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Pursuing a low-carbon rural energy transition in China and Germany

Perspectives on self-sufficiency and sector coupling from two villages

Sino-German Energy Transition Project

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Imprint

The report *Pursuing a low-carbon rural energy transition in China and Germany* introduces the results of parallel studies of rural villages in Germany and China with potential for a low-carbon, clean energy transition, and makes policy suggestions related to promoting clean energy policies that could accelerate that transition. The report is published in the framework of the Sino-German Energy Transition project, as part of the Sino-German Energy Partnership between the German Federal Ministry for Economic Affairs and Climate Action (BMWK) and the National Energy Administration of the People's Republic of China (NDRC). The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Agora Energiewende, and the German Energy Agency (Deutsche Energie-Agentur, or dena) jointly implement the project under commission of the political partners.

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Executive summary

Rural areas play a vital role in the low-carbon energy transition, given their ample open space, and considerable energy consumption. Yet much of the analysis of low-carbon technology adoption or low-carbon energy system forecasting omits mention of rural communities, focusing instead on wealthier, urban residents or overall installations of utility-scale renewable energy or storage.

For this study, the Sino-German Energy Transition project brought together scholars of energy modelling and rural ecology to examine the question of how clean energy technology will affect the energy flows and carbon emissions of rural areas in Germany and China. This report describes the results of case studies of two rural villages/towns—Dongqiaotou in Shandong province, China, and Schwaig in Bavaria, Germany—to examine the question of how to accelerate the clean energy transition in areas, and to identify the potential for rural communities to become more self-sufficient in their energy supply to enhance resilience and lower network costs.

In the case of Dongqiaotou village in Shandong province, a village-scale survey, semi-structured interviews, and a combination of top-down and bottom-up analysis enabled development of an energy flow model and scenario analysis of the village's current and future energy system. The analysis finds that the village has a potential to meet a large share of its electric power and heating/cooling demand via solar PV and heat pumps (which provide both heating and cooling). With a growing share of electric vehicles, villagers can save money for fuel by using solar energy for charging during daytime. Accelerating the village's plans to adopt PV panels and solar streetlights will not only benefit the residents through reduced energy costs, but also promote the development of a low-carbon society. Storage for electricity and heat could further enhance self-sufficiency in the future.

In the case of Schwaig, a combination of village-scale survey data, energy data from local utilities, and scenario analysis enabled the construction of an energy flow model and scenario analysis. The report finds that Schwaig has a high potential to further increase its already high degree of clean energy self-sufficiency, through the adoption of residential heat pumps and electric vehicles. However, seasonal energy storage and balancing from the grid will still be necessary.

Overall, the two villages/towns have commonalities in terms of the potential for clean energy, even though they exhibit marked differences in terms of income, occupations, and current fuels for heating and power.

From our scenario analysis and projections, we conclude:

Distributed energy and self-sufficiency are attractive in both Germany and China: In Germany, adoption of distributed solar, electric vehicles, and heat pumps is likely to continue, giving the region's high potential for energy self-sufficiency. Similarly, we find that Dongqiaotou has the potential to increase its self-sufficiency with EVs and PV, even as its energy consumption rises more rapidly due to rising incomes.

In Germany, heat pumps and insulation could help reduce the impact of solar variability: Adoption of distributed clean energy will also make daily electricity supply and loads more volatile, given that PV could supply up to a fourth of local energy production and far exceed the total household monthly load in summer. We estimate that heat pumps and well-insulated German houses have high potential for smoothing household net loads. While heat pump adoption in Oberding is presently low, 62% of homes could have heat pumps installed by 2035 according to the dena95 scenario. EV adoption and timed charging could play a role, but it is far smaller given that the EV load is expected to be just 4-5% of total energy consumption, compared to 16-17% for heating and cooling.

In China's rural areas, distributed energy technology adoption is more uncertain, but has high potential: In China, bioenergy will continue to play a larger role in boosting the village's renewable energy uptake. While there is uncertainty about adoption of distributed PV, heat pumps, or EVs, scenarios and estimates employed in this study suggest that by 2030 these technologies will likely have a significantly larger presence, particularly PV. Heat pumps are already economical for those homes that require both cooling and heating. Under the existing development model, the village was 16.8% energy self-sufficiency rate in 2020. Under an optimistic development scenario, the energy self-sufficiency rates could reach 80.70% in 2025 and 126.16% in 2030.

The analysis in both China and Germany employed a mixed approach that quantifies the present energy production and consumption based on existing datasets, estimates from national or regional data, data from the distribution grid (in the Schwaig case), and household surveys. For the household energy surveys, in Schwaig/Oberding the survey response rate was 19%, and in Dongqiaotou 18.8%.

Scenarios for PV, EV, and heat-pump adoption combine multiple sources including discussion with local officials and experts, dena, Agora, BDI, and BWP for Germany. For China, scenarios include information from local surveys; analyses on expected national and regional development of EVs and heat pumps served as a basis for estimates on village level.

The modelling approaches and methodologies that the researchers applied in the two villages differ, and therefore the resulting estimates on energy self-sufficiency for both villages are not directly comparable. For instance, in Dongqiaotou the researchers considered agricultural waste and all energy consumption, whereas in Schwaig the analysis only considered grid electricity and household electricity.

The rural energy transition is an important policy priority for both countries, given that rural communities have an important positive contribution to make to the energy transition, and policy makers want to ensure the benefits of the energy transition reach rural communities. In the future, studies like this can enable greater awareness among rural residents and facilitate exchange with policy makers about how to ensure a just energy transition in rural areas.

Introduction

It is critical that rural areas both participate in, and benefit from, the low-carbon energy transition. China's energy transition to date has involved massive deployment of wind and solar, efficiency upgrades to the country's coal plants and industry, and commercialisation of new energy technology in fields such as electric vehicles in major cities. In Germany, which was one of the first countries to deploy wind and solar energy at scale, rural communities have benefited from ownership in rural energy facilities. To realise the energy transition, both countries are likely to accelerate their deployment of renewables, electrification of transport and heating, and replacement of fossil fuel heating with electric heat pumps or other low-carbon options. How this will affect rural residents is an open question, especially given concerns that the trend towards electrification might entail major upgrades to rural distribution grids. If distributed energy and storage enable greater self-reliance, this could benefit local areas both by reducing infrastructure costs, and thereby lowering grid charges, as well as improving overall rural climate resilience.

China

The energy transition discussion in China sometimes focuses mainly on the energy industry or on urban areas. In the context of rapid urbanisation, it is easy to overlook the country's vast rural areas even though they still are home to over 509 million people, accounting for 36% of the total population. Achieving the energy transition in rural areas is an important part of realising China's national strategies and targets, such as the Energy Revolution, Rural Revitalisation, the Beautiful China Strategy, and carbon peaking and carbon neutrality.

Rural areas in China face challenges such as an aging population; soil and water pollution; and a large income and wealth gap to larger cities. Rural areas in China have lower incomes and often rely on older technologies such as two-stroke diesel three-wheeled vehicles or heating with loose coal (散煤 in Chinese) or biomass. Many villages employ older building practices with poor insulation. Smaller towns often have minimal connections to the power grid. Yet China is focusing on raising the living quality of rural areas, and the clean energy transition is part of that process—with the potential for improving local air quality and the efficiency of daily life tasks. Though rural areas use less energy per capita than urban areas, it is nevertheless important that they also play a role in carbon neutrality—not just through large energy projects, but also through distributed clean energy technologies and energy efficiency upgrades.

Germany

Germany's energy transition, in contrast to China's, early on focused on involving rural areas in deploying clean energy. The first impetus for Germany's energy transition came from the oil crises of the 1970s, but a crucial turning point was the 1997 Kyoto Protocol, which set the first climate policy targets for the industrialised countries to reduce greenhouse gas emissions.[1] According to this, the European Union (EU) set climate, renewable energy, and energy efficiency targets to reduce greenhouse gas emissions in 2007. The EU has steadily tightened and updated its targets under the 2015 Paris Agreement and the EU Green Deal.[2] After the reactor catastrophe in Fukushima 2011, Germany decided on a faster phase-out of nuclear energy by 2022.[3] In 2020, the German government decided to shut down all coal-fired power plants by 2038 at the latest, while the new Federal Government that took office in December 2021 intends to do so by 2030.[4] Germany aims to become climate neutral by 2045.

Germany only can achieve these goals with a large amount of renewable energy and a massive expansion of distributed energy resources (DERs). These targets also imply electrifying the transport and heating sectors, which today mainly rely on fossil fuels. This transition will further increase electricity demand, which also underlines the importance of installing as many distributed renewables as possible to reduce the need for imported energy and network upgrades. Distributed wind and solar are at the forefront of the German low-carbon energy transition, often owned directly by individuals or small communities. But the German rural energy transition is also a work in progress. Rural areas have ample room to adopt electric transportation and efficient heating and cooling, for example.

Comparison of rural energy transitions

The energy transition is creating opportunities, especially in rural areas. Rural areas in China and Germany often have more local renewable energy resources and more space for deploying renewable energy generation technologies than urban areas. Hence, they have a potential for achieving a high degree of self-sufficiency from their local renewable energy resources.

In general, rural areas often have various structural weaknesses compared to urban areas, reflected in lower incomes and fewer jobs. For example, in Bavaria in 2019, the per capita income in rural regions was about 9.3% lower than in urban areas.[5]

In this study, we seek to understand and compare the very different clean energy futures of German and Chinese towns and villages by both quantifying today's energy production and consumption, and by analysing future energy scenarios. We examine the town of Schwaig in Bavaria, located near the Munich airport, and Dongqiaotou in Shandong province. Both are agricultural towns, but the German community has a far higher per-capita income than the Chinese village, as well as more distributed energy installed. Dongqiaotou relies heavily on coal, electricity, and oil, but has installed solar water heating on most houses. The town has minimal PV, with just around 5% of households having PV installed.

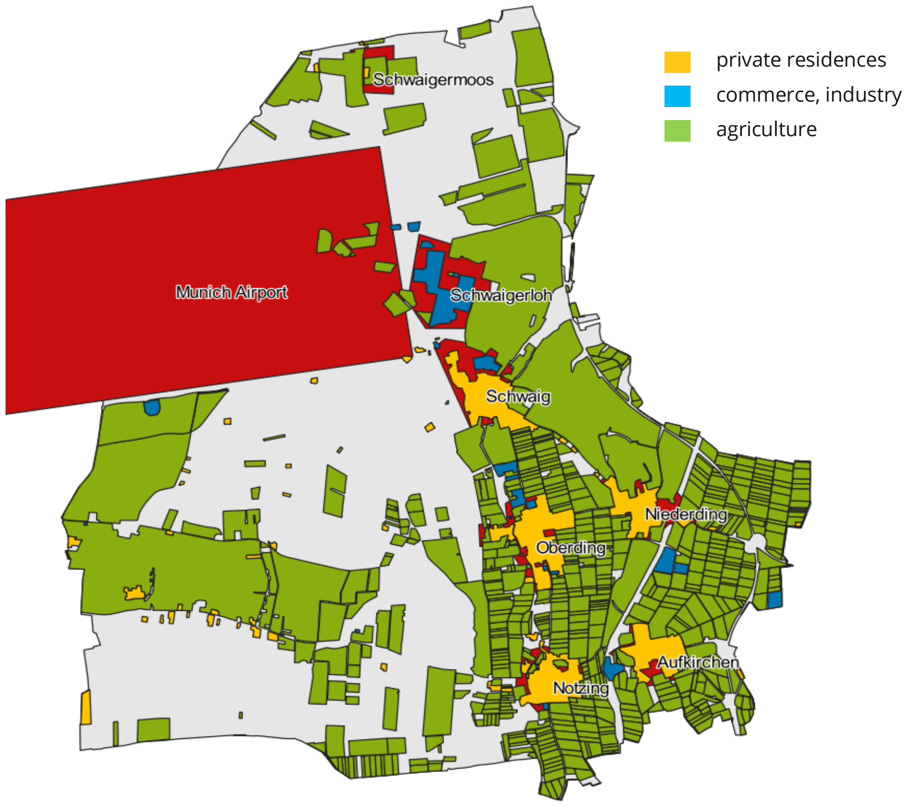
Both villages, despite their different development states, are part of their respective countries' energy transitions and will undergo changes in this decade. This study aims to contribute to understanding the possible direction of these changes and the villages' potentials to make an ambitious contribution in their respective contexts.

Comparing Dongqiaotou and Schwaig

Schwaig, Bavaria

The village of Schwaig is located in the German state of Bavaria, about 30 km northeast of Munich. Schwaig belongs to the community of Oberding which consists of six smaller villages: Aufkirchen, Niederding, Notzing, Oberding, Schwaig, Schwaigerloh and Schwaigermoos. Munich Airport is also part of the community of Oberding.[6] A total of 6,455 people live in the community, 1,140 of whom live in Schwaig.[7] The map below shows the community of Oberding with the different land uses.

Figure: QGIS map of Oberding with land use indicated



Source: Wuppertal University, 2021

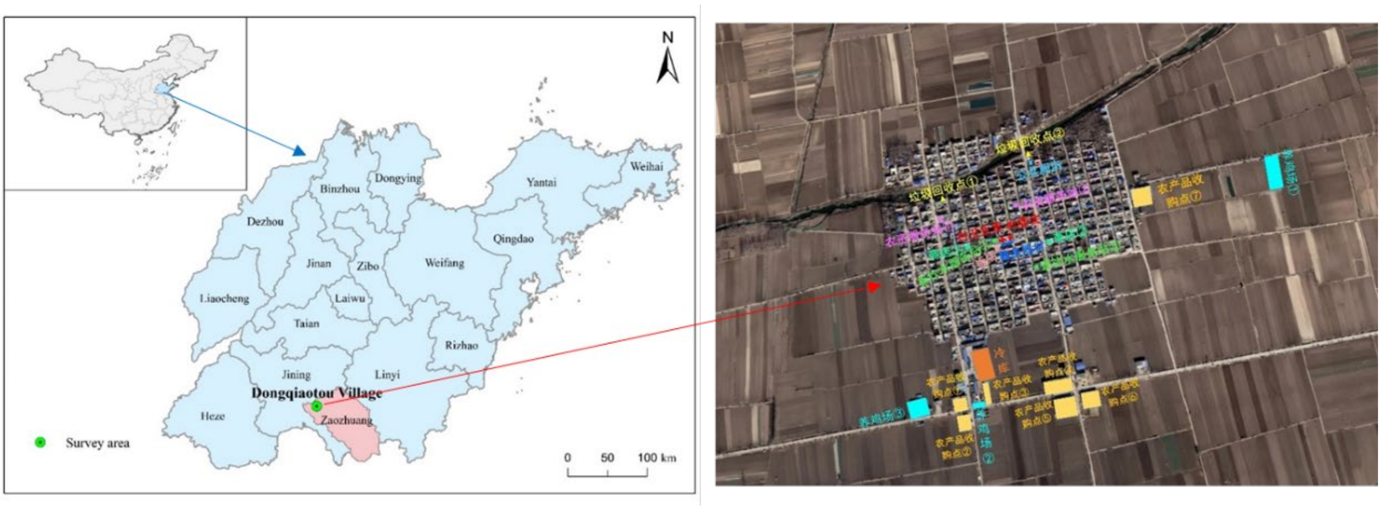
Schwaig has a high proportion of residential space and a low proportion of commercial space. It is mostly surrounded by agricultural land. In total, 253 residential buildings out of the total of 1,416 residential buildings in the community of Oberding can be assigned to Schwaig using the population key.[8] Schwaig has relatively few industrial and commercial businesses, with just around 30 companies present in Schwaig. Most local companies have ties to the airport, such as hotels, commercial parking lots, or logistics and transport companies.[9] Agriculture businesses are not included in this analysis, as they are not listed in the Chamber of Commerce and Industry. However, the land use map shows that there are agricultural businesses located in the area.

The average per capita income in the region is around €25,000.[10] Based on data of E-Werk Schweiger oHG, as of late 2021 Schwaig had 978 kW of PV installed.

Dongqiaotou

Dongqiaotou Village is situated in Shandong Province, 200 km from the province capital city of Jinan and circa 350 km from the important coastal city of Qingdao. The village has 446 households with a total population of 1,832. The population living outside the village is 380, including 210 working people, 170 attending school, and around 40-50 people working in the village and nearby companies or factories. Annual income per capita is RMB 22,500, equivalent to roughly € 3,000.

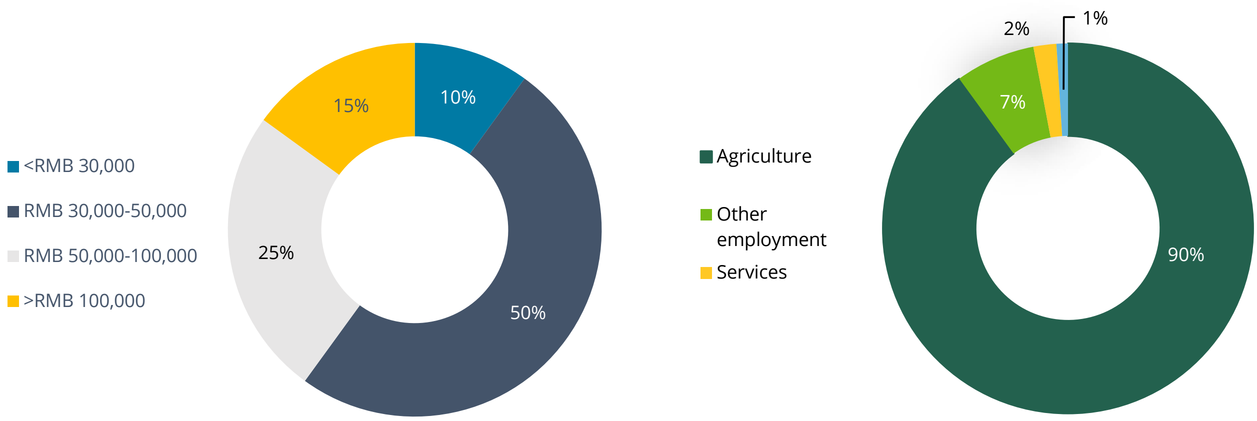
Figure: Location of Dongqiaotou in China and satellite image



Source: Institute of Applied Ecology at the Chinese Academy of Sciences

The graphs below show the income distribution among households in the village. For more than 90% of households, the main income source is agriculture, only a small part of income comes from working outside the village (7%), the service industry (2%), and aquaculture (1%).

