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Bidirectional charging as a strategy for rural PV integration in China

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Introduction

Bidirectional charging capabilities will soon be offered on more electric vehicle (EV) models, but the market appeal and economic potential of this technology are largely unknown and widely debated. China is the largest EV market, and is also in the midst of a major build-out of distributed rooftop PV. Both of these trends are relatively new: the EV share of vehicle sales has risen from 5 per cent to over 35 per cent in just three years, and rooftop solar has only recently become a major factor in the country's renewable energy expansion. The recency of these two trends, combined with the imminent arrival of bidirectional charging on the market, make it timely to evaluate the potential of combining these three technologies: PV, heat pumps, and bidirectional charging as an energy storage solution to enable home electrification.

This study extends an earlier analysis of rural PV and heat pumps to include an evaluation of the potential for bidirectional EV charging in these areas. Rural China is undergoing a vast build-out of rooftop solar, but also suffers from grid constraints that hinder absorption of midday PV, making local energy storage potentially important for shifting PV overproduction to other hours. Rural residents have less predictable driving schedules than urban commuters, and higher economic motivation to participate in smart charging or bidirectional charging if it saves money on charging. Hence, bidirectional charging could help resolve the problem of midday PV overproduction, providing stored energy for heating and cooling loads, without the excessive capital cost of a home battery system.

The analysis, which draws on county-level data of hourly solar output and climate data, shows:

- **Bidirectional charging offers modest electricity cost savings** in most Chinese provinces studied – around RMB 250 to 300 per year (Euro 33 to 40 per year). This rises to RMB 600 to 700 per year if excess solar production is compensated at lower prices. The upfront cost of bidirectional charging and structure of time-of-use tariffs (including for solar output sent to the grid) would need to decline considerably before bidirectional charging becomes economically attractive for rural households in China.
- **Bidirectional charging increases PV household self-sufficiency** to around 50 to 60 per cent, up from 30 to 40 per cent in the absence of bidirectional charging. However, even with bidirectional charging, households still have excess solar output at certain times, and **do not reach full self-sufficiency**, implying that V2H does not represent a complete solution to the problem of inadequate rural distribution grid investment.

Overall, bidirectional charging remains an area of heated debate in China and abroad, with many touting the benefits and other experts remaining sceptical of its potential. Barriers in China and abroad concern multiple aspects, including consumer acceptance, electricity pricing, market design, taxation, technology standards, and uncertainty about battery degradation. On the flip side, the rapid introduction of new car models and bidirectional-capable charging equipment could accelerate adoption of bidirectional charging in different applications, even if commercial adoption is limited to a small number of vehicles or user types, such as vehicle fleet owners.

China is also likely to increasingly promote vehicle-to-grid interaction. In 2023 several policies have mentioned or alluded to the possibility of using smart charging or V2G. The rapid expansion of rural rooftop PV underway since 2021 under the Whole County PV programme, combined with increasing EV penetration in rural areas, is likely to result in significant policy momentum around promoting bidirectional charging.

1. The overall potential for accelerating China's rural energy transition via integrating PV, heat pumps, and EV charging

1.1 Summary

- As China scales up rural rooftop solar PV under the Whole County PV programme, there are increasing concerns about integrating PV into the grid, given the midday oversupply of solar energy and the weakness of rural distribution grids.
- China is a leader in EV adoption, and a new campaign is promoting EVs and charging infrastructure in rural areas. Many rural residents already own electric two- and three-wheelers. China's power market reforms include several elements that could eventually encourage flexible charging to help absorb local solar output, including more widespread time-of-use pricing.

- V2G is increasingly mentioned in Chinese electricity market and EV policy documents. Chinese and international carmakers are introducing bidirectional-charging-capable models.

1.2 Background on China's rural energy transition

In a sense, China's rural clean energy transition has been underway for decades, as the country's rural areas have undergone a gradual shift away from traditional non-commercial sources of energy such as straw and firewood to coal, oil, and electricity, and then as coal use shifted towards cleaner forms of coal and alternatives to coal such as electricity, gas, and solar. In recent years, electric vehicle adoption has risen in rural China, thanks to the advent of low-cost two- and three-wheeled EVs.

Though there has been clear progress in both reducing emissions of traditional pollutants from rural energy and increasing energy access, the clean energy transition faces immense barriers in rural areas of China. A sharp urban-rural income disparity, as well as huge differences in construction standards and infrastructure, means that rural residents and businesses often opt for the lowest-cost materials and energy sources, even when cleaner options would be more economical when evaluated on a long-term basis. For this reason, rural areas are often dependent on major policy initiatives targeting rural livelihoods, such as the Poverty Alleviation PV programme, or the clean heating campaign that took place as part of the War on Air Pollution in 2013 to 2016.

