not necessarily built projects, with only the initial licensing date, not the total construction timeframe.

Developing an ecological evaluation score and applying it to land cover types would help provide more detailed insights into the potential local ecological impact of solar investments across different land use types. Actual longitudinal measurements and case studies in several representative locations would be required to acquire a detailed understanding of the environmental impact of land-use change over time.

An important addition to this research would be the identification of several representative projects that capture most of the commercial PV investments in Hungary, conducting a supply-chain analysis of those projects and using the resulting data to extrapolate the local economic effects of similar projects across the country.

7.6. 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 the renovation of their

roofs and the installation of PV systems, are mostly left out of the potential income effects 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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