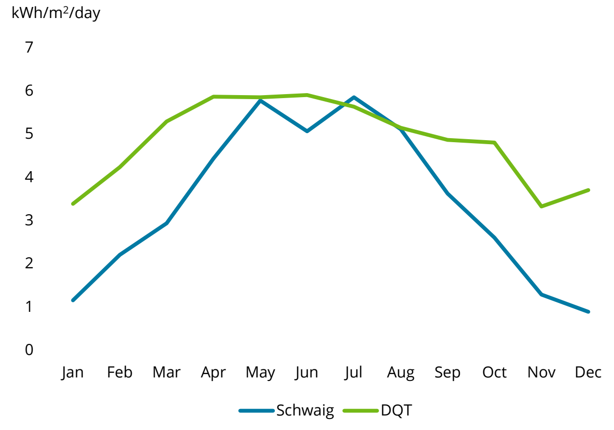
Figure: Household income composition and sources in Dongqiaotou

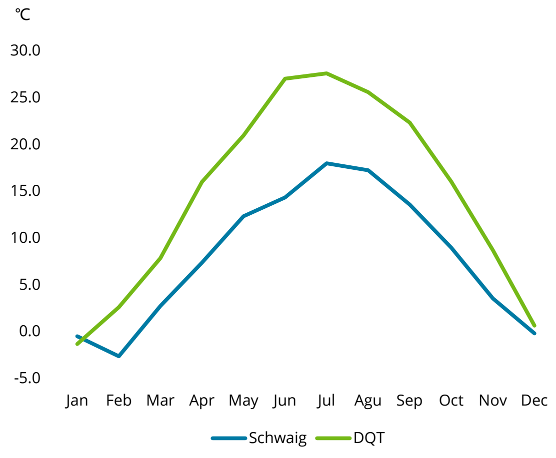


Source: Institute of Applied Ecology at the Chinese Academy of Sciences

Comparison of Schwaig and Dongqiaotou

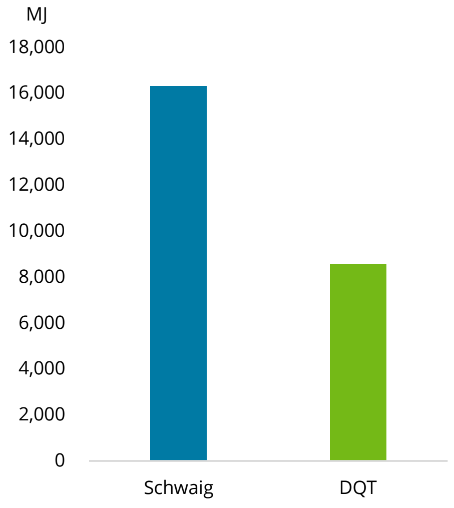
Figure: Monthly average solar insolation (left) and temperature (right)

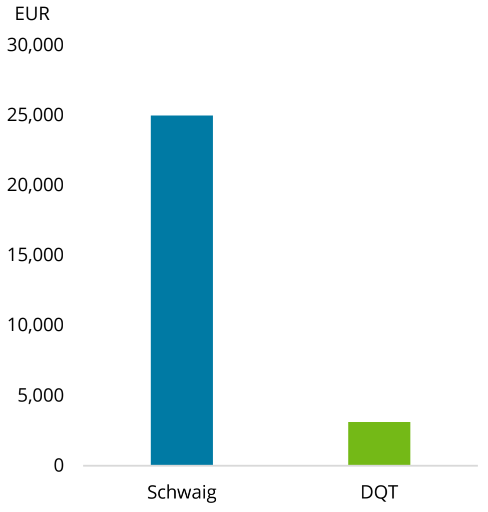




Source: NREL PVWatts, GIZ, 2022

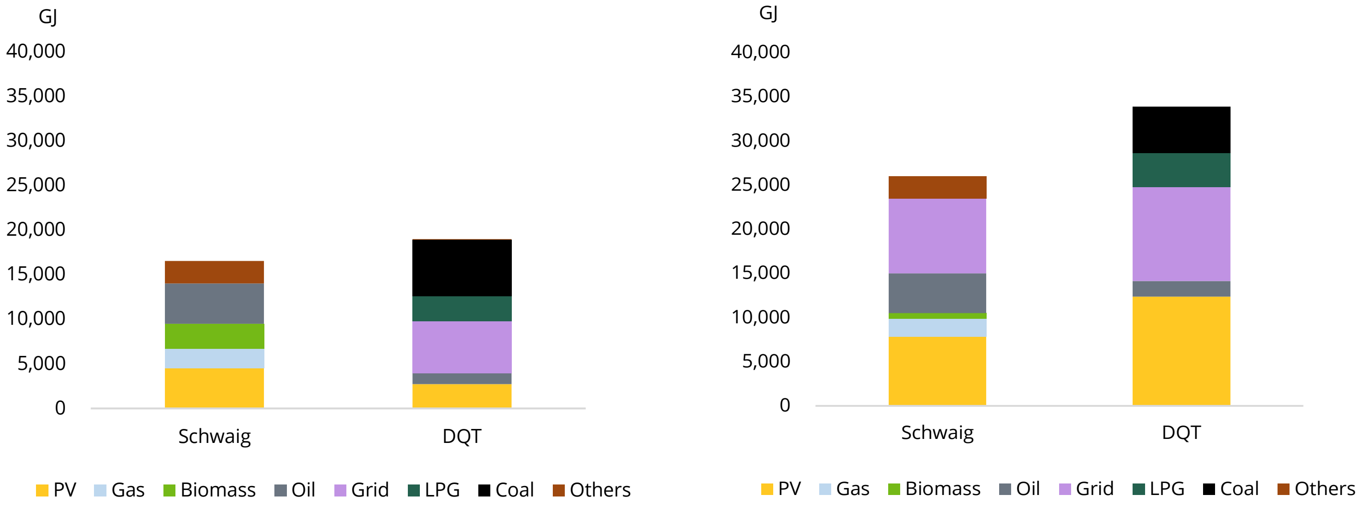
Figure: Estimated per capita energy consumption (left) and income (right) in Schwaig and Dongqiaotou





Source: GIZ, 2022

Figure: Estimated fuel mix of Schwaig and Dongqiaotou in 2022 (left) and 2030 (right)



Note: Note: grid electricity and liquid fuels excluded for Schwaig case.

Source: GIZ, 2022

Table: Comparison of socioeconomic and energy data on Schwaig and Dongqiaotou

	Germany	China
Name of village/town	Schwaig, Oberding	Dongqiaotou
Province/state	Bavaria	Shandong
Population	1,140	1,832
Households	388	446
Approximate per capita income	Euro 25,000	RMB 22,500
Annual per capita energy consumption	4,529 kWh	2,377 kWh
Annual per capita electricity consumption	1,082 kWh	1,257 kWh
Share of electricity in energy consumption	23.89%	52.88%
Coal consumption/share	none	41.54%
Oil consumption/share	1,769 MWh	6.49%
Gas consumption/share	590 MWh	12.67%
Bioenergy consumption/share	751 MWh	10.50%
Solar power consumption/share	1,209 MWh	
Wind power consumption/share	0 MWh	
Hydro power consumption/share	22,240 MWh	
Energy use cooling/heating (%)	10 %	33.10%

	Germany	China
Energy use transport (%)	78.22 %	10.81%
Energy use other (%)	11.78 %	56.09%
Carbon emissions per capita	5,500 kg (State of Bavaria)[11]	5,005kg
Car ownership rate (% of households, excluding 2- or 3-wheelers)	99 %	49.33%
Solar insolation (annual, kWh/m2/day)	3.42	3.85
Solar insolation (summer)	5.35 W/m^2	4.47 W/m^2
Solar insolation (winter)	1.42 W/m^2	2.89 W/m^2
Average temperature (annual)	8	13
Average temperature (summer)	16.5	24.5
Average temperature (winter)	-1	0.3
Main occupations		Agriculture (90%)
Main local industries	Agriculture, industry, services, logistics (airport)	Agriculture

Current situation and policy framework in China and Germany

Policies in Germany

To achieve Germany's climate targets, the country has steadily built up a framework of laws and various funding, starting with the Renewable Energy Sources Act (EEG), which came into force in 2000 and recently underwent significant updates. The law provides incentives to promote the expansion of DERs for electricity generation. PV systems received a feed-in tariff of at least €0.506/kWh if they were installed before 2001.[12] These feed-in tariffs have been reduced every year as the cost of purchasing the systems has also decreased. As of 2022, PV systems receive a feed-in tariff of at least €0.0475/kWh.[13] The fixed feed-in tariff expires after 20 years. In addition to the fixed feed-in tariffs, DERs also have feed-in priority, which means that the systems are generally not subject to curtailment.

Due to the decrease of the regulated feed-in tariff of DERs, today most of the owners of PV systems invest in storage systems to maximise their self-consumption, because in most cases the feed-in-only option is no longer profitable. Therefore, there is still a need for action by the policy to encourage households to invest in those systems.

The Combined Heat and Power Act (KWKG) also created a basis for supporting renewable energies across sectors.[14] The energy transition is also promoted by acts in the mobility and heating sectors. In the past, the Renewable Energies Heat Act (EEWärmeG) and the Energy Saving Ordinance (EnEV) helped promote renewable heating and heating efficiency upgrades. The 2020 Building Energy Act (GEG) supplanted these two measures. For new buildings as well as renovations of existing buildings, these regulations focus on energy efficiency, while also setting binding targets for the share of renewable energies for heating and cooling. The GEG bans oil heating in new heating systems in new buildings or renovations after 2026.[15] In 2021, the Building Electric Mobility Infrastructure Act (GEIG) came into force, which supports the expansion of the charging infrastructure for electric mobility. All these policy instruments promote the energy transition in Germany.[16]

Germany also incentivises the energy transition via numerous funding opportunities that support the development and expansion of renewable energy. The installation or upgrading of heating systems that are fully or partially powered by renewable energies is subsidised by the Federal Office of Economics and Export Control (BAFA) with up to €60,000. Oil heating systems are excluded from this funding. Another BAFA funding program supports electric mobility. For the purchase or lease of an electric car, the customer receives an environmental bonus of a maximum of €6,000. The Reconstruction Loan Corporation (KfW) provides further subsidies, with financial support of up to €75,000 for the renovation or new construction of energy efficient houses.

When it comes to expanding renewable energy, wind energy also plays an important role, even though this study does not consider it for the case of Schwaig, which is located immediately adjacent to the runways of one of Europe's busiest airports. Germany has in recent years faced challenges in expanding wind energy. The main reasons are lengthy and complex permitting procedures that can take many years to finish, lack of space for building projects, and lack of acceptance from the local residents, which often concerns the noise or appearance of wind turbines. These challenges have severely hampered the expansion of wind energy in Germany, up to the point of threating the existence of the industry in Germany. Another considerable challenge is the availability of areas for the construction wind energy turbines. Often, states in Germany have instated regulations for minimum distances between wind turbines and residential buildings. For example, in Bavaria, the distance between a wind turbine and a residential building must be ten times its height (2 km for a 200 m high turbine). Due to the high population density of Germany, this drastically reduces space for new wind turbines and imperils repowering of many old turbines.[17]

Policies in China

China's 13th Five-Year Plan for Energy Development, published in December 2016, emphasised electrification of both household and industrial energy, particularly in polluted regions in the Beijing, Tianjin, Hebei and surrounding areas. The plan mentioned substituting electric heating for coal, promoting time-of-use electricity pricing, and renovation of rural power distribution grids. The plan included measures for promoting renewable energy in rural areas, mentioning solar, wind, small hydro, agricultural waste-to-energy, and geothermal energy. The plan also emphasised rural power system reliability, targeting to achieve 99.8% reliable power supplies in rural areas by 2020, with average household distribution line capacity of at least 2 kVA.[18]

The 14th Five-Year Plan for a Modern Energy System, issued in early 2022, also prominently mentions rural energy development. The plan targets a second phase of power grid construction and upgrading to improve electricity reliability and security in rural area. This includes promoting rural microgrid pilots as well as supply of renewable electricity to rural areas. Under the Thousands of Village Households PV and Wind Power Action Plan, China promotes distributed PV and small-scale wind power. The plan also lists agricultural PV, biomass energy, and geothermal as priorities. The plan includes measures to increase gas supply in rural areas, reduce use of loose coal for heating, increase adoption of energy-efficient agricultural technologies, and create zero-carbon village pilots.[19]

The Chinese government has repeatedly emphasised strengthening rural public infrastructure, especially in the energy sector. In the traditional annual Document #1 on rural policy in 2021, policy makers targeted rural clean energy projects, enhancement of rural power grids, and improved rural electricity reliability. The document also promotes rural gas distribution infrastructure and gas storage, as well as rural biomass energy and cleaner use of coal.[20] In the 2022 edition of Document #1, the central government again emphasises upgrading rural power grids and promoting clean energy such as PV and biomass in rural areas.[21]

The 2021 Opinions on Promoting Green Development of Urban and Rural Construction, issued by China's State Council, listed various priorities for helping create a green, ecological, and beautiful countryside, while improving rural livelihoods. These included improving water, electricity, gas, and sewage facilities; strengthening the energy efficiency of farm buildings; improving the town and village facilities; and promoting rural garbage, sewage, and manure treatment.[22]

Shandong provincial policies

Shandong Province is promoting a green, ecological, and beautiful Shandong, and this includes the development of rural green energy on a good foundation.

Overall, the level of rural electrification has significantly improved: The average household distribution capacity in rural areas has reached 2.71 kVA, and the annual per capita electricity consumption is 427 kWh, reaching more than 80% of the average level in cities and towns. The ownership of refrigerators, washing machines, and air conditioners has increased significantly, while induction cookers and electric rice cookers have become common cooking tools. Motorcycles and agricultural vehicles are being gradually replaced with electric vehicles.

The cleanliness of energy use has improved. For cooking energy, methane gas, liquefied petroleum gas, and biogas accounted for a combined 48.2%, electricity accounted for 29.1%, coal accounted for 8.2%, wood and other 14.5%. For heating, Shandong had 5.1 million rural clean heating households, accounting for 40% of the total number of households. Of these, 2.65 million households are heated by methane gas; 1.55 million households are heated by electricity; while biomass, solar energy and other heating account for 900,000 households.

Rural clean energy use in Shandong has also experienced rapid growth in recent years. The province has 585,000 households with distributed PV, with an installed capacity of 10.41 GW, more PV capacity than most nations. Agricultural and forestry biomass have installed electric generation capacity of 1.83 GW; the annual use of crop straw and forestry residues is more than 18 million tons. Shandong has 95 MW of biogas power generation, of which livestock and poultry manure system biogas power generation has installed capacity of 25 MW. These consume 5.57 million tons annually in livestock and poultry manure.[23]

Methods and analysis

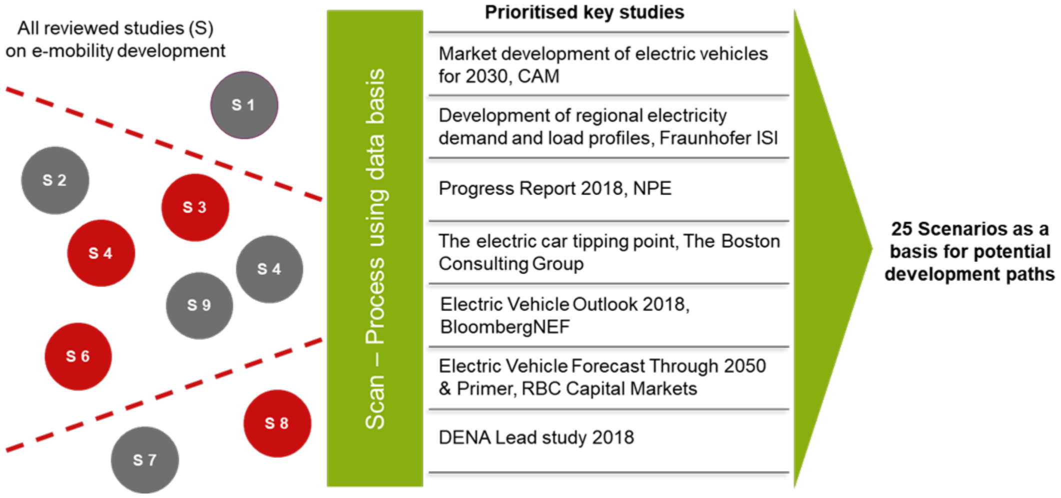
The German energy transition has already had a significant impact on rural regions, given the widespread adoption of wind and solar in many of Germany's rural areas.[24] In our approach to the energy transition in Schwaig, we sought to examine both (1) how far the rural energy transition has proceeded to date, and (2) what medium-term rural energy transition developments are likely, with a particular emphasis on electrification of key sectors for rural households, such as heating and personal transport.

To answer these questions, the study employed publicly available data as well as a village-level survey in cooperation with Wuppertal Institute to calculate the current status of rural development and develop scenarios for the future rural energy transition. The study deployed a three-step process, first by defining a scenario framework, then applying the scenario data to village level, and finally processing the resulting energy data together with the results of the survey to generate energy flow diagrams and future energy scenario outputs.

Scenario Framework for Germany

To determine future rural energy consumption and generation, we first identified various scenarios for key technologies. This study particularly focuses on the future penetration of EVs, heat pumps, and PV. For the development of the scenarios, we evaluated various existing studies on the trends in each of these individual categories. As an example, we show our process of scenario development for EVs as follows.

Figure: EV scenario development process for Germany



Source: Wuppertal University

We performed a meta-analysis of available studies in Germany to elaborate *pessimistic*, *moderate*, and *optimistic* EV adoption scenarios. To make the studies more comparable, we used interpolation methods to achieve a five-year resolution. The study applied a similar approach for both EV and heat pump development.

Given the already widespread adoption of PV, we developed PV scenarios based on the already well-established scenarios of the grid development plan (GDP) published by the four transmission system operators at regular intervals and reviewed by the Federal Grid Agency.[25] The grid development plan identifies three development paths for PV in Germany, which differ only minimally: From 2019 onwards, annual PV installations should range between 3.8 GW and 4.4 GW across the scenarios. Given the new federal government that took office in Germany after the 2021 GDP report's publication, higher annual installations appear likely. According to the current coalition agreement, Germany should reach an installed PV capacity of over 200 GW by 2030.[26]

The first step begins with the development data for the whole of Germany, as shown in the table below, and then breaking these national data down to the individual federal states, and then to community level based on population density and building stock.

Table: Overview of underlying EV, heat pump and PV scenario data for Schwaig scenarios

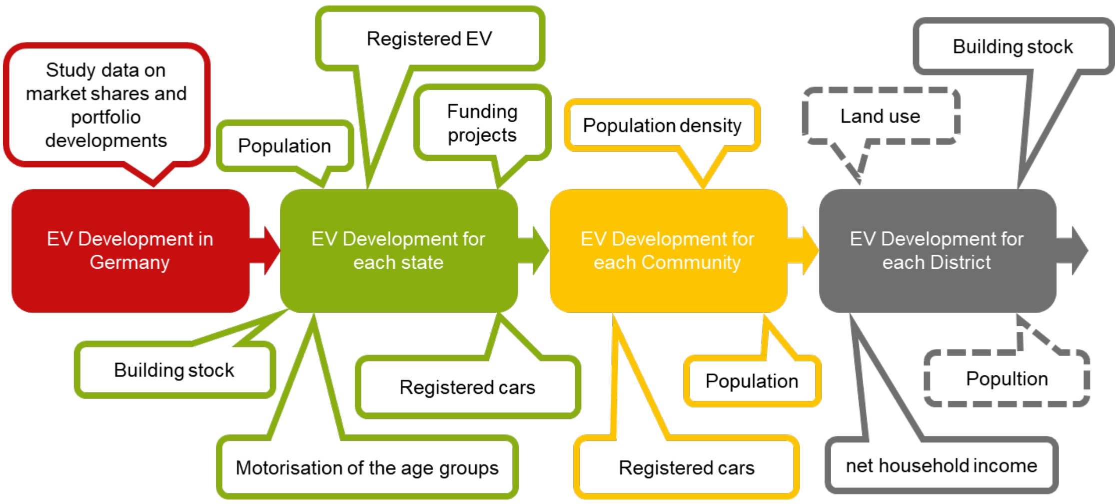
Technology	Scenario	Year	
		2030	2035
Electric Vehicles	Pessimistic	3.53 Mio	7.35 Mio
	Trend	4.16 Mio	8.65 Mio
	Optimistic	5.4 Mio	11.25 Mio
Heat Pumps	Dena TM-95	3.9 Mio	4.775 Mio
	Dena EL-95	7.9 Mio	10.1 Mio
PV	GDP Scenario A	90.8 GW	110.1 GW
	GDP Scenario B	96.3 GW	117.8 GW
	GDP Scenario C	97.4 GW	120.1 GW

Source: Wuppertal University, 2022; dena[27], Bundesnetzagentur[28]

Regionalisation Methodology

Based on the scenario framework and the overall national projections for each scenario, we extrapolate figures down to the selected village. As an example, we display the method for EVs. The methodology for heat pumps and PV differs only based on the input data. The figure below shows the general process of regionalisation methodology.

Figure: Principle of the regionalisation methodology with the example of EVs



Source: Wuppertal University

When it comes to heat pumps, the regionalisation procedure considered the building structure of a federal state or a community to estimate the diffusion of heat pumps, with detached and semi-detached houses as most suitable building types. Given the absence of detailed data including parameters such as the actual building age or the degree of insulation, the analysis assumes a uniform degree of building efficiency, so possibly variations in building characteristics have no effect on our estimate of the distribution of heat pumps.

For the study, we weighted the numbers of EVs and heat pumps from the community of Oberding among the different villages based on population and household size. Oberding publishes its population distribution on its public website.[29] We assumed the distribution of future PV installations based on the currently installed capacity in the villages, provided by the grid operator E-Werk Schweiger oHG.