In terms of fuel mix, rural households have seen a profound shift in energy sources over the past three decades. Coal has fallen as a share of rural household commercial energy use from 93.7 per cent in 1991 to 57.4 per cent in 2012, whereas electricity's share has risen from around 4 per cent to 27 per cent over a similar time frame, and oil rose from 2 per cent to 15 per cent. Such commercial sources of energy also largely displaced traditional biomass such as straw and firewood, which accounted for 77 per cent of household energy consumption in 1990 but only 38 per cent in 2015.[1]

In June 2021 China launched the Whole County PV Programme targeting rural areas.[2] The programme requires participating counties install rooftop solar on 50 per cent of government buildings, 40 per cent of public buildings such as schools and hospitals, 30 per cent of commercial and industrial buildings, and 20 per cent of households. The main benefit of participation is that counties are permitted to organize a single tender for a company that will install solar across all the required rooftops, with the potential to substantially reduce the various soft costs – customer acquisition, planning approvals, grid connection procedures – that normally burden smaller rooftop solar installations. By September 2021, over 650 counties or other entities had joined the programme,[3] accounting for roughly half of China's counties and around one quarter of the country's population.

The adoption of the Whole County PV programme has substantially increased an already apparent trend towards distributed solar PV and especially rooftop solar PV in China, which had initially focused on large utility-scale PV plants in remote regions. In 2022, the National Energy Administration reported that China added a total of 87 GW of solar PV, of which 51.1 GW was distributed. Of the latter figure, roughly half was household rooftop PV. Much of the new rooftop PV has been concentrated in the provinces most active in the Whole County PV programme, particularly Henan, Hebei, Shandong, Anhui and Jiangsu provinces, all in East Central China. Distributed PV (both commercial and residential) now makes up around 40% of China's solar capacity.[4]

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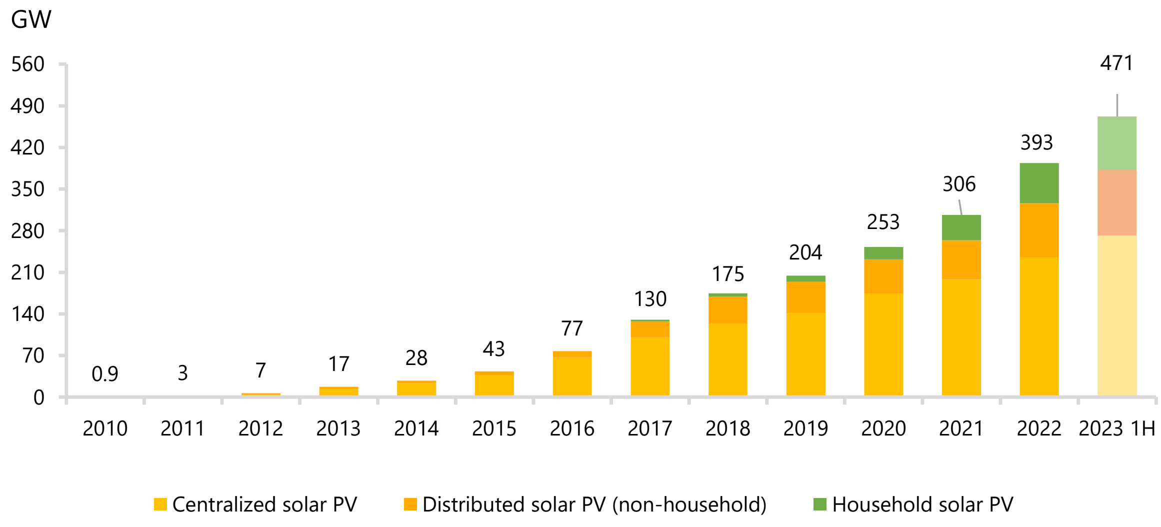
[1] Xinxin Zhang et al., 'A Review on the Rural Household Energy in China From 1990s—Transition, Regional Heterogeneity, Emissions, Energy-Saving, and Policy,' Front. Energy Res. 10, 25 May 2022, at https://doi.org/10.3389/fenrg.2022.907803.

[2] '国家能源局综合司关于报送整县（市、区）屋顶分布式光伏开发试点方案的通知 [NEA Comprehensive Department Issues Whole County/City/District Rooftop Distributed PV Pilot Plan],' National Energy Administration, 20 June 2021, at http://www.chic.org.cn/home/index/detail?id=1100.

[3] "国家能源局综合司关于公布整县（市、区）屋顶分布式光伏开发试点名单的通知 [NEA Comprehensive Department Issues Whole County/City/District Rooftop Distributed PV Pilot List]," National Energy Administration, 8 September 2021, at http://www.gov.cn/zhengce/zhengceku/2021-09/15/content_5637323.htm.