Simulation Assumptions for Germany

To translate the scenario data for Oberding into energy and power values for EV charging infrastructure and heat pumps, the energy flow models must account for the strong seasonal fluctuations in PV system output and heat pump energy consumption. For EV charging loads, we only consider private charging infrastructure, and thus only focus on AC charging technology. We assume most EV charging takes place at power levels of either 11 kW or 22 kW. Given the importance of estimating charging behaviour in calculating the energy demand for EVs, we employed stochastic data on user behaviour from the Mobility in Germany Study 2017 act as input parameters to create charging profiles via study's parking profiles.[30] This enables development of individual charging profiles for each EV in the community for an entire year, so we can estimate the energy demand for an EV down to the minute.

In contrast to EVs, which have unpredictable load patterns, heat pumps generally show very similar consumption behaviour and are strongly affected by seasonal influences. The energy consumption behaviour is strongly dependent on the respective outside temperature, which does not differ significantly within a community. The simulation assumes three power classes for heat pumps based on Wintzek et al.,[31] considering building heat demand and hot water demand: 3 KW, 6.5 kW, and 9 kW. To map seasonal influences, the simulation uses different normalised heat pump time series with a resolution of one minute. The time series reflect the load profile of a heat pump for an older house and a modernised house, as well as the behaviour with and without blocking periods in which grid operators switch off the heat pumps to reduce system load.

The analysis employs time series data to determine the energy fed into the grid by the PV systems. A representative time series is sufficient, since the weather conditions within the community or in the villages under consideration do not show any significant differences. E-Werk Schweiger oHG provided a measured time series from the year 2020 with a 15-minute resolution, which we normalised and used as a basis for further consideration in the distribution of PV power. In addition, we compared and validated the generated scenario data against information from the Energy Atlas of Bavaria.[32]

In addition to the new loads of EVs and heat pumps, typical household and commercial loads need to be modelled for a holistic view of the energy flows. There are no data available on the specific consumption of households, so the modelling relied on the published average consumption of different household sizes and derived power consumption per household from the published household sizes of Oberding census data.[33] The average electricity consumption can be divided into *low*, *medium*, and *high*. The consumption of typical households is also influenced by seasonal factors. In order to take these into account, the simulation used randomly assigned household profiles based on time series from Tjaden et al.[34]

Given the limited information available, this study does not go into the same level of detail on industrial consumption or load profiles. Generally, prior studies have shown that Germany's industrial and commercial loads approximately resemble household electricity consumption.[35] Since there are no large industrial operations in the region, we incorporated the overall estimate of local industrial loads into the simulation of the annual household energy consumption.[36] The total energy required by the industrial and commercial sectors is divided into industry and agriculture. Agriculture in particular forms a large part of the industrial load in rural regions compared to urban areas. For the modelling of the energy flows, we used synthetic electricity load profiles for agriculture and industry adapted from APCS Power Clearing and Settlement data.[37]

With this approach, we created various time series with energy flows modelled in 15-minute intervals. We also incorporated the heating sector by means of an annual analysis. Average heat demands for building types from different years of construction or renovation can reflect the household consumption for the households in the simulation.[38] We developed simulations for *low*, *medium*, and *high* heating demand, and matched these against typical apartment or house sizes for the corresponding building structure. As before, we used a comparison factor to incorporate the local industrial heating demand; this factor represents the ratio of the industrial heat demand to household heat demand. The industrial demand is higher than the household heat demand by a factor of 0.38.[39]

Survey Design for Schwaig

The final step in modelling the energy flows is a survey of the population. After obtaining the formal approval of the local community, we administered the survey in the village of Schwaig in the community of Oberding. We designed three different survey forms to collect data from households, local businesses, and the local administration. The survey designs were tailored to help to evaluate the previous and future development of sector coupling and the energy transition in Schwaig and to compare and potentially adjust scenario assumptions. The surveys requested data and attitudes on three key sub-areas: mobility, heating, and electricity use. For further classification and validation, additional socio-demographic characteristics were also collected. The household survey differs from the business and administration survey in that it includes more questions related to the subjective opinions of the participants. The business and administration surveys only request concrete data, with the proviso that respondents should not go to special efforts to retrieve such data. The household survey does not request concrete energy consumption data due to concerns that this would require a significant time burden and likely reduce the willingness to participate.

Part 1 of the questionnaire looks at the mobility sector, requesting information about existing vehicles, fuel, and annual mileage. Using the results of these questions, we developed an estimate of the current number of EVs in the vehicle stock. The survey also asked participants whether they could imagine buying an EV in the future and where they would charge it.

Part 2 of the survey deals with heating and power. To approach this issue without requesting private data, the survey requested participants evaluate their household demand for heating and power using the categories *low*, *normal,* and *high* for each. The survey asked respondents about their current heating fuels and technologies, and whether they could imagine converting their heating and cooling system into an electric system like a heat pump. We used these questions to develop both energy flow diagrams for current household consumption as well as to refine the heating and cooling scenarios for Schwaig. The survey also asked whether respondents own their home or are renters, and requested that owners evaluate whether they can imagine heating with renewable energy in the future.

Lastly, the survey requested some socio-demographic data on household size, number of employed persons, age structure, and house type. This allowed us to estimate what percentage of the population the survey represented and the employment and demographic structure of the participants.

Survey results in Schwaig

The survey in Schwaig took place over a period of three weeks in June 2021 and was conducted by Wuppertal Institute. A total of 18 companies with no connection to Munich Airport were contacted but their response rate was too low; therefore, this part of the survey is not considered further. The response for the household survey reached the target of about 20%, which provides a good foundation for further evaluation. When scaled up and applied to the entire village of Schwaig, the survey results enable generalisations about the current and future energy transition:

Table: Summary of Schwaig survey results

Category	Result	
Mobility		
Car ownership	98.9% of respondents own at least 1 car, 73.3% own at least 2 cars and 11.5% own 3 cars	
Average distance driven per year per vehicle	13,000 km	
EV ownership	5%, mostly charging at home 35% can imagine purchasing an EV in the future, 87% of which would charge at home 28% are undecided, 40% of which would charge at home if they had an EV	
Energy supply and consumption		
Power consumption self-assessment	Low: 10%, Normal: 62%, High: 28%	
Heat consumption self-assessment	Low: 13%, Normal: 69%, High: 18%	
Heating technologies and fuels	Oil 47%, Gas 15%, Heat pump 14%, Biomass 5%, Other 19%, Night storage 1%	
Attitudes towards renewable energy	Solar thermal: Already owning 27%, Considering 27%, Not considering 30%, Undecided 15% Solar PV: Already owning 23%, Considering 33%, Not considering 26%, Undecided 18% Heat pump: Already owning 13%, Considering 30%, Not considering 44%, Undecided 14% CHP: Already owning 0%, Considering 25%, Not considering 52%, Undecided 23%	
Population and building properties		
Household size	1 person 13% 2 persons 39% 3 persons 27%	4 persons 18% 5 persons 1% 6 persons 2%
Employment	At least one person: 74% of households Two persons: 62% of households	
Age	Households without children (persons aged under 18): 74%	

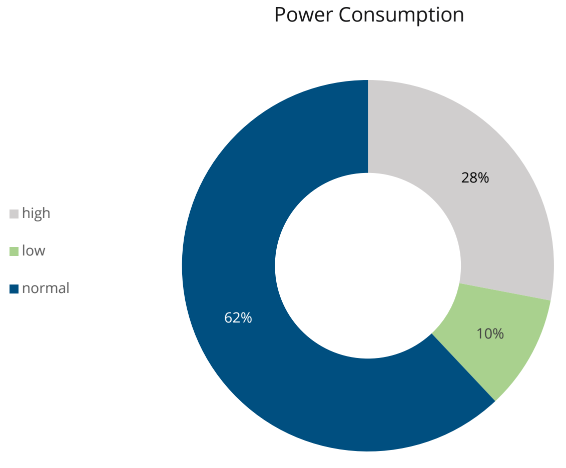
Source: Wuppertal University, 2022

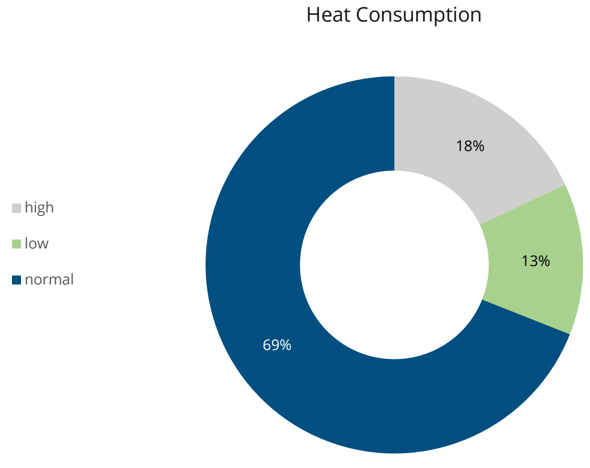
The first part of the survey covered mobility. In Schwaig, almost all the surveyed households have at least one car. In total, 98.9% of respondents own at least one car, 73.3% own at least two, and 11.5% own three cars. Each vehicle drives between 12,000-14,000 km per year on average. As of 2021, about 5% of Schwaig vehicle owners have an EV.

The majority of EV owners can charge at home, only one respondent charges exclusively at public charging points or at work. 35% of respondents can imagine buying an EV in the future, while another 28% are still undecided. Of those who would buy an EV, 87% indicate they would charge at home, whereas 40% of the undecided state that they would charge at home.

The second part of the survey covered the topic of energy production and energy consumption, including both the electricity and heat sectors. For reasons of privacy, and to encourage responses, the survey did not attempt to gather information on precise consumption figures; instead, the survey asked respondents to evaluate their own consumption of electricity and heat as *high*, *normal*, or *low*. While these categories may seem imprecise, and excessively difficult for respondents to objectively evaluate, we believe asking for precise data would result in most recipients declining to fill in or return the survey.

Figure: Subjective assessment of power and heat consumption

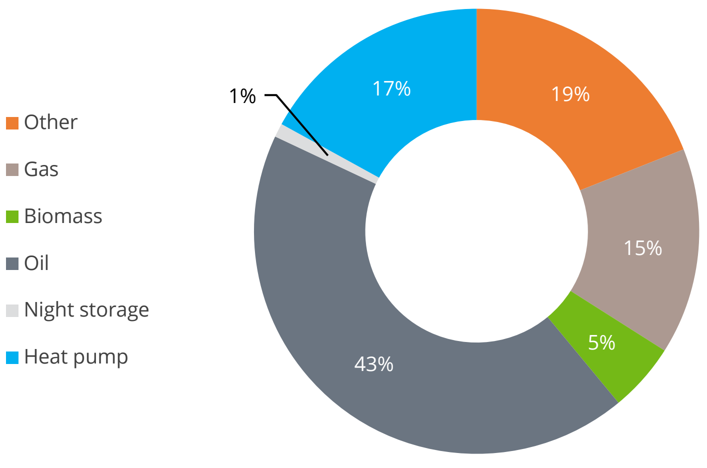




Source: Wuppertal University, 2021

For both power and heat consumption, perhaps not surprisingly, most participants evaluate their consumption as *normal*. Respondents showed a greater propensity to evaluate their household as having *high* electricity consumption rather than *high* heat consumption. Only 10% to 13% of respondents rate their consumption as *low*. This distribution is used in the further analysis for the determination of the household power consumption.

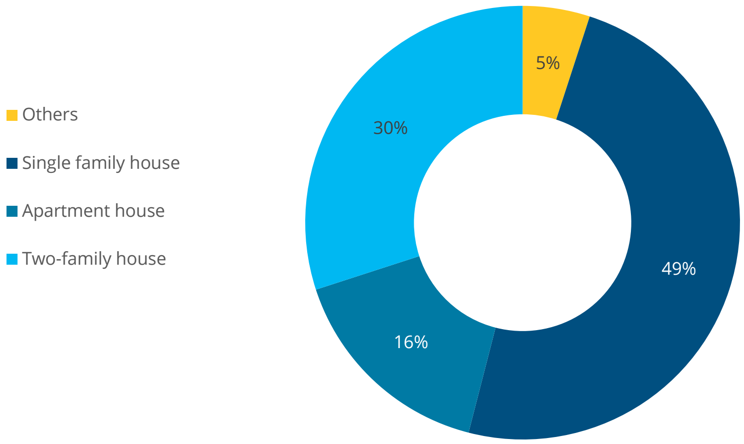
Figure: Current heating technologies in Schwaig



Source: Wuppertal University, 2021

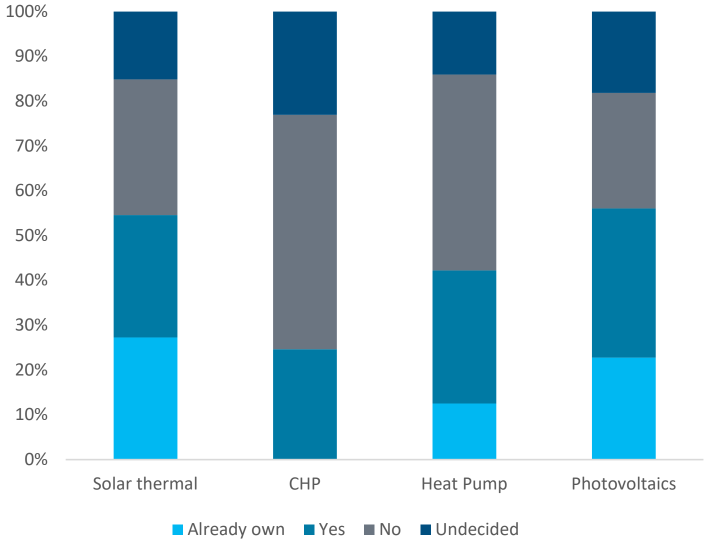
The survey also requested information on household heating sources. Heating in Schwaig relies on a diverse range of fuels, with oil heating presently the most common with a share of 43%. Electric heat pumps, natural gas heating, and other types of heating not explicitly listed are fairly evenly distributed with shares between 15% and 19%. Biomass and night storage heaters have the lowest shares of 5% and 1%. 76% of respondents own their apartment or house and could therefore decide for themselves to adopt heat pumps and/or renewable energy.

Figure: Present distribution of housing types in Schwaig



Source: Wuppertal University, 2021

Figure: Attitudes towards energy transition technologies in Schwaig

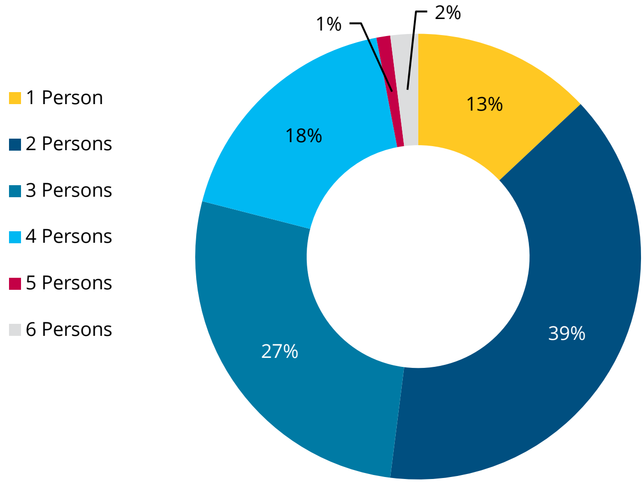


Source: Wuppertal University, 2021

Almost 23% of respondents already own a PV system, for example, and another 33.3% can imagine generating their own electricity in the future, whereas 26% are still undecided on the subject. In terms of home heating, solar thermal already has a high share among owners at 27%, another 27% can imagine a change in the future, and 15% are still undecided. The current share of heat pumps is lower at 13%, but another 30% can imagine using them in the future and 14% are still undecided. 25% would consider a combined heat and power generation and further 23% are still undecided on the topic.

Given these survey results, we classified respondents by group and refined the assumptions of each scenario, particularly regarding adoption of PV, heat pumps, and EVs. In the case of both technologies, survey respondents expressed interest in both technologies, and a part of the population has already adopted heat pumps. Respondents are also willing to consider generating electricity with PV systems, and many already have PV systems installed—indeed, the community of Oberding has a total of 6,820 MW, an impressively high rate for a community of this size.

Figure: Household size in Schwaig



Source: Wuppertal University, 2021

Overall, the survey results show that the residents of Schwaig have a high level of open-mindedness towards energy transition technologies. This becomes particularly clear when we scale up the survey results to estimate technology penetration among all Schwaig residents. We estimate that Schwaig already has 20 EVs and 40 heat pumps. To forecast future development, in this section we generalise the survey results to the total population in Schwaig. Since the survey did not further specify the time horizon for questions about the future purchase of an EV or heat pump, it is still assumed that the purchase will occur by 2030. A *yes* means acquisition by 2030, and those undecided are assumed for an optimistic approach to also decide to purchase by 2030. Based on this logic, for the target year 2030, we estimate 175 EVs and 135 heat pumps in Schwaig for the *trend* scenario and 300 EVs and 180 heat pumps for the *optimistic* scenario. It is noticeable that the calculated ramp-up data for the selected scenarios (see Annex) for the year 2030 are more pessimistic than the survey results for the same year. This analysis employed the figures for 2035 due to their greater consistency. The matching scenarios to the survey evaluations are contrasted in the table below.

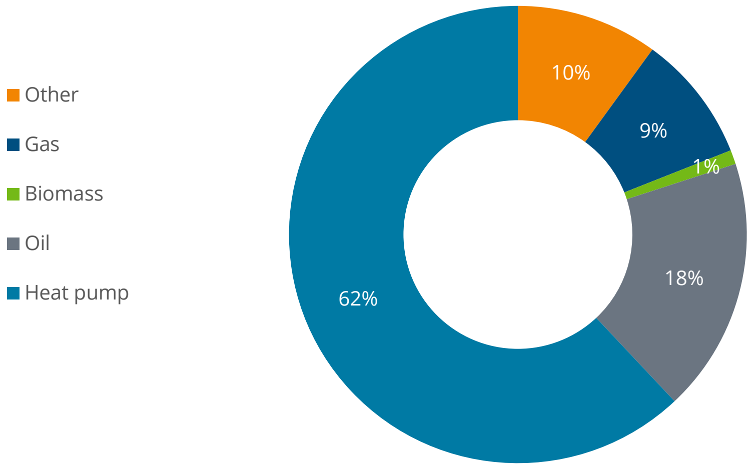
Table: Scenario selection based on the survey

	Number of EVs		Number of heat pumps		Scenario Selection
	Survey	Matching Scenario	Survey	Matching Scenario	
Current	20		40		
Trend Scenario	175	157	135	102	Trend scenario 2035, dena-TM95 2035
Optimistic Scenario	300	204	180	216	Optimistic scenario 2035, dena-EL95 2035

Source: Wuppertal University, 2021

We selected two scenarios for further analysis. The first, called the Trend scenario, incorporates the trend scenario 2035, the dena TM-95 scenario 2035, and the GDP scenario A 2035. In general, the Trend scenario represents more conservative assumptions about electrification and PV expansion and an extrapolation of trends around 2020. The second, the Optimistic scenario, consists of the optimistic scenario 2035, the dena EL-95 scenario 2035 and the GDP scenario C 2035.[40] These two scenarios enable estimation of overall electricity demand, given that they incorporate information about increasing electrification in the mobility and heating sector, as well as the future electricity generation primarily by PV systems and the associated potential for self-supply. We assume no change in the total heat demand, with only the source of the heating demand changing over time. Due to the increasing electrification in the heating sector described above and the progressive substitution of oil heating, which is also described in the dena scenarios, the distribution of heating demand in 2030 will be significantly different from the current situation. The resulting distribution is shown as an example for the dena EL 95 scenario in the figure below.

Figure: Heating situation in Schwaig with dena EL 95 Scenario 2035



Source: Wuppertal University, 2021

The share of oil heating will decrease drastically and eventually disappear completely. Biomass, methane gas, and other technologies will also account for a smaller share of heat generation. According to the study's findings, electric heat pumps in 2030 could meet more than 62% of heating and cooling demand.

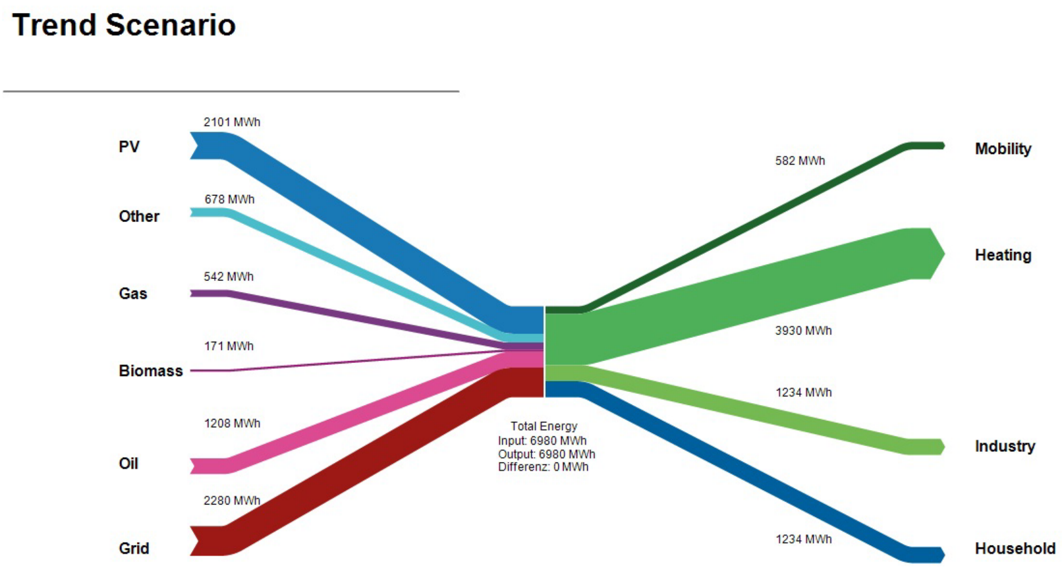
Based on these results, and incorporating *low*, *normal*, and *high* power consumption estimates, we can develop estimates for household and commercial electricity consumption for the whole village of Schwaig, excluding EVs and heat pumps, of 1,234 MWh. Based on the assumptions used for this study discussed in more detail below, we assume the same electricity consumption for the commercial sector.

Analysis – Schwaig

Our analysis employs a combination of energy survey results, public data, utility data, and various forecasts for the adoption of energy transition technologies such as EVs, heat pumps, and PV. Using these data and forecasts, we have developed a series of energy flow diagrams for Schwaig now and in the future, and simulated monthly and hourly energy production and consumption at the village and household levels. Overall, we find that Schwaig has high potential for energy self-sufficiency, but with high daily and seasonal variability, implying the need for the village to remain highly connected in the medium term and the potential to increase the adoption of energy storage technologies in the longer term.

The results for the *Trend* and *Optimistic* scenarios suggest that Schwaig's annual energy consumption will differ minimally between the two scenarios. The *Optimistic* scenario has a higher share of heat pumps and EVs, but since we do not include oil consumption in the energy flow models for simplicity, this implies that EV adoption increases net consumption, offsetting the efficiency gains from heat pump adoption in the *Optimistic* scenario.

Figure: Annual energy flows in Schwaig for the Trend scenario

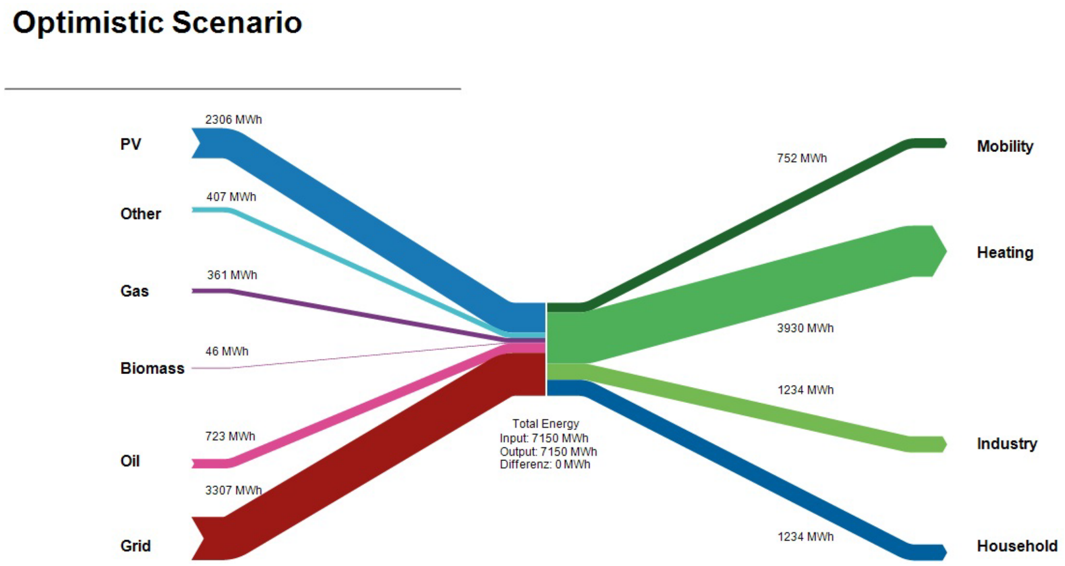


Source: Wuppertal University

A simplified Sankey diagram displays the results for the *Trend* scenario, measured in MWh. The input side shows how energy production mainly takes the form of electricity—from the grid and from PV installed locally. Overall, electrical energy accounts for around 63% of total energy required in this scenario. We assume energy provided by solar takes the form of electricity from PV; we group any solar thermal into the category *other*. In the *Trend* scenario, fossil fuels maintain a relatively high 25% share of energy supply. Note that the fossil fuels included in this model only represent those used in heat sector, not the oil used for transport. The 25% figure also excludes any fossil fuels used for grid electricity.

Heat demand represents the largest share of energy consumption, accounting for 56% of the total demand. Heat pumps provide only part of the heat demand. Electricity demand for industry and households is identical, as already described in the assumptions. In the energy flow diagrams, the *household* category excludes any heat pump or mobility energy consumption. Overall, the *industry* and *household* categories account for 35% of total energy demand. The *mobility* category exclusively refers to electricity demand for charging EVs. Overall, EVs have a share of 8% of the total energy demand. Over the year, Schwaig achieves a self-sufficiency rate of 30% in total energy consumption in the trend scenario only when considering PV feed-in.

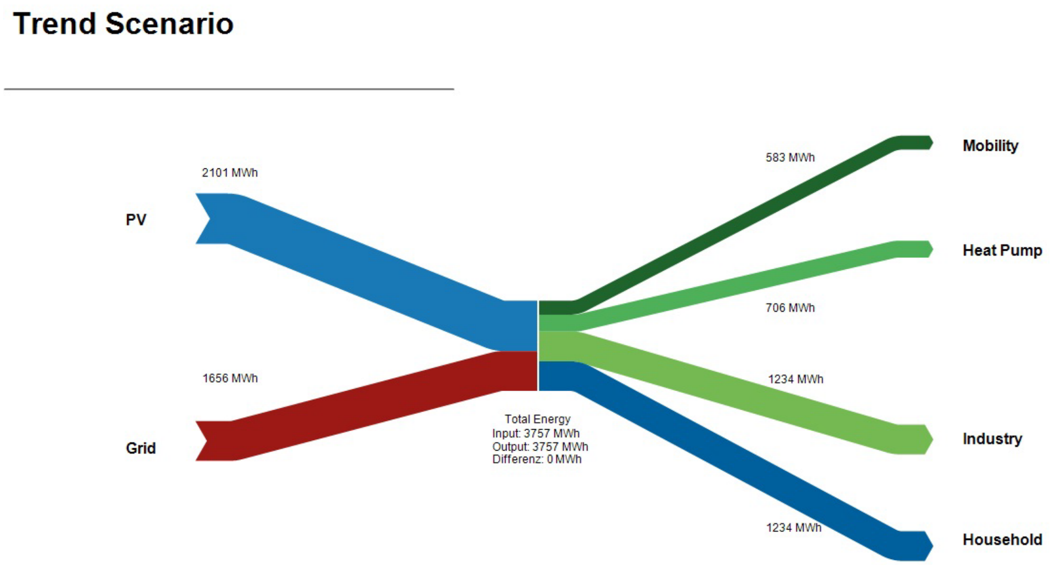
Figure: Annual energy flows in Schwaig for the optimistic scenario



Source: Wuppertal University

The next figure shows the energy flows for the *Optimistic* scenario, which look quite similar on the output side to the *Trend* scenario. The main difference is in the energy requirements for the EVs, which is due to the significantly higher number of EVs in the *Optimistic* scenario. About 11% of total energy demand is used for charging EVs in this scenario. On the input side, there are greater differences versus the *Trend*. The *Optimistic* scenario features a significantly lower share of fossil fuels at only 15%, versus 25% for the *Trend* scenario. The share of PV is 32% in the Optimistic scenario, versus 30% in the *Trend* scenario. This relatively small difference is due to the small deviations between the Grid Development Plan (GDP) scenario A and GDP scenario C. At 46%, the supply from the grid covers the largest share of energy demand. This is due to the increasing number of EVs and to the high electrification of the heating sector in the dena EL-95 scenario. In the *Optimistic* scenario, Schwaig achieves an annual self-sufficiency rate of 32%.

Figure: Annual power flow for Schwaig in the trend scenario

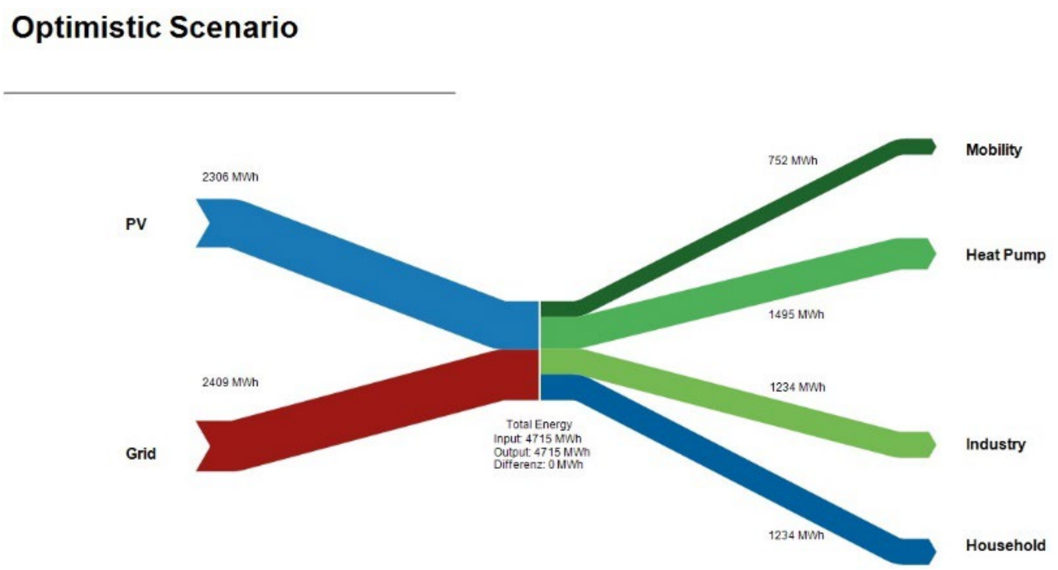


Source: Wuppertal University

If we consider only the electrical energy flows, the self-sufficiency picture is quite different. Since heat accounts for over 50% of electrical energy demand, an exclusive consideration of electricity shows clearly different self-supply rates. The above figure shows the electrical view for Schwaig of the trend scenario. The annual electrical energy demand for Schwaig is 3,757 MWh in the *Trend* scenario. The *household* and *industry* categories each account for nearly one-third of demand. EV charging has a share of about 16% and heat pumps about 19% of the total electricity demand. On the input side, only 44% of the electricity demand still has to be provided by the grid. PV systems can provide 56% of the electricity load over the course of the year.

The figure below shows the electrical view for Schwaig of the *Optimistic* scenario, which features much higher demand for electricity. Overall, demand increases by around 25%, due to higher electrification of heating and transport in the *Optimistic* Scenario. Although consumption by the *industry* and *household* categories remains unchanged, the share of electricity provided by the grid rises to meet the added demand from heating and EV charging. PV systems provide 49% of electricity, and consequently, the degree of self-sufficiency in the *Optimistic* scenario is slightly lower than in the *Trend* scenario. Given the significantly higher electrification in the *Optimistic* scenario and the relatively small differences in PV output between the two scenarios, the lower self-sufficiency rate is unsurprising.

Figure: Annual power flow for Schwaig in the optimistic scenario

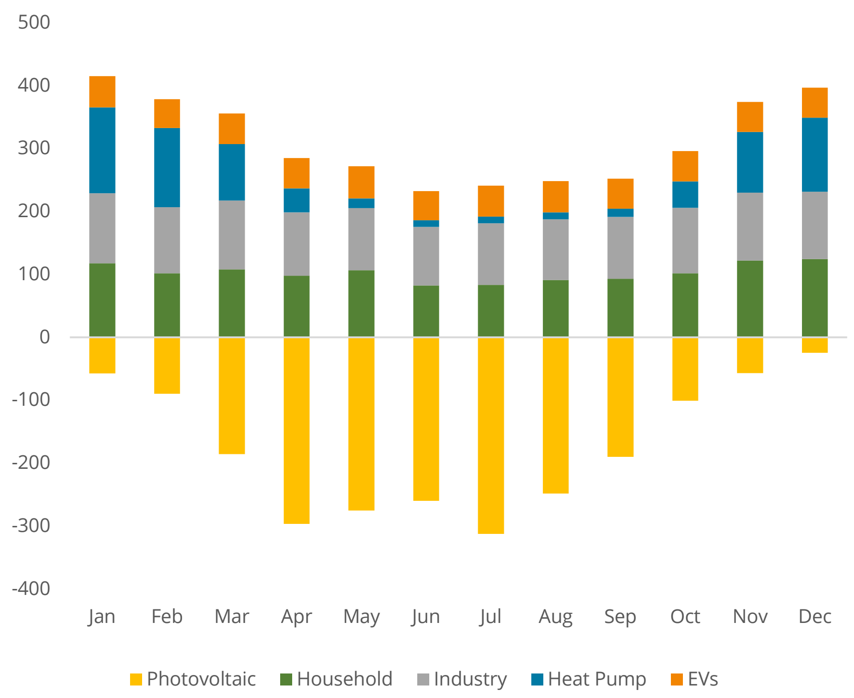


Source: Wuppertal University

However, the self-sufficiency rates for the trend and optimistic scenarios can vary significantly within a year. In particular, the PV output and the electricity demand for heating display a negative correlation, with PV output greatest in the summer and heating required in the winter.

The seasonal imbalance between electricity demand and PV output is greater in the case of Schwaig than in the case of Dongqiaotou, China.

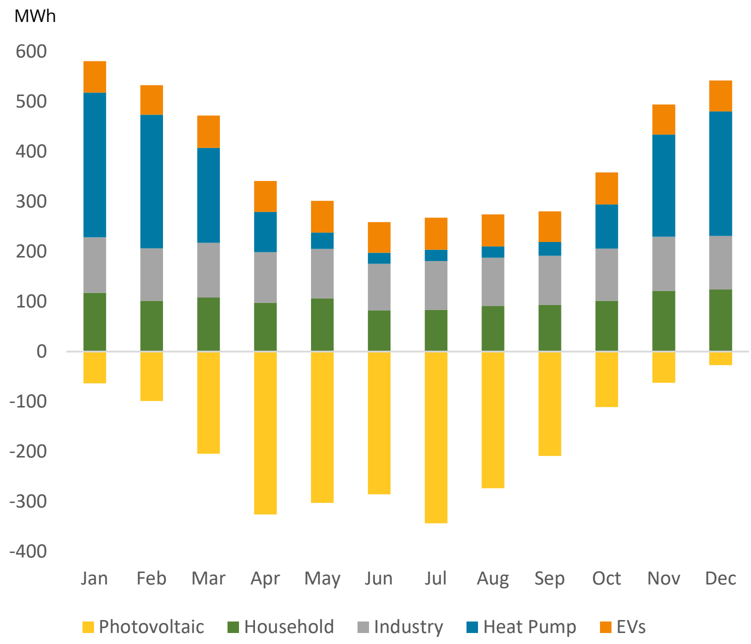
Figure: Comparison of monthly electricity demand for Schwaig in the trend scenario



Source: Wuppertal University

As the figure above shows, heat pump electricity demand increases significantly during the heating season between November and March. Between April and September, households mainly use heat pumps for water heating—we estimate little cooling demand for the typical household in the region as summers in Germany are mostly mild, making air conditioning unnecessary most of the time. The EV charging demand displays little seasonal variation. (As with EV load, industrial demand exhibits relatively low seasonal variation.) Overall, due to heating loads as well as demand for lighting, households have higher electricity consumption during the winter months. The seasonal variability is most obvious in the case of PV feed-in. While the feed-in between March and September is quite high, the feed-in between October and February is tiny in comparison. Monthly electricity consumption varies between 230 MWh and 415 MWh. This results in a high overall range of self-sufficiency rates for the individual months. In December, a household can reach self-sufficiency of only 6%, while in July a household could reach self-sufficiency of 130%.

Figure: Comparison of monthly electricity demand for Schwaig in the optimistic scenario



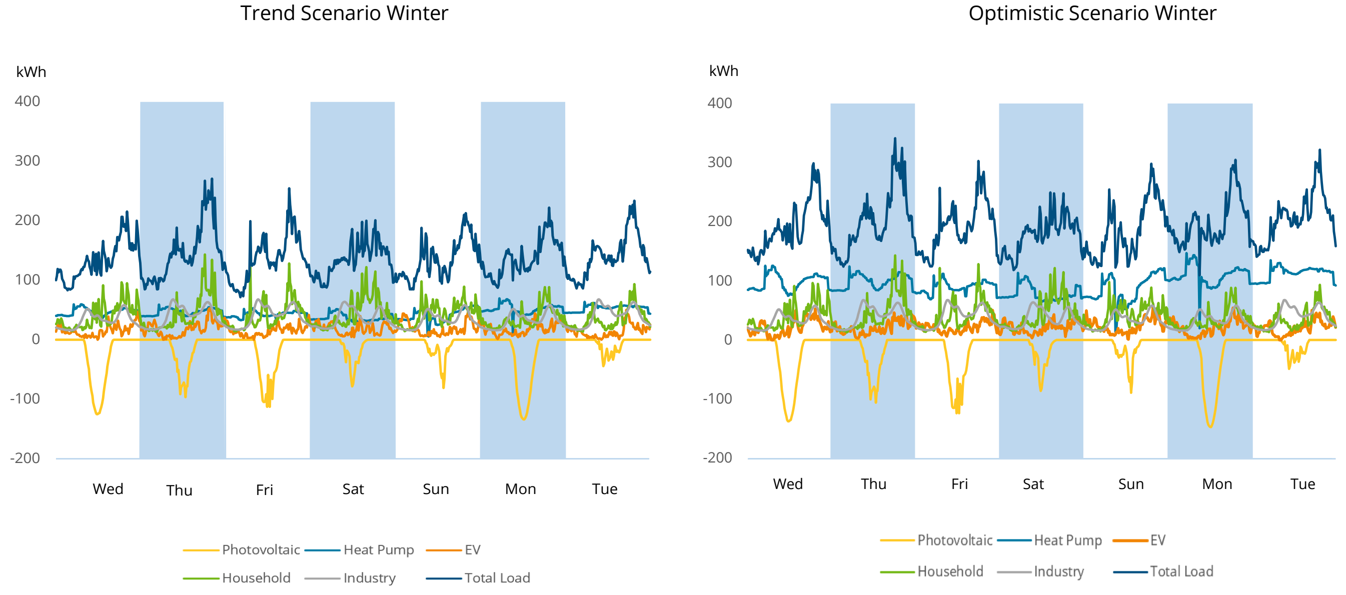
Source: Wuppertal University

In the *Optimistic* scenario, the PV output is quite similar to the *Trend* scenario across the individual months. For heat pumps, the difference between the summer and winter months is much more significant than in the *Trend* scenario. As in the *Trend* scenario, EV charging varies little during the year. However, EV electricity consumption differs sharply across scenarios, with the *Optimistic* scenario showing monthly EV consumption of 14 MWh higher versus the *Trend* scenario.