[4] '2022 年光伏发电建设运行情况 [2022 PV electricity additions situation],' National Energy Administration, 17 February 2023, at http://www.nea.gov.cn/2023-02/17/c_1310698128.htm.

Figure 1: China's total installed solar capacity by category



Source: OIES, based on NEA data

Though the programme is on track to deliver a major increase in rural solar PV capacity, aside from policy barriers the inadequate distribution grids in many rural areas pose a challenge to further scaling up the programme. The NEA, in its policy document noting examples of local governments blocking new PV installations, stated that 'in the process of promoting distributed photovoltaics in the whole county, some areas have experienced the phenomenon that the distributed power generation connected to the grid exceeds the carrying capacity of the grid in a short period of time, and applications for and grid connections of distributed photovoltaics have been postponed.'[5] In other words, the rapid build-out of rooftop PV has resulted in officials blocking new additions due to insufficient grid capacity.

Electricity pricing is one area where policy makers have sought to make adjustments that might help with the absorption of distributed solar. In the 2010s, China already had widespread time-of-use pricing available at the retail level, and peak rates have trended higher and valley rates lower, with peak rates currently around 70 per cent above shoulder rates, valley rates 58 per cent below shoulder rates, and in some provinces a super-peak rate in the early evening and sometimes mid-morning 20 per cent above the peak rate.[6] In the NDRC/NEA power pricing work plan for 2023, the central government urges provinces, localities, and grid companies to increase the granularity of retail TOU electricity prices from three to five daily price segments to more than five, and to adapt them to reflect both peak demand and wind and solar output conditions.[7] Provinces across China have begun to offer time-of-use prices with low midday power prices, whereas previously low prices were mainly offered at night. As of mid-2023, at least 10 provinces had low midday retail pricing to encourage shifting loads to periods when surplus solar is available.[8]

Time-of-use pricing has the potential to incentivize self-consumption of midday solar and, potentially, installation of energy storage, but it has significant limitations. First, time-of-use rates are typically set far in advance, such as for an entire year or longer. Variable renewable energy can see dramatic changes in output on a daily or even sub-hourly basis. Some days may have a surplus of midday solar output, while

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[5] '国家能源局：不得以任何方式增加新能源不合理投资成本！ [National Energy Administration: Do not increase the unreasonable investment cost of new energy in any way],' China Power Net, 19 April 2023, at http://mm.chinapower.com.cn/tynfd/zcdt/20230426/198097.html.

[6] '全国 23 个省市完善分时电价机制政策汇总 [Comprehensive summary of 23 provincial policies to improve time-of-use pricing mechanisms],' In-en.com, 9 December 2021, at https://m.in-en.com/article/html/energy-2310448.shtml.

[7] '发改委、能源局发布关于做好 2023 年电力中长期合同签订履约工作的通知 [NDRC, NEA publish 2023 mid-to-long-term contract coverage work notice],' National Development and Reform Commission, 2 December 2022, at https://zfxxgk.ndrc.gov.cn/web/iteminfo.jsp?id=19042.

[8] '10 省中午执行谷段电价！[10 provinces have instituted midday trough power prices],' WeEnergy Net, 1 August 2023, at https://mp.weixin.qq.com/s/S0M8tB6jd9vao8skngWvMg.

other days have a shortage of electricity supply over the same hours. This lack of flexibility could worsen the problem of insufficient distribution grid capacity.

To some extent, electrification of heating and transport can result in greater demand for building out local grids, but could also increase self-consumption of PV. China's winter PV output as a share of summer PV output is relatively strong compared to other world regions, heat pumps on a stand-alone basis can only result in self-consumption of PV output of 20 per cent to 30 per cent in the top provinces of the Whole County PV programme. Adding two hours of energy storage can boost this self-consumption rate to 40 percent to as high as 60 per cent in those provinces, but storage capital costs result in a substantially longer payback versus adoption of heat pumps paired with PV.[9]

1.3 EV adoption in rural China

China is the world's leading manufacturer of EVs and the largest market for EVs. In China, the term New Energy Vehicle (NEV) includes pure battery-electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell vehicles (FCVs), the bulk of NEVs are either BEVs or PHEVs. Although China's NEV market share stands above 30%, it has seen a dramatic increase in the past three years, rising from around 1 million NEV sales annually in 2020 to 5.8 million in 2022. In September 2023, the Ministry of Industry and Information Technology set a target or forecast for NEV sales of 9 million for the full year, which would represent annual growth of around 50 per cent.[10]

In part due to their relatively low cost, currently two- and three-wheeled EVs are common in rural areas. In a 2022 survey of a rural agricultural village (population 1,140) in Shandong province, researchers found 560 two-wheeled electric vehicles, 400 three-wheeled electric vehicles, and 50 four-wheeled electric vehicles—plus 170 four-wheeled internal combustion vehicles.[11] Hence, rural areas are not necessarily lagging in EV adoption, at least when considering smaller vehicles. Furthermore, while car ownership in China's rural areas is low compared to urban areas, it is rising rapidly, from fewer than 2 per 100 households in 2007 to over 25 per 100 households in 2020.[12]

Typical three-wheeled vehicles range from passenger tricycles to small cargo haulers, and shade gradually into small four-wheeled cargo haulers with similar size and battery capacity. The smallest personal EV tricycles range from RMB 2500-6000, and the mid-range cargo three-wheeled vehicle ranges from RMB 10,000-15,000. Battery sizes marketed for these vehicles range from as little as 1.5 kWh to 15 kWh.[13]

In 2023, China's central government has taken steps to encourage greater uptake of EVs in rural areas. On 15 June 2023, the Ministry of Industry and Information Technology (MIIT) together with NEA, NDRC, and the Ministry of Commerce announced a series of 2023 New Energy Vehicles (NEV) for the Countryside Activities. The series of activities, to be coordinated by the China Association of Auto Manufacturers (CAAM), includes having EV makers recommend EV models suitable for the rural market, formulating promotional policies, improving after-sales services in rural areas; coordinating charging providers to improve rural charging facilities and launch charging preferential policies; and organizing live car sales or virtual exhibitions.[14]

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[9] Anders Hove, 'Synergies between China's Whole County PV program and rural heating electrification,' Oxford Institute for Energy Studies, May 2023, at https://www.oxfordenergy.org/publications/synergies-between-chinas-whole-county-pv-program-and-rural-heating-electrification/.

[10] '工业和信息化部等七部门关于印发汽车行业稳增长工作方案 [MIIT and seven ministries issue auto sector stable growth plan],' Ministry of Industry and Information Technology, 1 September 2023, at https://mp.weixin.qq.com/s/p52GfxG7ajFVW-qWCluvvQ.

[11] Bing Xue et al., "Pursuing a low-carbon rural energy transition in China and Germany," Deutsche Gesellschaft für Internationale Zusammenarbeit, May 2022, at https://www.energypartnership.cn/fileadmin/user_upload/china/media_elements/publications/2022/GIZ_Rural_energy_transition_report_EN.pdf.

[12] Yan Wang et al., 'Impact of the Built Environment and Bicycling Psychological Factors on the Acceptable Bicycling Distance of Rural Residents,' Sustainability, 11, 2019, at https://doi.org/10.3390/su11164404; Yan Li, 'Vehicle ownership, sustainable mobility and well-being in rural China,' Environment, Development and Sustainability, 22 September 2023, at https://doi.org/10.1007/s10668-023-03890-x; 'Number of cars per 100 households in urban and rural China between 2019 and 2020,' Statista, 23 March 2023, at https://www.statista.com/statistics/233678/number-of-cars-per-100-households-in-china-by-income/.

[13] Author analysis, based on Taobao prices as of August 2023.

[14] '关于开展 2023 年新能源汽车下乡活动的通知 [Developing the 2023 New Energy Vehicles for the Countryside Activities,' Ministry of Industry and Information Technology, 23 June 2023, at https://www.gov.cn/zhengce/zhengceku/202306/content_6886788.htm.

1.4 Smart charging in China

In the past several years, as EV adoption has surged in China, prices for charging have undergone significant changes. Early on, China adopted time-of-use pricing for charging, particularly public charging, and recently peak prices have risen. Charging prices are reportedly up by as much as 80% in some cities versus just a few years prior. Many drivers are choosing to charge at night to avoid high costs.[15] In addition, during power shortages, such as in Sichuan in mid-2022, local officials and grid companies shut down chargers entirely at midday, or even for several days, stranding drivers and encouraging some to switch back to driving internal combustion vehicles.[16] Effectively, prioritizing EV chargers for outages or throttling charging speeds constitutes a form of uncompensated and involuntary demand response, while also sending a negative signal to consumers about the potential unreliability of EV chargers during emergencies or power shortages.

In terms of charging behaviour, as in most countries Chinese EV drivers rarely use a large proportion of battery capacity in their daily routines. A study of driving and charging patterns in Beijing found that EV owners typically discharge only around 13% of battery capacity daily, though there is substantial seasonal variation of up to 20%.[17] Regarding driving patterns, parking, and charging in Beijing, most drivers seek to charge almost full, but rarely arrive to charge at a low state of charge (SOC). Most charging events appear to be opportunistic, based on timing and convenience, as opposed to necessity.