Overall, the *Optimistic* scenario displays much greater seasonal variation in consumption than the *Trend* scenario, mainly due to higher adoption of heat pumps and corresponding increases in winter electricity consumption. In the *Optimistic* scenario, there are differences of up to 270 MWh between different months, which corresponds to about one fifth of the annual consumption of all households. In the *Trend* scenario, the maximum difference between summer and winter months is less than half as high. As noted, PV output in the *Optimistic* scenario is similar to that in the trend scenario, with only a slightly higher overall feed-in. In the *Optimistic* scenario, the self-sufficiency rate for the individual months also varies greatly, ranging from a minimum of 5% in winter to a maximum of 128% in summer. Hence, the self-sufficiency rate in the *Trend* scenario is slightly higher than in the *Optimistic* scenario. If we look further at the self-sufficiency rates of the individual months of the two scenarios, in the trend scenario five months have a self-sufficiency rate of at least 100%. In the optimistic scenario, only three months achieve self-sufficiency greater than 100%. Lower self-sufficiency relates mainly to greater heat pump adoption and, consequently, greater mismatch between seasonal PV production and heat pump consumption.

Not only does Schwaig feature strong seasonal variation in PV output and household heating loads, but intraday consumption also shows high volatility. The following charts display simulation results for the two scenarios during an illustrative winter week.

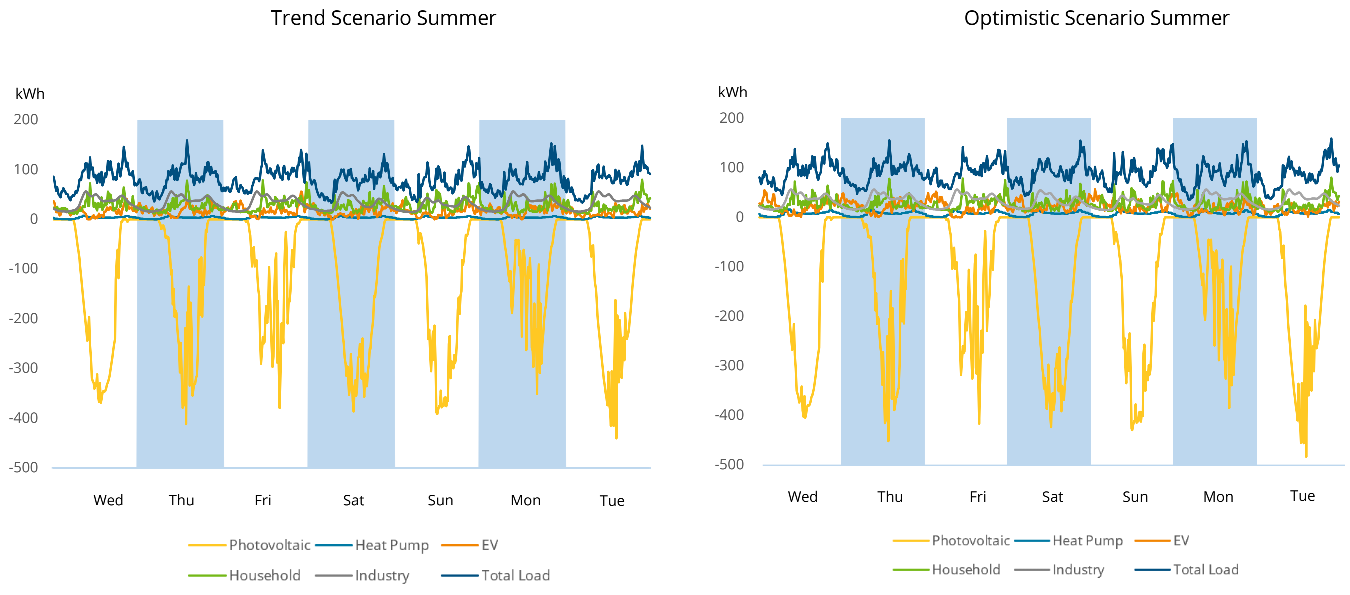
Figure: Load curve for an exemplary winter week in both scenarios



Source: Wuppertal University

In a typical German winter week, PV systems generate little output relative to other seasons. Indeed, though Schwaig in Germany and Dongiaotou in China have similar solar insolation in the summer months (June through August), insolation in Schwaig is just 40% that of Dongqiaotou during the months of December through February. In Schwaig, PV panels only produce power between 9 am and 4 pm in the best case, and winter energy production exhibits high volatility due to variable cloud cover and weather conditions. Maximum output peaks differ by up to a factor of three. PV output rarely exceeds minimal village load. In the optimistic scenario, PV load is significantly higher than in the trend scenario, and this applies both in the load peaks, which are up to 70 kWh higher in the optimistic scenario, and in the minimum load, which differs by up to 40 kWh. Furthermore, load peaks typically precede or follow peak PV output. This pattern can lead to quite high self-sufficiency rates even in winter, but only in a few time periods. The *Optimistic* scenario achieves 91% self-sufficiency ratio, while the *Trend* scenario (with lower load for heat pumps and EVs) achieves 115% self-sufficiency in time periods with peak solar output. Over the entire sample week, however, the energy load significantly exceeds the energy fed into the grid, so that the self-sufficiency rates for the optimistic scenario are 9% and for the trend scenario 11%.

Figure: Load curve for an exemplary summer week in both scenarios



Source: Wuppertal University

A similar situation holds for summer months, which feature longer and more consistent sunlight hours. The example winter week has seven hours of sunlight, the summer week has almost twice as many with 13 hours of sunlight. The daily feed-in peaks differ only minimally compared to the winter week and are sometimes more than three times higher than in winter. While in the winter example the summed load curves show significant differences between the two scenarios, the minimum and maximum loads in the summer week are almost identical in both scenarios. This is mainly due to the fact that in summer heat pumps are usually used only for hot water, and cooling loads in Bavaria remain low. The average summer (July) temperature in Schwaig is 16.5 °C, with the average high at 23 °C and the average low at 12 °C. The higher number of EVs in the optimistic scenario also does not necessarily lead to larger load peaks, since EVs do not need to charge simultaneously with the load peaks.

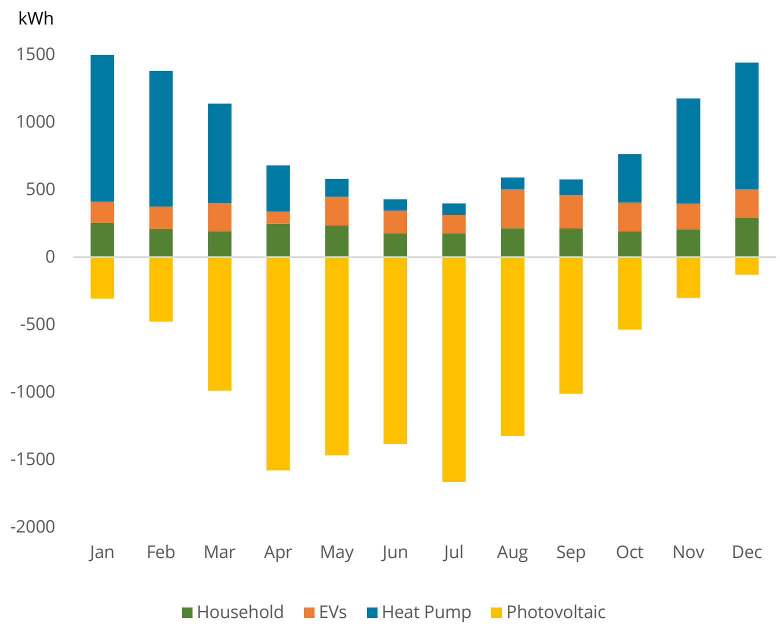
Winter heat pump loads account for a large part of daily peak loads and therefore coincide with peak load nearly 100% of the time, producing a much greater load peak in the *Optimistic* scenario during winter. The significantly lower load and higher and longer feed-in is clearly noticeable in the self-sufficiency rates. For both scenarios, in the week shown, the self-sufficiency rate is greater than or equal to 100% for most of the time that PV electricity is produced. In some cases, the energy fed into the grid exceeds the required energy by a factor of 6 to 7. For the week, the two scenarios yield fairly similar self-sufficiency rates in the trend scenario at 138% and in the optimistic scenario at 137%.

Overall, the comparisons in above Figure show the need for storage of PV output. Especially in summer, the electricity generated by PV significantly exceeds both total electricity consumption and daytime peak electricity demand, so that storage could keep the surplus power available during the night and other periods with lacking PV output. Even in some time periods in in winter, households would need energy storage to make the best use of the energy generated.

In addition to the studies for the entire village in Schwaig, individual households can also be analysed for their degree of self-sufficiency. By modelling the energy flows with the time series-based simulations, we can examine a household in 2030 with regard to electricity demand. Here we consider an illustrative four-person household with one EV, a heat pump, and a PV system. The household energy demand is set at a normal consumption for four persons. This results in a consumption of 3,800 kWh. The household operates their EV for about 13,000 km per year, the household's heat pump has an installed power of 3 kW, and its PV system has an installed capacity of 12 kW. The PV system is designed to theoretically cover the entire electricity demand of a year for the household, in terms of kWh consumed.

A comparison of monthly electricity demand and generation is shown below. Strong seasonal differences in demand and generation are also evident for individual households. The heat pump is the main driver of household electricity consumption. Especially in the winter months, the heat pump accounts for the majority of the electricity demand. On the other hand, the normal household consumption and the energy required to charge the EV is quite constant throughout the year. However, this is far too small to compensate for the strong feed-in in summer. This leads to the fact that in the summer months up to 4 times more energy is produced than is consumed. In winter, on the other hand, the feed is not sufficient to cover the demand. In the shown example, this circumstance results in a minimum self-sufficiency rate of 9%. Over the entire year, the household could be completely self-sufficient on a net energy basis. The annual consumption is about 11,000 kWh and also a little more than 11,000 kWh of electricity is generated by the PV system. Compared to the household in 2021, the electricity demand for the household in 2030 increases by almost a factor of three, but the household in 2030 could be completely self-sufficient over the year on a net energy basis.

Figure: Monthly energy consumption of a 4-person household in 2030



Source: Wuppertal University

Research questions, assumptions and methodologies – Dongqiaotou

Research framework

The research in the village of Dongqiaotou focused on following research questions:

- How large are the flows of energy between various local subsystems?
- What are the energy consumption patterns and energy flows of an average household?
- Which local renewable energy resources exist and how high is the self-sufficiency potential of the village?
- Which direction could the energy system development take up to the year 2030?

The study takes a village as the research unit and examined energy consumption activities within its administrative geographical boundary. The framework mainly includes:

- Input and output of energy consumption,
- the calculation and identification of energy production potential,
- energy mix and services at the village scale,
- energy transformation within the village system,

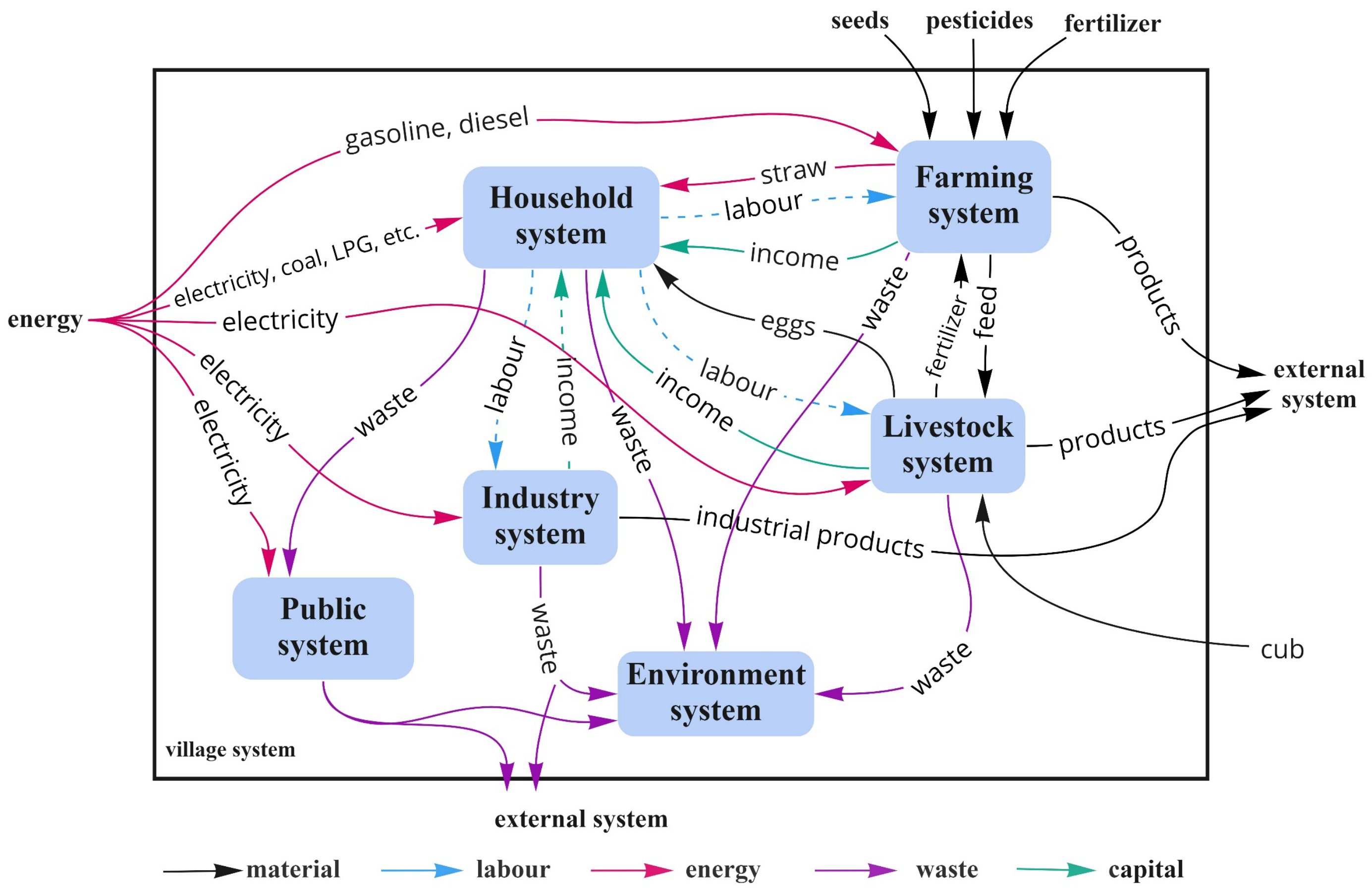
- the flows of energy consumption within the village.

Covering the characteristics of production and living activities, the model divides the whole energy system into six subsystems:

- Households
- Public spaces and systems
- Farming
- Livestock
- Industry
- Environment

The model explores the flows of energy, people, and materials/products (with regard to energy, biomass in particular) within the administrative boundary of the whole village. Energy flows are measured in kilograms of coal equivalent (kgce). Regarding the input section, the main sources of energy available at the regional scale are considered. In addition to the material flow in individual systems, it includes the interactions between the subsystems. The products, services and waste generated in the process of interaction are partly used to meet the local production and living needs or they are being directly discharged into the local environment, while the remainder enters the market in the socio-economic system outside the village to generate more revenue. The waste generated is further transported and consumed through the interaction with the environmental system outside the village.

Figure: Schematic depiction of the energy flow model

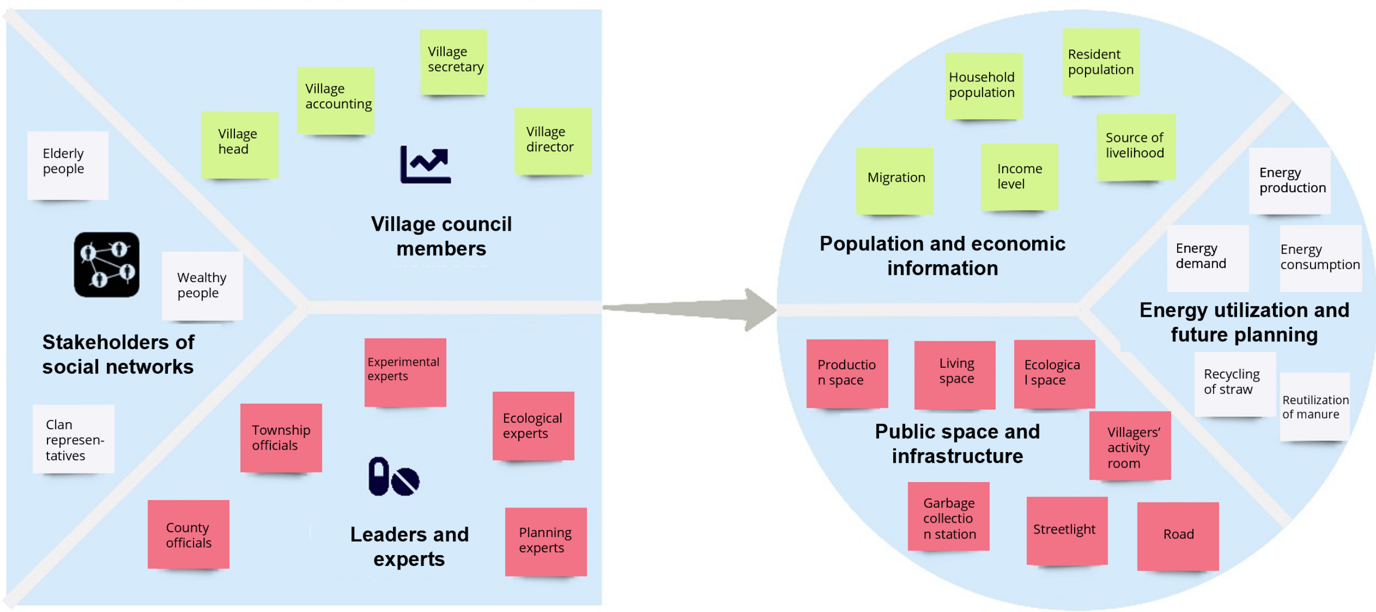


Source: Institute of Applied Ecology at the Chinese Academy of Sciences

Questionnaire-based survey and semi-structured interview in Dongqiaotou

The questionnaire design and research relied on a combination of top-down and bottom-up approaches. The top-down approach developed the framework and determined the relevant energy indicators through discussions with experts and researchers. The bottom-up approach relied on village inhabitants and local cadres to understand the information on household attributes and resource utilisation from the perspective of the most basic social units, thus enabling their participation in the research process. Through communication with township cadres, researchers understood the local development level and from village cadres, they learned about the basic situation and future development trends of the whole village. Interviewing villagers helped the research team gain insight into the current development status of families. Lastly, the elderly provided information on the development history of the whole village.

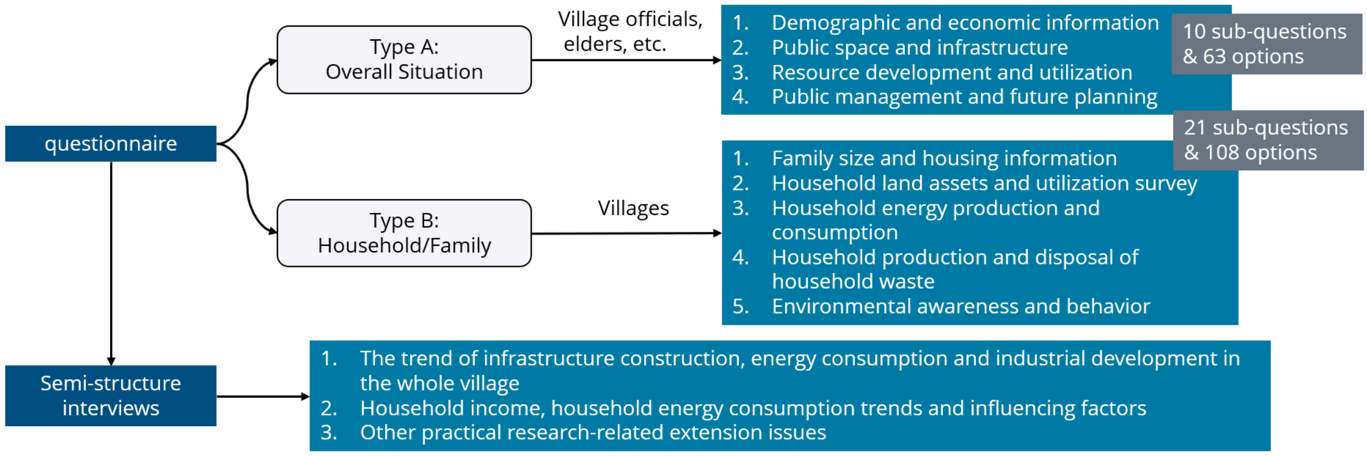
Figure: Overview of survey target group and surveyed information



Source: Institute of Applied Ecology at the Chinese Academy of Sciences

The objectives of data collection are divided into socio-economic information, village public space and infrastructure, and energy use and future planning. At the level of public space and infrastructure in the village, the focus is on transformation of the spatial type of the village from the perspective of production space, living space, and ecological space. A comprehensive analysis examined the configuration of household space and public space and extrapolates the change in the use of public infrastructure such as streetlights, roads, and garbage disposal points. Concerning energy use and future planning, the analysis also explores the transformation of the village's energy demand in terms of energy production and consumption. The analysis examines resource use development in relation to the availability of local resources to assess the potential to maximise utilisation of these resources.