1.5 V2G policy in China

Vehicle-to-grid technology has received significant attention in China. A study of V2G in Shanghai, where several smart charging pilots have taken place, found there are substantial economic benefits from using V2G to capture low-priced electricity, but far greater benefits to pairing V2G with solar PV as opposed to only TOU. [18] A separate study of smart charging and V2G have substantial potential to reduce carbon emissions in rural Ruicheng county in Shanxi province, a location noted for its early adoption of renewable energy and efforts to deploy renewable energy in rural areas as a poverty alleviation strategy.[19]

Modelling studies have also found substantial benefits of adopting V2G. Research has included developing planning models to optimize deployment of V2G given constraints in the distribution grid as well as the current and future deployment of PV and EVs.[20] Studies on the overall impact of smart charging and V2G given forecasts of RE penetration and carbon emissions of the power sector have found that V2G offers benefits beyond those of smart charging: 'Although smart charging is a cost-efficient EV [demand response] coordination strategy in the short term, V2G could be more economically attractive in the long run.'[21]

In Chinese media, there exists a lively debate about the costs and benefits of V2G. Some major experts have touted the benefits of V2G for helping absorb intermittent renewables. Arguing in favour of V2G, Hang Hewu of the Innovation Center for Energy and Transportation (ICET) notes that by 2040 there could be 300 million EVs on the road in China with battery capacity of 20 billion kWh, sufficient to balance the daily renewable energy output at a national level provided V2G becomes widespread.[22] Tsinghua University EV expert Ouyang Minggao has proposed a three-step process for adopting V2G, starting with establishing industry standards and safety measures and then beginning to upgrade charging infrastructure while

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[15] Cao Tingting, '开电车，不省钱了吗？ [Does driving an EV no longer save money?]' Super Electric Lab, 11 August 2023, at https://mp.weixin.qq.com/s/Se4He80B4kcZ_m7qgQNCsA.

[16] Zeyi Yang, 'China's heat wave is causing havoc for electric vehicle drivers,' MIT Technology Review, 26 August 2022, at https://www.technologyreview.com/2022/08/26/1058727/chinas-heat-wave-electric-vehicle/.

[17] Yang Zhao et al., 'Assessment of battery utilization and energy consumption in the large-scale development of urban electric vehicles,' Proceedings of the National Academy of Sciences (PNAS) 118, 19 April 2021, at https://doi.org/10.1073/pnas.2017318118

[18] Jianhong Chen et al., 'Strategic integration of vehicle-to-home system with home distributed photovoltaic power generation in Shanghai,' Applied Energy, 263, 1 April 2020, at https://doi.org/10.1016/j.apenergy.2020.114603.

[19] Dexi Sun and Jianjun Xia, 'Research on road transport planning aiming at near zero carbon emissions: Taking Ruicheng County as an example,' Energy 263, 15 January 2023, at https://doi.org/10.1016/j.energy.2022.125834.

[20] Lizi Luo et al., 'Coordinated allocation of distributed generation resources and electric vehicle charging stations in distribution systems with vehicle-to-grid interaction,' Energy 192, 1 February 2020, at https://doi.org/10.1016/j.energy.2019.116631.

[21] Jian Liu and Caifu Zhong, 'An economic evaluation of the coordination between electric vehicle storage and distributed renewable energy,' Energy 186, November 2019, at https://doi.org/10.1016/j.energy.2019.07.151.

[22] Hang Hewu, '道路交通碳排放或将在 2025 年前达峰 [Road transport emissions will peak in 2025],' China Clean Transportation Partnership, 9 August 2023, at https://mp.weixin.qq.com/s/v0h_dsYJ0H78ALmxgHnGUw.

adopting smart charging by 2030, then proceeding with V2G on major traffic corridors and charging stations by 2040.[23] Arguing against V2G, some Chinese commenters have argued that the economics will never pan out, either for home chargers or for commercial or grid players.[24] One reason cited is cost: converting a home charger to V2G carries an added cost of RMB 7,000, and while private EVs spend most time parked, given that most cars charge overnight there are relatively few hours in the year when peak-shaving needs overlap with parked cars that have available battery capacity for providing V2G.[25]

Other commonly-cited obstacles to V2G cited include the high cost of converting existing charging infrastructure, concerns about safety, lack of consumer interest, concern about battery degradation (whether or not such concerns are technically accurate), lack of V2G at home chargers and, for EVs that mainly slow charge at home, lack of time parked at home for injecting power back to the grid (especially midday, when high electricity prices could make this attractive). Aggregators can resolve some issues around coordination of market players,[26] but there is no near-term solution to other obstacles. For example, regulations and pricing for V2G might require power market reforms and supporting policies from the central and local governments and grid companies. (See below for discussion of Chinese power market policies and EV charging.) Commenters on the practicalities of V2G have noted the cautionary experience of stationary energy storage in China, which has faced a patchwork of changing local regulations that hinder the development of a national policy.[27]

Meanwhile, major companies operating in China have promoted V2G in new car models. Nissan has long boasted the bidirectional charging capability of the Nissan Leaf, although Nissan only began selling a bidirectional home charger in 2022.[28] Renault, Ford and Volkswagen have all stated they are pursuing V2G, and Chinese domestic brands that have explored V2G or made V2G announcements include Great Wall Motors, BYD, Geely, FAW, Xiaopeng, NIO, and Seres Automobile.[29] V2G was also a major theme at the 2023 Shanghai auto show, including V2G technology showcased by both GAC Aon and Dongfeng Motors.[30] GAC Aon has also touted the potential benefits of V2G for individual vehicle owners. Most recently, in July 2023, battery-swap pioneer NIO completed its first 20 V2G charging spots (at the Qilian National Park pilot, mentioned below), launched a 20 kW version of its V2G charger, and touted its plans to operate as a virtual power plant.[31]

V2G remains at the early pilot stage in China. The largest V2G pilot has taken place in 2022 in Qilian National Park, with a V2G-capable charging station co-located with a PV station.[32] Other V2G pilots have mainly been carried out by State Grid at its own facilities or large industry parks. As of April 2021, State Grid Electric Vehicle Service Company reported that it had completed 42 V2G pilot projects in 15 provinces and cities including Zhejiang, Shanghai, Jiangsu, and Hebei, with 612 V2G terminals deployed and nearly 4,000

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[23] Zhang Yueyue and Wang Wei, '欧阳明高：从有序充电到消纳绿电，V2G 技术应更有作为,' Energy Comments, 7 March 2022, at https://mp.weixin.qq.com/s/q9lEleDL5Dpn4w5FH7uJBw.

[24] 'V2G 这门生意，可能真的不是想象中那样的美 [The V2G dream may not be as beautiful as people imagine],' Power Meow, 29 August 2022, at https://mp.weixin.qq.com/s/mwPFfzH0znG8VBTXL-LA7Q.

[25] Based on products available on Taobao in mid-2023 bidirectional home charger, such as the Star Charge 220 Volt, 6.6 kW bidirectional DC charger, could cost up to RMB 20,000, lower but comparable to prices for similar equipment in Europe.

[26] 'V2G 技术介绍系列 [V2G technology examples],' EV Charging Home, 15 March 2023, at https://mp.weixin.qq.com/s/N2Iavwd-fu63JVh6ZI9HQQ.

[27] Liu Guanwei, '为什么我看好电动汽车有序充电，不看好车电互联（V2G） [Why am I optimistic on orderly charging and not on V2G?],' Sohu, 2020, at https://www.sohu.com/a/395114261_100209427.

[28] Umar Shakir, 'The Nissan Leaf can now officially power buildings using bidirectional charging,' The Verge, 12 September 2022, at https://www.theverge.com/2022/9/12/23349971/nissan-leaf-bidirectional-charging-approved-v2h-v2g-fermata-energy.

[29] Zhang Changlong and Shi Xueqian, 'V2G：电动汽车的"能源 V2X" [V2G: EV's energy V2X],' Severn Transport Net, 10 August 2023, at https://mp.weixin.qq.com/s/4pG-hqgZbbh0s21IyisShQ.

[30] '车企纷纷布局 V2G，电动车车主躺赚时代到来？ [As more car companies adopt V2G, is the V2G era coming to EV owners?],' Global Zero Carbon Research Centre, 20 April 2023, at https://mp.weixin.qq.com/s/AN-bQTNcK5jp0afW0OM2sg.

[31] Yusuf Latief, 'Self-consumption V2G system launched for Chinese national park ,' Smart Energy International, 22 August 2023, at https://www.smart-energy.com/industry-sectors/electric-vehicles/self-consumption-v2g-system-launched-for-chinese-national-park/; 'NIO launches V2G charging pile, new pricing standard for battery swap service,' Gasgoo, 23 July 2023, at https://autonews.gasgoo.com/m/70024822.html.

[32] '光伏+新能源车新应用！蔚来全球首个 V2G 光伏自循环补能体系落成 [PV + EVs: NIO completed the world's first V2G PV system],' SolarZoom, 20 August 2023, at https://mp.weixin.qq.com/s/--Crr3fPlXKgnAogOlqAOA.

electric vehicles in total. The largest State Grid demonstration was at Baoding Great Wall Automobile Industrial Park, which installed 50 sets of 15-kW DC V2G charging piles.[33]

Given the limitations on rural distribution grids, and efforts in 2023 to encourage adoption of EVs in rural areas, there has been greater attention recently to the issue of integrating EVs via smart charging, demand response programmes, or V2G – with the latter confined to small pilots and studies. The 2020 New Energy Vehicle Development Plan (2021-2035) called local governments to launch demonstration of V2G and to support 'other policies to achieve efficient interaction between new energy vehicles and grid energy, and reduce the electricity costs of new energy vehicles.' The Plan also called for coordinating EV charging with wind and solar output and 'encouraging the construction of distributed PV-storage-charging-and-discharging multi-functional integrated stations.'[34]