Figure Dongqiaotou survey and interview process



Source: Institute of Applied Ecology at the Chinese Academy of Sciences

Scenarios and assumptions

To analyse the potential future energy supply and consumption structure in the village, the study uses three scenarios based on the current situation in the village regarding PV, mobility, and heating.

Regarding mobility, there are about 1,010 electric vehicles in the village in 2020. Most of these, however, are small-scale two- or three-wheeled vehicles for shorter distances. This is made up of 560 two-wheeled electric vehicles, 400 three-wheeled electric vehicles, and 50 four-wheeled electric vehicles. Including internal combustion engine cars, there are 220 four-wheeled vehicles. Two-wheeled electric vehicles are light and fast, and are suitable for short-distance travel for one or two people. Three-wheeled electric vehicles are more suitable for families or for households that need to transport goods or large items. At the same time, with the promotion of urbanisation, the aging of the population in rural areas is progressing. Older people often prefer three-wheeled electric vehicles. Four-wheeled electric vehicles have become the means of transportation for some families in the village under the promotion of new energy vehicles and have become more popular given their higher speed and comfort. We assume two-wheeled electric vehicles and three-wheeled electric vehicles on average charge during six hours every three days and that four-wheeled electric vehicles charge for eight hours every five days.

Currently, the village relies on coal for heating, and only a small number of households use electricity for heating. The heating season in Dongqiaotou typically lasts four months, from mid-November to mid-March.

Regarding solar PV, a total of 32 households in the village had solar PV installed as of 2020. Households whose roof areas are spacious and suitable for solar panels can rent their rooftops to the power supply company. Communication with villagers showed that more and more families report a willingness to install PV panels and expect to benefit from it.

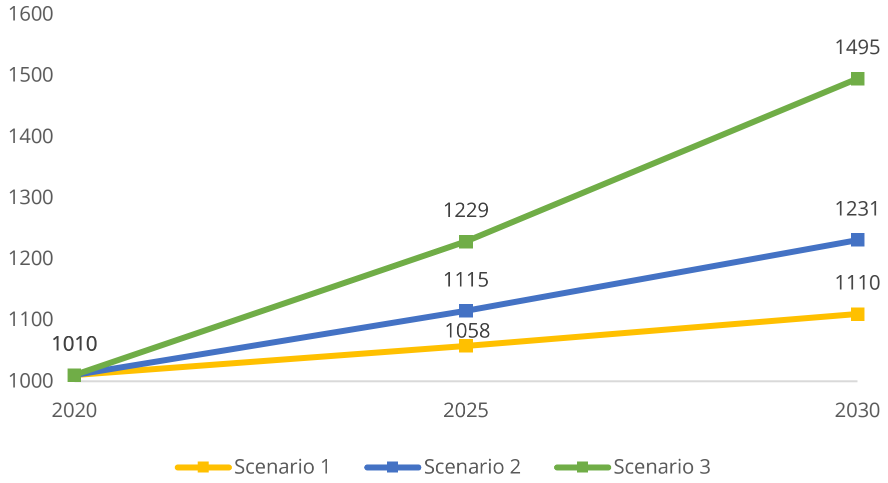
This paper sets up three future scenarios based on the current development status of the whole village: scenario 1 (baseline scenario), scenario 2 (moderate growth scenario) and scenario 3 (optimistic scenario).

Scenario 1 (baseline scenario): The future development of various energy-using devices in households in the investigated village is based on the current trends in the whole village. The total number of electric vehicles in the village will reach 1,058 by 2025, and 1,110 by 2030. The number of air-source heat pumps will be 10 in 2025 and 30 in 2030. The number of households with PV power generation will be 80 in 2025 and 145 in 2030.

Scenario 2 (moderate growth scenario): The number of various energy-using devices in the surveyed village households shows a moderate growth trend. In terms of the use of electric vehicles, the total number of electric vehicles will be 1,115 in 2025 and 1,231 in 2030. The number of air-source heat pumps will be 25 in 2025 and 60 in 2030. The number of households with PV power generation will be 130 in 2025 and 250 in 2030.

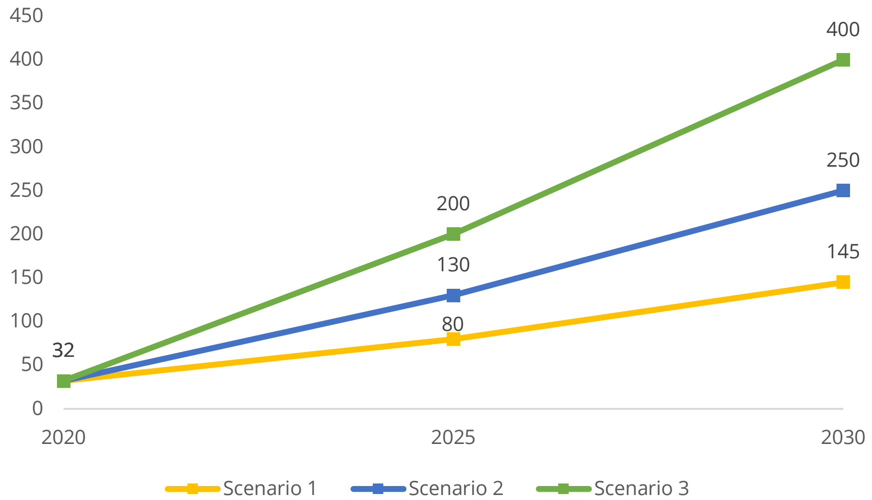
Scenario 3 (optimistic scenario): Various clean energy technologies in the village show a rapid growth trend. In terms of the use of electric vehicles, four-wheeled electric vehicles have huge development space in the future, so the total number of electric vehicles will be 1,229 in 2025 and 1,495 in 2030. The number of air source heat pumps will be 50 in 2025 and 110 in 2030. The number of households with PV power generation installed will be 200 in 2025 and 400 in 2030.

Figure: Total number of electric vehicles under three scenarios in Dongqiaotou



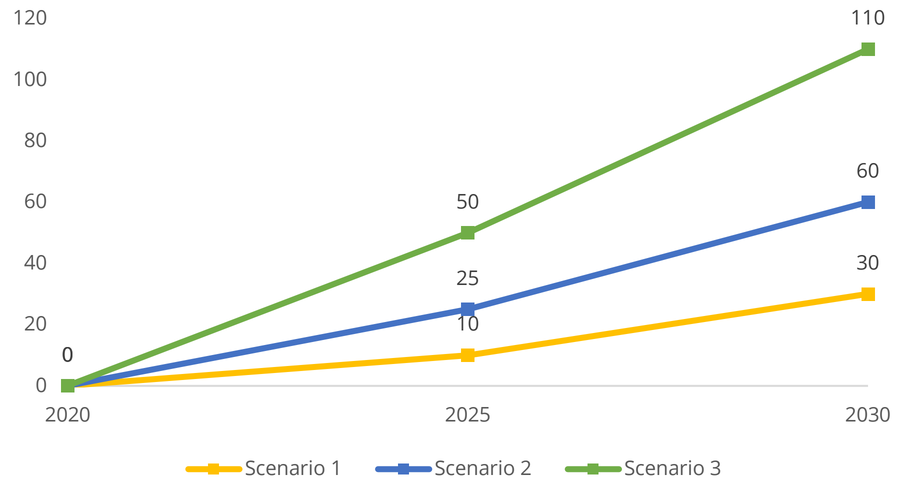
Source: Institute of Applied Ecology at the Chinese Academy of Sciences

Figure: Total number of households with solar PV under the three scenarios in Dongqiaotou



Source: Institute of Applied Ecology at the Chinese Academy of Sciences

Figure: Total number of air-source heat pumps under the three scenarios in Dongqiaotou



Source: Institute of Applied Ecology at the Chinese Academy of Sciences

Survey results - Dongqiaotou

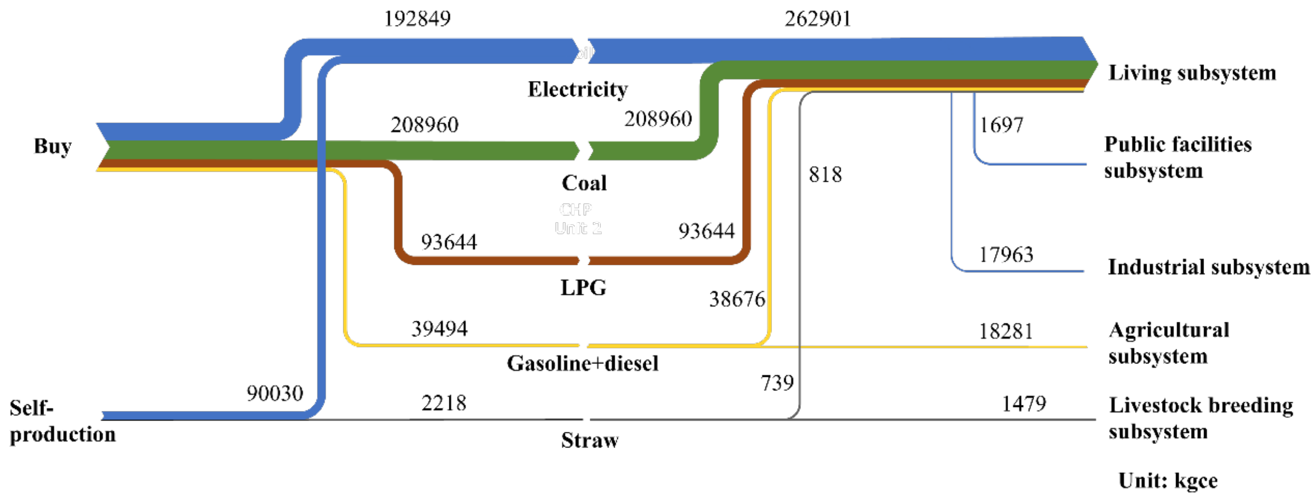
Overall energy structure of the village

In 2020, the whole village consumed 626,196 kgce of energy (5,106 MWh), made up of 192,849 kgce of electricity from the grid (1,570 MWh, 30.7% of total energy consumption), 208,960 kgce of coal (1,701 MWh, 33.3% of total), 93,644 kgce of liquefied gas (762 MWh, 14.9% of total), and 39,494 kgce of gasoline and diesel (322 MWh, 6.3% of total) from the social and economic systems outside the region. Straw and household PV account for the bulk of the energy produced locally. Household PV yielded 90,030 kgce (733 MWh, 14.4% of total) and straw accounted for 2,218 kgce (18 MWh, 0.03% of total).

In the use of energy, electricity is mainly consumed in the household, public facilities, and industrial development subsystems, of which the household subsystem is the largest category of electricity consumption, accounting for about 90.06% of the total. The household subsystem is also where virtually all coal and liquefied gas consumption occurs. About 97.93% of the fuel oil consumption occurs in the household living subsystem, and less than 3% is used for the agricultural planting subsystem. Most of the locally produced straw returns to the fields. The quantities used for the household subsystem are 739 kgce (6 MWh), and 1,479 kgce (12 MWh) in the livestock and poultry breeding subsystem.

Overall, about 70% of the village's energy input comes from external purchases, and about 30% of its energy is produced locally.

Figure: Flows of energy and material in Dongqiaotou in kg of coal equivalent (2020)



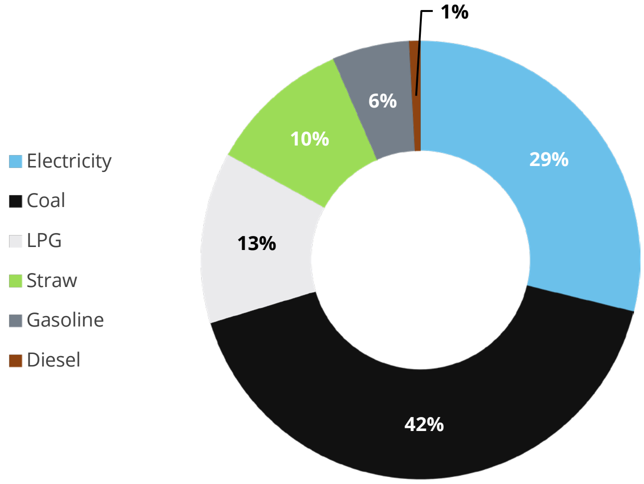
Source: Institute of Applied Ecology at the Chinese Academy of Sciences

Household energy consumption structure and characteristics

Electricity is the main source of energy for household appliances in the home and acts as a supplementary energy source for daily cooking and heating. Coal is the most common type of energy used for home heating and coal also acts as a supplementary source of cooking energy. Gasoline and diesel are the most common types of transportation energy used in households and serve as fuels for mechanised farming. About 300 households in the village use solar water heaters for activities such as daily bathwater, with a penetration rate of 67.26%. Due to the negative impact of burning straw on the environment, local residents mostly apply waste straw to fields, and less than 5% of households use straw as a household energy source.

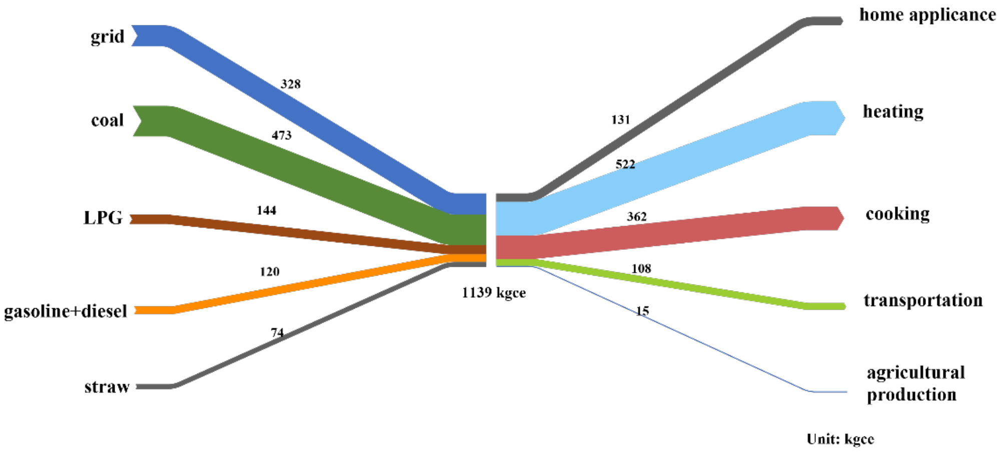
Residents meet energy demand through purchases and own production. In 2020 the purchased energy accounted for 89.46% of the total energy use, and 10.54% of the energy came from the straw produced by itself. The use of energy at home is mainly reflected in household appliances, heating, cooking and transportation. Cooking has the largest share in household energy consumption, with 48.42% of the total energy. This energy comes from electricity, coal, liquefied petroleum gas (LPG), and straw. Heating is the second largest energy consuming activity in the surveyed villages, accounting for 29.26% of total energy use, mostly from coal and to a small part from electricity. Transportation energy use includes electric vehicles, internal combustion cars, and motorcycles, which consume 10.81% of the total energy.

Figure: Average household energy consumption structure in Dongqiaotou (2020)



Source: Institute of Applied Ecology at the Chinese Academy of Sciences

Figure: Energy and material flows in an average Dongqiaotou household (2020)



Source: Institute of Applied Ecology at the Chinese Academy of Sciences

Analysis - Dongqiaotou

Self-sufficiency potential

In the household subsystem, the total energy consumption of the whole village is 514,812 kgce (the energy equivalent to 4,191 MWh). Given that there are already about 350 households and families in the village using solar water heaters, if the heat collected by the solar water heaters can be used more efficiently, the energy production potential that can be realised is 406,634 kgce (3,310 MWh), which means that the external dependence of energy in the household can be reduced by 78.99%.

In the public facilities subsystem, the energy consumption mainly comes from the electricity consumption of street-lights, village committee and the village health room, totalling 1,697 kgce (14 MWh). Considering the economic benefits and usage costs of the existing streetlights, if they are replaced with solar streetlights, the total annual electricity generation will be 11,455 kgce (93 MWh). Besides solving the energy consumption problem in this system, PV streetlights can also supplement other energy use subsystems.

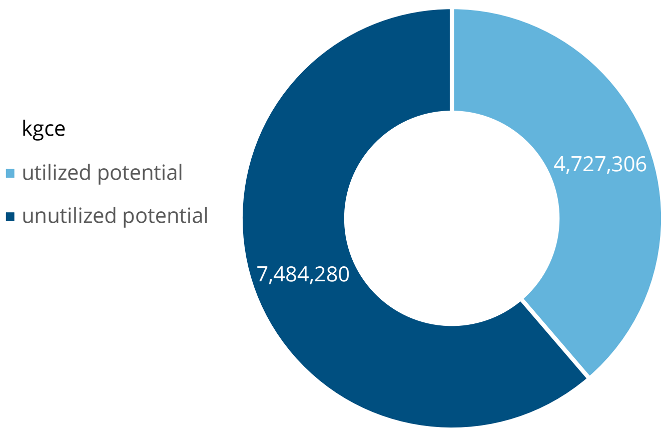
In the agricultural planting subsystem, the amount of crop straw produced is 7,394,465 kgce (60,198 MWh). As mentioned above, most of the straw is applied to the fields, and only a small portion is used for feed and household fuel. If the straw is utilised as a resource, the usable potential of straw is 3,459,821 kgce (104,832,576 MJ), which would meet the energy supply demand in this system.

In the livestock breeding subsystem, the total amount of livestock manure produced by large-scale breeding and retail breeding is 89,851 kgce (2,722,485 MJ). Specialised institutions directly purchase much of the livestock manure produced by large-scale breeding, while the livestock manure produced by small-scale breeding is mostly dumped directly as waste. Collecting it in a unified manner would yield a fertilisation and energy potential from livestock manure of 798,142 kgce (24,183,703 MJ).

In the industrial development subsystem, the total energy consumption brought by cold storage is 18,281 kgce (553,914 MJ), and for the short- and medium-term, no resource potential has yet been identified and we assume this will continue to rely on external energy supply.

Through the comprehensive analysis of each subsystem, it can be seen that in the entire village system the energy consumption is 7,484,280 kgce (226,773,684 MJ), and the production potential is 4,727,071 kgce (143,230,251 MJ). If the energy in each system is reasonably developed, the energy self-sufficiency will rise to 63.16%.

Figure: Utilised and unutilised energy potentials in Dongqiaotou (2020)



Source: Institute of Applied Ecology at the Chinese Academy of Sciences

Seasonal energy consumption characteristics of Dongqiaotou

Energy consumption of the village subsystems varies across the year. For households, energy consumption changes relatively much throughout the year. Hot summer weather from June to August leads to an increase in energy consumption for air conditioning and refrigeration. During the Chinese New Year holidays, workers and students return home to rural areas, which increases household energy consumption during this period. In terms of household energy production, there is no significant difference in the amount of energy produced in the rest of the months, except during the winter months, when cold temperatures cause a drop in solar water heating.

Streetlights and village council sessions accounts for the majority of the public space energy consumption. There is no noticeable difference in usage throughout the year. In the agricultural subsystem, the local crops of potatoes and corn are planted in January-February for potatoes, and corn in May. Mechanised tools in the planting process causes an increase in fuel and other energy use during these periods. The harvest season is May-June for potatoes and September-October for corn. There is an increase in agricultural waste during these months.