In October 2020, the Society of Automobile Engineers presented a New Energy Vehicle Roadmap 2.0, commissioned by the Ministry of Industry and Information Technology (MIIT), that laid out various targets developed through an industry-wide expert consultation.[35] The Roadmap, which includes the present 20% NEV target for 2025, also mentions a timetable for smart charging and V2G, namely to achieve 'interactive commercialization of V2G electric energy with regular charging facilities in residential areas and parking lots' by 2030 and reach 'basic dissemination of V2G electric energy interactive capability in parking facilities such as residential areas and the application of solar charging in industrial areas' by 2035. New vehicles and newly-added chargers would all have V2G capability by 2035.

Since 2022, the pace of policies mentioning EV smart charging and V2G has picked up. In early 2022, the NDRC and several other ministries issued a policy opinion on EV charging service quality.[36] The policy calls for 'promoting pilot demonstrations [of smart charging], explore implementation paths for new energy vehicles to participate in the electricity spot market, and study and improve trading and dispatch of new energy vehicle consumption and green power storage.' The policy says companies and industry parks should pilot 'integrated PV-storage-charging-discharging,'[37] which could refer to bidirectional charging and/or V2G. Zhejiang, Henan, and Sichuan have since instituted pilots under the 'integrated PV-storage-charging-discharging' heading that included V2G,[38] and Zhejiang, Hebei and Shandong have included the concept in provincial NEV plans, including for rural charging infrastructure in the case of Shandong.[39]

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[33] 'V2G 技术介绍系列 [V2G technology examples],' EV Charging Home, 15 March 2023, at https://mp.weixin.qq.com/s/N2Iavwd-fu63JVh6ZI9HQQ.

[34] '新能源汽车产业发展规划（2021—2035 年） [New Energy Vehicle Manufacturing Development Plan],' National Development and Reform Commission, November 2020, at https://www.gov.cn/zhengce/content/2020-11/02/content_5556716.htm.

[35] '节能与新能源汽车技术路线图 2.0 正式发布 [Energy-efficient and New Energy Vehicle Technology Roadmap 2.0 formally released],' China Society of Automotive Engineers, 27 October 2020, at https://www.sae-china.org/news/society/202010/3957.html; Li Jun, '节能与新能源汽车技术路线图 2.0 [Energy-efficient and New Energy Vehicle Technology Roadmap 2.0],' PowerPoint Summary and Evaluation, Society of Automotive Engineers, 17 February 2022, at http://www.evinchina.com/uploadfile/file/20220217/2022021709402808334.pdf; China Energy-saving Vehicle & NEV Roadmap 2.0: Curbing Carbon Emissions for a Green Society,' Marklines, 23 April 2021, at https://www.marklines.com/en/report_all/rep2142_202104#report_area_6.

[36] '关于进一步提升电动汽车充电基础设施服务保障能力的实施意见 [Opinions on Further Raising EV Charging Infrastructure Service],' National Development and Reform Commission, 10 January 2022, at https://www.ndrc.gov.cn/xxgk/zcfb/ghxwj/202201/t20220121_1312634.html.

[37] In Chinese: '光储充放一体化.'

[38] '浙江: 14 个光储充一体化项目建成投产,2023 年将重点推广 [Zhejing: 14 integrated PV-storage-charging projects built; will strongly promote in 2023],' Kesolar, 30 May 2023, at https://www.kesolar.com/headline/229970.html; '西南首个 "光储充放"一体化停车场在四川成都投运 [Southwest's first integrated PV-storage-charging-discharging parking lot starts operating in Chengdu, Sichuan],' Beijixing, 21 September 2023, at https://m.bjx.com.cn/mnews/20230921/1333416.shtml; '国家电投调研全国首个风光储充放一体化综合智慧零碳电厂 [CPIC researches nation's first wind-solar-storage-charging-discharging integrated smart grid low carbon power plant],' Beijixing, 10 August 2023, at https://m.bjx.com.cn/mnews/20230810/1324786.shtml.

[39] '河北：支持开展光储充放充电站技术创新与试点应用 [Hebei: Support Development of PV-Storage-Charging-Discharging Station Technology and Pilots],' Beijixing, 17 August 2023, at https://m.bjx.com.cn/mnews/20230817/1326310.shtml; '省政府新闻办举行新闻发布会，解读山东省推动新能源汽车下乡三年行动计划（2023-2025）[Provincial government press conference on the Shandong Promotion of New Energy Vehicles in the Countryside Three-Year Plan],' Shandong Provincial Industry and Information Department, 4 September 2023, at http://gxt.shandong.gov.cn/art/2023/9/4/art_299272_10335468.html.