In the livestock farming system, for farms raising a large number of poultry the electricity consumption for ventilation and temperature management is relatively higher in June-August.

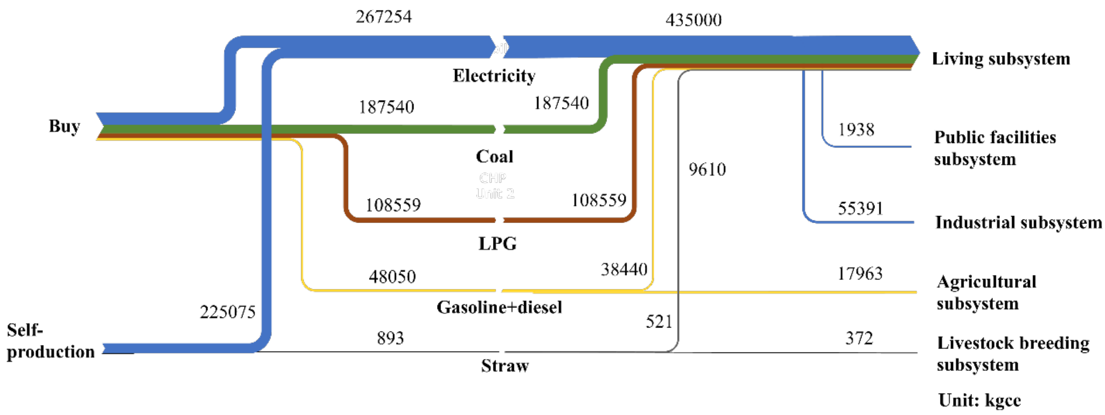
Scenario Results for Dongqiaotou

Scenario 1(baseline scenario): The annual electricity consumption for charging of the three types of electric vehicles is 384,182 kWh (on average 861 kWh per household) in 2025 and 609,365 kWh (on average 1,366 kWh per household) in 2030. The use of air source heat pumps in heating can replace 12 tons of coal in 2025 and 36 tons of coal in 2030. Regarding PV power generation on rooftop typical houses have rooftop area dimensions of around 14 meters by 19 meters. The rooftop area available for PV is about 112 m^2. Dongqiaotou has 1,982 sunlight hours per year on average, implying the maximum potential rooftop output in this scenario is 1,829.875 MWh in 2025 (225,075 kgce) and 3,316.648 MWh in 2030 (407,948 kgce).

Scenario 2 (moderate growth scenario): Electricity consumption for EV charging is 418.267 MWh in 2025 (on average 938 kWh per household) and 693.471 MWh in 2030 (on average 1,555 kWh per household). The use of air source heat pumps in heating can replace 30 tons of coal in 2025 and 72 tons of coal in 2030. The total amount of electricity that PV-powered households can generate is 2,973,547 kWh (365,746 kgce) in 2025 and 5,718,359 kWh (703,358 kgce) in 2030.

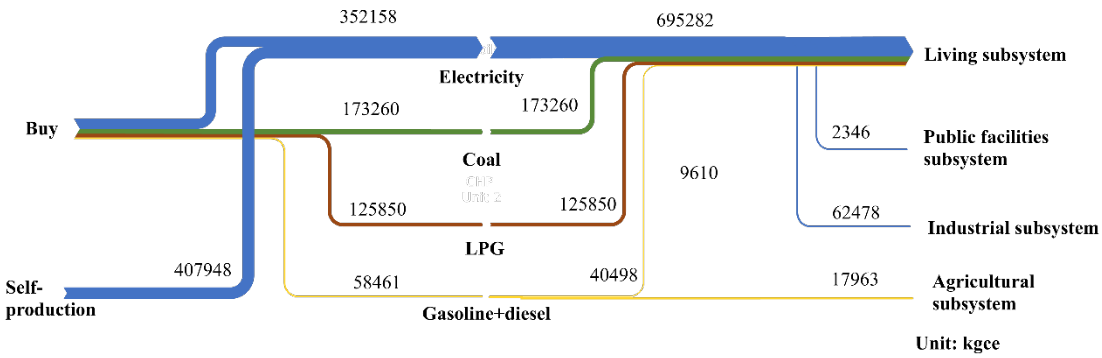
Scenario 3 (optimistic scenario): In the energy substitution effect under this scenario, the electricity consumption of EV charging is 513.154 MWh in 2025 (on average 1,151 kWh per household) and 112.937 MWh in 2030. The use of air source heat pumps in heating can replace 6,000 kg of coal in 2025 and 132,000 kg in 2030. The total amount of electricity that PV-powered households can generate is 562,687 kgce (4,574.687 MWh) in 2025 and 1,142,254 kgce (9,286.616 MWh) in 2030.

Figure: Energy and material flows in Dongqiaotou (Scenario 1, 2025)



Source: Institute of Applied Ecology at the Chinese Academy of Sciences

Figure: Energy and material flows in Dongqiaotou (Scenario 1, 2030)



Source: Institute of Applied Ecology at the Chinese Academy of Sciences

Under the existing development model, the energy self-sufficiency rate of the surveyed villages in 2020 is 16.83%. In Scenario 1 (baseline scenario), the self-sufficiency rate of the whole village is 36.81% in 2025 and 57.48% in 2030. Considering only the electricity production and usage of the whole village, the village's self-sufficiency rate of the electricity supply in 2020 is 46.68%, and it can reach 84.22% in 2025. By 2030, the annual electricity production from local resources would be at 115.84% of annual demand and thus would exceed the total annual electricity consumption of the whole village.

In Scenario 2 (moderate growth scenario), the self-sufficiency rate of the whole village is 56.98% in 2025 and 89.94% in 2030. If only the electricity production and usage of the whole village is considered, the annual electricity production in 2025 exceeds the electricity consumption of the whole village, at 122.85% of consumption; and 165.69% of consumption in 2030.

In Scenario 3 (optimistic scenario), the self-sufficiency rates of the whole village are 80.70% in 2025 and 126.16% in 2030. If only the electricity production and usage of the whole village is considered, the annual electricity production in 2025 and 2030 exceeds the electricity consumption of the whole village, at 159.33% in 2025, and 208.50% of consumption in 2030.

The scenario analysis shows that Dongqiaotou can produce more power than it needs over a year. However, as in the case of Schwaig, energy consumption does not always coincide with solar PV output times. This means that without significant energy storage capacities, during the daytime the village and its households would be more likely to feed in surplus power into the grid (as far as grid capacity permits), thus generating revenue, while purchasing power during the night.

This analysis focused on the self-sufficiency potential of Dongqiaotou with regard to solar PV and assuming intensifying electrification in heating and mobility. Solar thermal solutions already are being used in Dongqiaotou and the village still can extend their application. They can make an additional contribution in hot water generation. Moreover, the self-sufficiency modelling did not consider in-depth the potential from the biomass produced in and around the village. This biomass could be processed further and either utilised to supplement heating energy and power through small combined-heat-and-power plants if no solar energy is available or sold to larger centres in the region.

Household self-sufficiency potential under continuing electrification

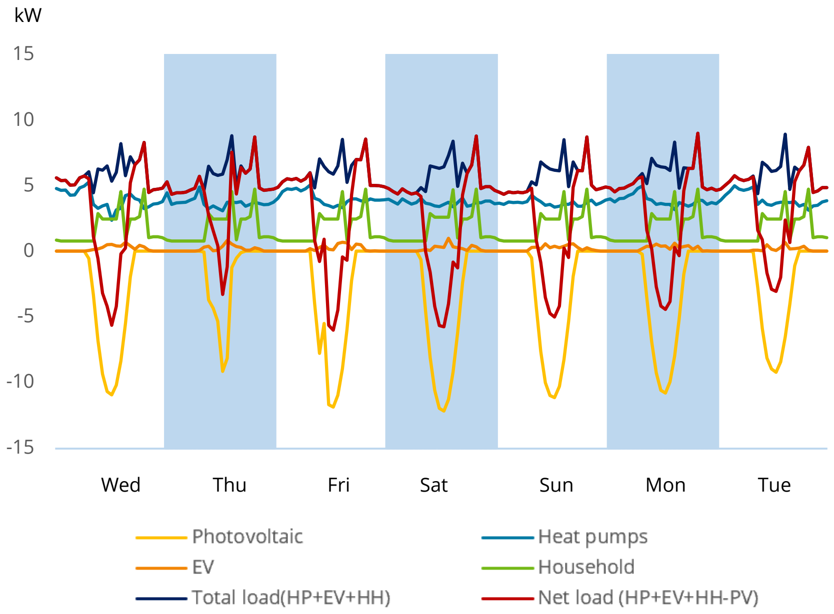
In contrast to the research conducted in Schwaig, limited data availability in China compared to Germany required a different approach to modelling and assessing self-sufficiency potentials with an increasing amount of PV power generation and adoption of EVs and heat pumps. Therefore, the modelling focuses on the situation of a hypothetical household that has rooftop PV, an air-source heat pump, a (four-wheeled) electric vehicle, and a household energy consumption in line with the survey findings. This represents a household configuration that is likely to become increasingly common up to 2030.

The model simulates the household's PV power generation, the power consumption of electric vehicles and air source heat pumps, and household electricity consumption of a typical household in the week of 1 January 2020 to 7 January 2020. The diagram below shows the energy consumption load of a single household. The total energy consumption of a single family for a week is 962 kWh, and the net load is 523 kWh.

Most of the houses in Dongqiaotou Village are free-standing houses. The average roof area for installing PV panels is 112 square meters. The total PV power generation of a household in a week is about 439 kWh. The daily PV power generation time generally is 9 hours. On average, the daily PV power generation capacity of one household is relatively stable, maintaining an output mostly between 50-70 kWh.

The average daily outdoor temperature selected under which the air source heat pump operates is -3.03 °C, the minimum is - 11.3 °C, and the maximum is 5.7 °C. The thermal coefficient of performance (COP) of the air source heat pump unit system is between 2.2-2.9. The average daily power consumption of the system is 92 kWh, with a maximum power consumption of 5.25 kW per hour and a minimum of 2.36 kW. The daily charging peak period of electric vehicles is mainly from 5 pm into the night. The average daily charging capacity is 3.95 kWh, the daily maximum charging capacity can reach 4.46 kWh, and the minimum is 2.74kW. The average daily electricity consumption of the household for other activities is 42.13 kWh. Because cooking and other tools mostly rely on electricity, the daily peak hours of electricity consumption are mostly in the morning, noon and evening.

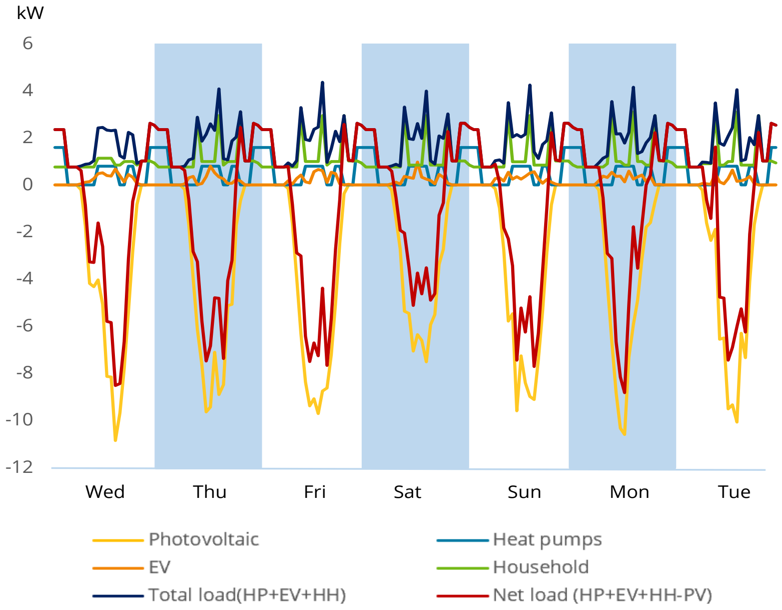
Figure: Energy generation and consumption of a hypothetical household with rooftop PV, air-source heat pump and an EV, in winter week (2020)



Source: Institute of Applied Ecology at the Chinese Academy of Sciences

The energy consumption load of a typical household in the summer of 2020 (July 1, 2020 - July 7, 2020) is shown in the figure above. The total energy consumption of a single household for a week is 311 kWh, with a net load of -191 kWh. The total PV generation of a household for a week in summer is about 502 kWh, with a producing period from 6 a.m. to 7 p.m., in total of about 13 hours. The daily PV generation is maintained at about 60-80 kW. The total energy consumption of heat pump refrigeration is 95.2 kWh and the average daily energy consumption is 13.6 kWh. The use time is mostly concentrated in the daytime from 10:00 am to 2:00 noon and at night. Regarding the load of EVs, the model assumes the same figures as in the winter week. The average daily electricity consumption of the household for other activities 26.49 kWh, with a maximum daily consumption of 27.54 kWh and a minimum of 21.71 kWh.

Figure: Energy generation and consumption of a hypothetical household with rooftop PV, air-source heat pump and an EV, in summer week (2020)



Source: Institute of Applied Ecology at the Chinese Academy of Sciences

These modelling results for one household show that usually solar PV output exceeds the load during the day, giving the household the opportunity to generate revenue from feeding power into the grid during the day or, if battery storage is present, to reduce expenditures for purchasing power from the grid during the night.

Discussion of differences between the two research approaches

Due to different situations regarding data availability and economic development status, research activities in Schwaig and Dongqiaotou followed different approaches and methodologies. Whereas both cases included a survey of residents, the study of Schwaig also employed local grid data and a regionalisation methodology to complement the survey data and validate the results. In Dongqiaotou, no local grid data were available, and the national and provincial data and statistics available did not enable a comparable regionalisation methodology. The Chinese research team had explored the viability of applying a regionalisation methodology to Dongqiaotou, however.

Due to the good data availability, the research conducted in Schwaig could produce modelling results for the entire village during summer and winter. Due to the more limited availability of data in Dongqiaotou, this kind of modelling was not viable. However, based on survey data, scenarios, and weather and insolation data, it was possible to model the situation of a household with solar PV, a heat pump, and an electric vehicle over a winter week. A comparable household would become increasingly common by 2030 under the scenarios developed in this study. While the aggregate of households and consumers in Dongqiaotou is likely to show certain differences for individual households, households still make up most of Dongqiaotou's energy consumption, therefore even modelling a single typical household provides meaningful information about the entire village and gives insights into its self-sufficiency potential.

It should be noted that due to the differences in methodologies and models that the two research teams applied and due to different kinds of input data, the self-sufficiency estimates that resulted for the two village are not directly comparable. Nevertheless, the two different approaches still point to certain similarities like excess generation of solar power at certain times and shortfalls at others.

A village in Germany and China in the year 2030

Schwaig

The analysis in this study shows that households in Schwaig, and the village as a whole, have a high potential for self-sufficiency in the summer, provided either energy storage or V2G are adopted locally, whereas winter heating loads and low renewable output in the winter will entail heavy usage of grid energy or addition of some sort of seasonal storage technology.

Demand for electrical energy in Schwaig will increase significantly by 2030, while other energy sources such as oil and gas will be substituted gradually. In Schwaig, electrical energy consumption may rise to between 3,750 MWh and 4,700 MWh, based on the scenarios. If purely electrical household and industrial consumption is used as a comparison, this means an increase of 50% to just under 90% compared with current demand. Heat pumps are the main driver of the increase in demand for electricity. These require a lot of electricity, especially in winter. The additional demand from EVs is less significant, especially when comparing the *Trend* and *Optimistic* scenarios. It can be seen that in the *Trend* scenario the energy demand of EVs and heat pumps is quite similar, while in the *Optimistic* scenario the energy demand of heat pumps exceeds the energy demand of EVs by almost a factor of 2x.

On the energy supply side, PV will play a central role. There is already a comparatively high installed capacity there, which will more than double by the year 2030. In both scenarios described above, PV can provide around 30% of total energy consumption over the course of a full year. If considering only the demand for electricity, PV can provide as much as 49-56% of the total annual electricity consumption. If the electricity supply is broken down by month, self-sufficiency rates differ widely from the annual mean value. In the winter months, only about a tenth of the demand can be covered by PV, while in the summer months more than 100% of the demand can be covered. For this reason, long-term storage systems such as battery storage or hydrogen storage would have to be considered for Schwaig to achieve greater overall self-sufficiency in 2030.

When considering energy supply and demand over 15-minute intervals, two points stand out. **First is the necessity of daily energy storage capacity**. Especially in summer, when there is a significant overproduction of PV power, storage can lead to high self-sufficiency rates. **Second, it is unnecessary for Schwaig to install large amounts of stand-alone storage if the residents adopt EVs with V2G technology**, since at night, when the vehicles are stationary, vehicle-to-grid (V2g) technology could make a major contribution to high self-sufficiency rates.

In summary, in Schwaig 2030, a large part of the energy will be provided by PV and the demand for electrical energy will keep increasing due to heat pumps and EVs. If seasonal energy storage systems become available, the excess electricity production in the summer can also be used in the winter months and a high self-sufficiency rate can be achieved for Schwaig overall. Furthermore, for daily loads, V2G offers the possibility to use the excess production of daily PV power during the night. For long-term storage, however, separate storage units must be installed because EVs are not a practical solution for long-term storage, even though they are stationary for much of the time.

Dongqiaotou

The simulations and scenarios used in this study show that rooftop **solar PV capacity and PV power generation could increase significantly in Dongqiaotou, and that electrification of transport and heating may also increase**, although the degree of electrification depends on technology developments and policy support. Heat pumps and electric vehicles should experience significant growth up to 2030, although there is a large variance between scenarios and adequate policy support will be necessary to realise this potential. Common trends are an increased use of locally produced power while imports of power and other fuels decrease, therefore leading to an increased self-sufficiency rate.

The local energy production of Dongqiaotou in 2020 meets 16.8% of all energy demand. Under the assumption that renewable energy development and electrification continues steadily as foreseen in China's national policy, self-sufficiency on an annual basis could increase to 90% or up to 126% in 2030, depending on the scenario. This means that **by 2030, Dongqiaotou has the potential to produce more energy than it consumes over one year**, in principle. Indeed, solar energy production in Dongqiaotou has lower seasonal variation than in Schwaig, reducing the seasonal imbalance in electricity supply and demand in a high electrification scenario. However, just as in Schwaig, renewable energy generation largely occurs during the day and solar power is unavailable at night-time unless storage is available. While Dongqiaotou in 2030 might have the technical potential to reach complete self-sufficiency in electricity, the cost of required storage probably would be uneconomical.

As demonstrated by the simulation a hypothetical household with PV, heat pump, and an EV, Dongqiaotou in 2030 could generate a surplus of electricity during the day that usually can meet all its demand during daylight hours. While some of the excess power may be stored in batteries or heat storage for use during nighttime, the most economical approach for Dongqiaotou, and other villages with similar conditions, likely entails avoiding high peak-hour power prices via self-consumption and export of surplus power during the day, while importing power during the night, benefitting from lower nighttime power prices.

Policy recommendations

Germany

Our research on energy flows and technology adoption in Schwaig shows that small, rural communities have the potential to become highly self-sufficient by 2030, at least on a net basis. Due to low building density and the resulting large open spaces, rural towns have room for large amounts of renewable energy capacity. Not only can they achieve high self-sufficiency, but their energy surpluses can feed into the grid and thereby raise the share of CO_2-neutral electricity regionally, compensating for shortfalls in urban areas with lower renewable potential.

Since rural areas play a central role in the energy transition, political frameworks should facilitate expansion and further development of rural renewable energy and storage, in tandem with electrification of rural transport and heating in rural communities.

A range of measures can promote an accelerated expansion of wind energy in Germany. Many experts and industry groups therefore have called for permitting procedures to become as short and simple as possible while still meeting the legitimate interests of stakeholders and adequate environmental protection standards. Procedures should be reorganised in a way that protracted and consecutive legal challenges give way to more condensed processing of legal claims within a shorter time frame.

Moreover, distributed wind and solar energy projects should become more financially attractive for the hosting rural community. This can be achieved by remunerating rural communities with a payment per kWh produced and further improve incentives for household rooftop PV that combine feed-in tariffs and self-consumption. This can contribute to greater acceptance by rural residents.

Another instrument that Germany already is using to improve acceptance is comprehensive stakeholder involvement early on in project planning. Germany's new federal government has set the target of making 2% of Germany's area available for wind energy. Addressing these obstacles to renewable energy expansion is of high importance. The German Federal Government already has started to address the problems based on the above suggestions in 2022, including nationally unified species protection standards, accelerated permitting, and working towards lower minimum distance requirements. Regarding distributed solar energy, the German government has announced that newly built buildings should in general include rooftop solar and is working towards making hybrid feed-in tariff and self-consumption models more attractive.[41]

Germany presently lags some other European countries in electric heat pump adoption. Greater incentives for replacement of older boilers, and for home energy retrofits in general, are likely necessary to promote the energy transition in rural areas, given present low rates of energy retrofit and the common tendency of consumers to seek the lowest-cost replacement of older heating systems, which often results in lost energy savings and missed opportunities for electrification. A scrappage premium for fossil fuel boilers replaced with electric heat pumps, along with a public information campaign on the health benefits of eliminating household oil and gas combustion, could help push more homeowners to make the switch, while simultaneously encouraging the industry to move away from fossil fuel technologies. Availability of qualified technicians and mechanics to install a high number of heat pumps also can be a bottleneck that vocational training must address in a timely manner.

Given the high variability of daily and seasonal energy consumption and production, energy storage will likely become an important element of the rural energy transition. Policies to promote energy storage systems in rural areas can help ensure that these technologies keep pace with renewable deployment. The case of Schwaig suggests that long-term (seasonal) and short-term (daily) storage are both necessary in such regions. For long-term storage, hydrogen storage and electrolysis appear to offer strong potential. While we did not explicitly study vehicle-to-grid in this modelling, V2G offers potential for short-term or intraday storage, because electricity consumption for daily EV trips is far lower than the capacity of typical EV batteries. V2G appears attractive even assuming battery life-related concerns limit V2G to just 20-30% of battery capacity for balancing peak loads. Of course, the economics of daily and seasonal energy storage are likely to be a critical factor in determining whether households or rural towns should opt to invest in storage to achieve self-sufficiency for greater resilience and attaining low-carbon goals.

Smart meters, dynamic tariffs, and bonuses for participation in load-balancing activities such as virtual power plants or utility load management could help encourage such technologies in Germany. Digitisation will also require a political framework and corresponding incentives to enable roll-out of information and communication technology (ICT).

Suggestions:

1. Encourage rural communities to pursue comprehensive renewable energy and electrification schemes, through community planning, information sharing platforms, and public campaigns.
2. Develop national and regional policies to promote heat pump adoption through scrappage premiums, public health campaigns, and support for transformation of local heating service providers. Ensure that incentives reach both households and local heating suppliers.
3. As more EV models with V2G capability reach the market, explore village-level pilots linking V2G with local excess solar production.
4. Accelerate adoption of digital energy platforms and services, including smart meters, dynamic energy tariffs, and related business models. Explore virtual power plant pilots aimed at the village level in regions with high penetration of PV.

China

In some respects, China's rural energy transition is at an earlier phase than that of Germany, and that is certainly the case when comparing the two villages of Schwaig and Dongqiaotou, given that the former has a considerable amount of rooftop PV. China also has rural PV, but it may be more concentrated in pilot villages under the poverty alleviation subsidy program. Our parallel analyses of the two villages suggests that the two villages have similar potential for energy transformation, involving adoption of rooftop PV, EVs, and electric heating/cooling. However, their pathways to achieve such a transformation are likely to differ. For example, the rapidly falling costs of small EVs in China could enable relatively rapid adoption of this technology, while the low cost of coal heating may hinder adoption of heat pumps and energy efficiency retrofits in low-income, rural regions. Given these differences, policies and programs also will differ.

Distributed energy in rural areas faces more barriers in China than in Germany. These include slow grid connections, inadequate distribution grids in rural areas, and low awareness. Household PV could help poverty alleviation efforts in Shandong by lowering household energy expenditures or generating revenue. Agrivoltaics and distributed wind energy could also supplement agricultural incomes, though this will likely entail changes to present land use and planning processes. However, enabling this transformation will necessitate grid companies have adequate incentives to invest in upgrading rural distribution grids. Given the cost of such upgrades, and the potential for EVs, energy storage, and heat pumps to enable load-shifting and peak-shaving at the village and household level, we expect it will also become economical to create incentives for households to prevent overgeneration or excessive peak load.

Biomass and biogas power and heat generation has a considerable potential. Depending on the local demand situation and infrastructure, biomass or biogas plants either could supply villages through small heating grids or local producers could sell biomass/biogas to nearby larger consumption centres. Enabling this may require access for biomass producers to financing and support by regional governments in convening and coordinating relevant actors and create a conducive business environment. Utilisation of biomass must be sustainable and should not compete with food production and should ensure conservation of local biodiversity.

Given the high up-front cost and low awareness of PV, rural collective economic organisations should be encouraged to jointly invest and operate renewable energy power generation projects with companies by means of land use rights or joint ventures. Germany's citizen cooperatives provide experiences and a model that can inform the development of comparable organisations that suit the Chinese context. Financial institutions should be encouraged to provide financing support for small-scale, village renewable energy projects.

Due to the high cost of centralised heating systems in rural areas, decentralised solutions appear the better option for replacing coal. The abundance of solar PV electricity in many areas in China creates ideal conditions for operating heat pumps in conjunction with PV. In combination with heat storage, PV and heat pumps in tandem can drastically lower operating expenditures for heating while improving local air quality. However, currently heat pump adoption still is hampered by high up-front investment costs which can be a particular challenge for less affluent rural households. Many buildings in rural areas have poor insulation and high heat losses. Improving building efficiency is particularly effective in conjunction with heat pumps, because this allows servicing the building with smaller, less expensive systems. However, efficiency improvements covering the entire building may exceed the means of most households. The study did not cover solar thermal solutions extensively, but these also can make an important contribution to hot water supply. These systems are already widespread in many rural areas and have scope for further expansion.

For these reasons, financial incentives for household-level energy improvements are necessary. Preferential loans or government subsidies for heat pump purchase and installation can lower the financial barriers by bringing costs to a level that is equal or sufficiently close to incumbent technologies. In addition, support schemes could incentivise the retirement or replacement of existing inefficient heating/cooling systems with heat pumps and could complement purchase subsidies with a scrappage premium for retiring inefficient heating systems. Another avenue for promoting heat pump installations is setting a target for electrification of heating in a village.

Support schemes could focus on selective efficiency improvements are likely necessary to encourage energy retrofits of older buildings. Higher building energy standards should be enforced for all new buildings, with subsidies available to ensure affordability. Besides financial support in form of preferential loans, provincial and local governments should promote the local presence of qualified experts to assess and select suitable energy efficiency measures and enhance training opportunities if necessary.

Present policies on energy storage focus on centralised or grid-sited storage. As this study shows, village-sited storage has advantages in levelling local load profiles and reducing the need for distribution grid investment. Due to a comparatively small load from larger electric vehicles in the upcoming decade, innovative solutions like vehicle-to-grid are unlikely to play a significant role in this time frame. However, pilot trials in rural areas that are more advanced when it comes to distributed PV and EV ownership could be of interest.

The potential for abundant power generation from solar PV in many rural areas in China creates synergies with electric vehicles as households with own PV generation can save spending on fossil fuels for transportation. Similar to the heating sector, additional financial incentives may be required to induce households to switch from the incumbent fossil technology. Provincial or local governments can purchase subsidies or scrappage premiums where owners can exchange old fossil fuel vehicles for a discount on a new EV purchase. In addition to the financial aspect, increased EV adoption also requires sufficient availability of charging infrastructure as well as skilled technicians and service points for repairs and maintenance in the surrounding area.

We also suggest that local governments pursuing local energy transition measures will also require a comprehensive national framework. For local and provincial governments to enact regulatory and financial measures to promote renewable energy expansion and electrification in mobility and heating in accordance with local conditions, it is important that they have the necessary financial means and a national level framework with clear targets and responsibilities, which requires support and coordination from the central government.

Suggestions:

1. Promote rural renewable energy via PV and biomass, with a focus on enabling greater self-sufficiency in rural energy consumption. Encourage rural villages to pursue renewable energy in tandem with China's national framework of carbon peaking and carbon neutrality, step-by-step boosting energy production to substitute fossil fuel consumption in heating, transport, and grid electricity consumption.
2. Improve incentives for grid modernisation in rural areas while also incentivizing peak-shaving and load smoothing at the village level via tariffs, advanced metering, and incentives for local energy storage.
3. Develop comprehensive local incentives for electrification of heating and transport, including potential targets for electrification as well as complementary building energy efficiency retrofits to reduce the overall cost of electric heating.
4. Strongly encourage green financial products and low-cost financing for village-level renewable energy projects, energy efficiency upgrades, and electrification of heat pumps and transport.

Conclusions

The research in Schwaig and Dongqiaotou has shown that despite differences in economic development level and different stages of the energy transition in China and Germany, villages and rural areas in both countries have the potential to play significant roles in their countries' energy transitions. Analysis based on surveys and subsequent scenario modelling showed that both in Germany and China, villages could produce more electricity from renewable sources than they consume over the year, even if electrification in heating and mobility accelerates and leads to increased demand. In both villages, power generation from solar PV modules usually exceeds power demand during the day, while demand that occurs before or after sunset cannot be met and requires power from other sources.

The misalignment of solar power abundance during the day and power demand before sunrise and after sunset could to some extent be compensated with storage, such as for hot water produced by heat pumps during the day, or battery storage for electricity. However, at current battery energy storage prices, capturing all the surplus power production would be uneconomical, even if technically feasible.

Rather than aiming for full self-sufficiency or island grid operation, a more balanced approach would target a combination of steadily increasing local renewable energy output, gradually upgrading local grids, and incentivizing smoothing peak loads via smart adoption of heat pumps and EV smart charging. Such an approach offers several advantages. Villages can drastically cut their dependence on power and fuel imports in general and can benefit from lower power prices at night for the demand they cannot meet with their own resources. This frees up household means previously tied up in energy spending for other purposes such as education, investment, or domestic consumption, that are beneficial for rural development and standard of living – especially desirable in poorer rural agricultural communities in China. By exporting their daytime renewable power surpluses to more energy-hungry regions, like cities or industry clusters, rural areas in both countries can generate additional revenue wand play a meaningful role in the entire country's energy transition. Realising these potentials to their fullest will require additional efforts both in Germany and China.

In Germany, operators should adjust grids to a growing infeed from many distributed installations and strengthen their ability to feed power into higher-voltage grids. This also includes advancing digitalisation of infrastructure, so that an increasingly decentral and variable power system can be managed flexibly and rapidly. Incentives for owners of distributed PV should promote self-consumption or feed-in during times of peak load. Incentive structures should promote storage by reducing or fully eliminating any costs for storing surplus power and enable owners of storage to sell balancing power as ancillary service in times of high-power demand. The analysis here shows that vehicle-to-grid could play a certain role to carry over surplus power into times without or with low PV power generation. However, vehicle-to-grid requires a range of technical conditions both in cars and in charging infrastructure and will need a clear and supportive legal and market framework if it is to establish itself. Pilot projects and political initiatives could promote this.

In China, it is important to expand and adjust distribution grids to enable more feed-in of distributed renewable energy. Grid operators should coordinate their planning with communities and jointly determine the expected additional renewable energy capacity in the planning timeframe. On the one hand, grid expansion must keep pace at acceptable cost; on the other hand, grid capacity bottlenecks should not impede further distributed renewable energy expansion.

Rural communities in China could reap significant economic benefits from reducing their need for power imports and becoming net power exporters. However, due to the significant up-front investment costs, adequate incentives and market conditions are important. Citizen cooperatives modelled on German examples are a model that China could explore in more depth and promote in local pilots.

Electrification of heating via heat pumps is an important part of the rural energy transition and is particularly attractive when combined with self-produced solar power and a degree of heat storage to provide heating at night. Due to the higher up-front costs of heat pumps, financial support and tighter building efficiency standards will likely be necessary to promote the technology. In mobility, villagers could all but eliminate the need for fuel imports if they adopt electric vehicles in various forms (two, three, four-wheeled), particularly if they charge vehicles during daytime when plenty of solar power is available.

Lastly, rural energy potentials are even higher when agrivoltaics are considered. Not having been considered in the modelling within this study, agrivoltaics can provide additional revenue, but will require suitable investment and operation incentives and must be well coordinated with grid operators and land-use ministries.

This study demonstrates the enormous potential of rural areas to complement centralised forms of energy production such as power plants and large-scale renewable installations. This study largely focused on the potential of rooftop PV in conjunction with heat pumps and electric vehicles. Aspects that merit further exploration and should be added to this framework in future research projects are agrivoltaics, distributed wind energy, and a more comprehensive analysis of storage, biomass and biogas potential. The economics of rural clean energy technology should also be studied in detail via scenario analysis, taking into account both technology costs as well as various considerations related to upgrading distribution grids.

Annexes

Overview of the regionalised scenario data

Technology	Scenario	Year	Community Oberding	Village Oberding	Village Nie-derding	Village Schwaig
EV	Trend	2030	423	89	42	75
		2035	881	185	87	157
	Optimistic	2030	550	115	54	98
		2035	1146	240	113	204
	Pessimistic	2030	360	75	35	64
		2035	749	157	74	134
Heat Pump	dena-EL95	2030	947	199	93	169
		2035	1211	254	119	216
	dena-TM95	2030	468	98	46	83
		2035	573	120	56	102
PV	Scenario A	2030	12,986 kW	3,940 kW	1,933 kW	1,862 kW
		2035	15,712 kW	4,767 kW	2,338 kW	2,253 kW
	Scenario B	2030	13,806 kW	4,188 kW	2,055 kW	1,980 kW
		2035	16,888 kW	5,123 kW	2,513 kW	2,422 kW
	Scenario C	2030	14,044 kW	4,260 kW	2,090 kW	2,014 kW
		2035	17,244 kW	5,231 kW	2,566 kW	2,473 kW

Overview of population and household sizes in Schwaig

Household size	Community Oberding	Village Oberding	Village Niederding	Village Schwaig
Overall	2,176	456	214	388
1 Person	614	129	61	110
2 Persons	613	129	60	109
3 Persons	418	88	41	75
4 Persons	360	75	35	64
5 Persons	130	27	13	23
6 and more persons	44	9	4	8

Breakdown of annual electricity consumption in Germany for different household sizes[42]

Household size	Annual electricity consumption in kWh		
	Low	**Medium**	**High**
1 Person	1,300	1,900	2,500
2 Persons	2,000	2,750	3,500
3 Persons	2,500	3,500	4,500
4 Persons	2,600	3,800	5,000
5 Persons	3,000	4,550	6,100
6 and more persons	5,800	6,450	7,100

Distribution of the heat demand

	Household heat demand in MWh	Industry heat demand in MWh
Community Oberding	15,970	6,069
Village Oberding	3,348	1,272
Village Niederding	15,748	5,984
Village Schwaig	2,848	1,082

Household survey questionnaire (German)

Fragen zum Handlungsfeld Mobilität

1. **Besitzt Ihr Haushalt ein Auto?**

- ☐ ja
- ☐ nein (> bitte Fragen 2 und 3 überspringen, weiter zu Frage 4)

2. **Bitte geben Sie für jedes Auto in Ihrem Haushalt Fahrzeugklasse, Antriebsart und Jahresfahrleistung an. (Falls Ihr Haushalt kein weiteres Auto / keine weiteren Autos besitzt, lassen Sie die Felder für Auto 2 / Auto 3 bitte frei.)**

	Auto 1	Auto 2	Auto 3
Fahrzeug-klasse	☐ Klein/Kompaktklasse ☐ Mittel/Oberklasse ☐ SUV/ Geländewagen ☐ Van/Kleinbus ☐ andere	☐ Klein/Kompaktklasse ☐ Mittel/Oberklasse ☐ SUV/ Geländewagen ☐ Van/Kleinbus ☐ andere	☐ Klein/Kompaktklasse ☐ Mittel/Oberklasse ☐ SUV/ Geländewagen ☐ Van/Kleinbus ☐ andere
Antriebsart	☐ Benzin ☐ Diesel ☐ Erdgas ☐ Autogas ☐ Hybrid ☐ Plug in-Hybrid (PHEV) ☐ Batterie-elektrisch (BEV) ☐ andere	☐ Benzin ☐ Diesel ☐ Erdgas ☐ Autogas ☐ Hybrid ☐ Plug in-Hybrid (PHEV) ☐ Batterie-elektrisch (BEV) ☐ andere	☐ Benzin ☐ Diesel ☐ Erdgas ☐ Autogas ☐ Hybrid ☐ Plug in-Hybrid (PHEV) ☐ Batterie-elektrisch (BEV) ☐ andere
Fahrleistung (Kilometer pro Jahr)			

Sie besitzen bereits ein Elektroauto (PHEV oder BEV)? > bitte Fragen 4 und 5 überspringen
Sie besitzen noch kein Elektroauto? > bitte Frage 3 überspringen

3. **Wo laden Sie ihr Elektroauto? (Mehrfachnennung möglich)**

	häufig	gelegentlich	nie
zu Hause	☐	☐	☐
am Arbeitsplatz	☐	☐	☐
an öffentlichen Ladepunkten	☐	☐	☐

4. **Können Sie sich vorstellen zukünftig ein Elektroauto zu kaufen?**

- ☐ ja
- ☐ nein
- ☐ weiß nicht

5. **Wo würden Sie ihr Elektroauto voraussichtlich laden? (Mehrfachnennung möglich)**

- ☐ zu Hause
- ☐ am Arbeitsplatz
- ☐ an öffentlichen Ladepunkten
- ☐ weiß nicht

Fragen zum Handlungsfeld Energie

6. **Wie hoch schätzen Sie Ihren jährlichen Stromverbrauch ein?**

- ☐ niedrig
- ☐ normal
- ☐ hoch
- ☐ weiß nicht

7. **Wie hoch schätzen Sie Ihren jährlichen Heizwärmebedarf ein?**

- ☐ niedrig
- ☐ normal
- ☐ hoch
- ☐ weiß nicht

8. **Welche Art von Heizung nutzen Sie?**

- ☐ Erdgas
- ☐ Öl
- ☐ Holz / Pellets
- ☐ Strom direkt / Nachtspeicherheizung
- ☐ Strom-Wärmepumpe
- ☐ Gas-Wärmepumpe
- ☐ andere
- ☐ weiß nicht

9. **Wohnen Sie zur Miete oder in Eigentum?**

- ☐ Miete (> bitte Fragen 10 bis 13 überspringen)
- ☐ Eigentum (> bitte weiter mit Frage 10)

10. **Können Sie sich vorstellen, zukünftig mit einer Photovoltaikanlage selber Strom zu erzeugen?**

- ☐ ja
- ☐ nein
- ☐ habe schon eine Photovoltaikanlage
- ☐ weiß nicht

11. **Können Sie sich vorstellen, zukünftig mit einer Solarthermieanlage selber Wärme zu erzeugen?**

- ☐ ja
- ☐ nein
- ☐ habe schon eine Solarthermieanlage
- ☐ weiß nicht

12. **Können Sie sich vorstellen, anstatt einer Heizung zukünftig mit einem Blockheizkraftwerk selbst Wärme und zugleich Strom zu erzeugen?**

- ☐ ja
- ☐ nein
- ☐ habe schon ein Blockheizkraftwerk
- ☐ weiß nicht

13. **Können Sie sich vorstellen, zukünftig eine elektrisch betriebene Wärmepumpe zu nutzen?**

- ☐ ja
- ☐ nein
- ☐ habe schon eine Wärmepumpe
- ☐ weiß nicht

Angaben zu ihrem Haushalt

14. **Wie viele Personen leben in Ihrem Haushalt?**

____

15. **Wie viele Personen in Ihrem Haushalt sind berufstätig?**

____

16. **Wie viele Personen unter 18 Jahren leben in Ihrem Haushalt?**

____

17. **In welcher Art von Haus leben Sie?**

- ☐ Einfamilienhaus
- ☐ Zweifamilienhaus
- ☐ Mehrfamilienhaus
- ☐ andere

Ende des Dokuments

Source: Wuppertal Institute

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