A draft policy released in March 2023 encourages participation of EVs in demand response, encourages aggregation of EV loads, and encourages rural areas to participate.[40] A May 2023 policy issued by NDRC explicitly mentions V2G.[41] The policy states that China will promote rural EVs to include smart charging capability and encourage vehicles to come with smart home chargers as a default. China will study 'two-way interaction between electric vehicles and the power grid (V2G), and coordinated control of PV, storage and charging; and explore the construction of charging infrastructure that provides integrated photovoltaic power generation, energy storage, and charging in rural areas where the utilization rate of charging piles is low.' Charging infrastructure policies are also mentioning the need to integrate EV charging with renewables. A June 2023 charging infrastructure policy issued by the State Council noted the need to integrate charging with storage and PV, as well as to include it in demand response.[42] Most recently, in November 2023, the NDRC issued a policy draft on new energy storage that explicitly encourages the integration of PV, storage, and EV charging.[43]

Table 1: Timeline of key 2023 policies on charging infrastructure relating to rural areas or power markets

Date	Policy	Issuer	Relates to
March 2023	Electricity Demand-side Management Rules: Draft for Comment	NDRC	Demand response, rural EV charging
• encourages participation of EVs in demand response, encourage aggregation of EV loads, and encourage rural areas to participate in demand response			
May 2023	Opinions on Accelerating Charging Infrastructure Construction and Increasing Support for New Energy Vehicles in the Countryside and Implementing the Rural Revitalization Programme	NDRC, NEA	Charging infrastructure, rural EV charging, smart charging, V2G
• Promote rural EVs to include smart charging capability and smart home chargers • Study two-way interaction between electric vehicles and the power grid (V2G), and coordinated control of PV, storage and charging			
June 2023	Opinions on Further Building Out Charging Infrastructure System	China State Council	Charging infrastructure, smart charging
• Calls for implementation of time-of-use prices for EV charging • Guide users to participate in demand response and orderly charging • By 2030, exempt smart charging and swap stations from electricity demand charges.			
July 2023	Opinions on Raising the Quality of Rural Electricity Grid Stability	NDRC, NEA, National Rural Revitalization Dept	Rural renewable integration
• strengthen grids to handle increased distributed renewables, and raise local consumption of renewable energy			

Source: OIES, 2023

1.6 Expert interviews on the potential for bidirectional charging:

As part of this study, European and Chinese EV and EV charging experts were interviewed about the potential for bidirectional charging in rural areas and barriers to its adoption. Interviewees in China expressed that relatively low incomes, narrow rural roads, but good private charging conditions are the main

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[40] '电力需求侧管理办法: 征求意见稿 [Electricity Demand-side Management Rules: Draft for Comment],' National Development and Reform Commission, 5 March 2023, at https://yyglxxbs.ndrc.gov.cn/file-submission/20230519102727235060.pdf.
[41] '关于加快推进充电基础设施建设 更好支持新能源汽车下乡和乡村振兴的实施意见 [Opinions on Accelerating Charging Infrastructure Construction and Increasing Support for New Energy Vehicles in the Countryside and Implementing the Rural Revitalization Programme],' National Development and Reform Commission and National Energy Administration, 14 May 2023, at https://www.ndrc.gov.cn/xxgk/zcfb/tz/202305/t20230517_1355814.html.
[42] '关于进一步构建高质量充电基础设施体系的指导意见 [Opinions on Further Building Out Charging Infrastructure System],' China State Council, 8 June 2023, at https://www.gov.cn/zhengce/content/202306/content_6887167.htm.
[43] '关于促进新型储能并网和调度运用的通知征求意见稿 [Notice on Promoting New Energy Storage Grid Connection, draft for comment],' National Development and Reform Commission, 20 November 2023, at http://zfxxgk.nea.gov.cn/2023-11/20/c_1310751675.htm.

factors determining that the purchase preference in China's rural areas are low-cost, short-range electric vehicles. Whilst migrant workers and farmers who work close to their home tend to prefer two wheeled electric vehicles, farmer vendors of agricultural products tend to prefer three- or four wheeled vehicles. All these groups are quite different from urban areas in terms of vehicle ownership and usage.

In terms of driving patterns, Chinese EV expert interviewees believe in rural areas EVs may be used in less regular time periods than those in urban areas, because rural residents need to carry out a variety of agricultural activities, such as field farming or transportation of agricultural products. This is in contrast to cities, where EVs are mainly used for commuting to and from work or other daily travel needs, or for social and recreational activities on weekends. Rural EV usage patterns are less predictable and more seasonal.

Interest in smart charging or bidirectional charging: The majority of Chinese interviewees believe that many rural EV owners have interest or potential to participate in smart charging if offered. Three interviewees said their estimates are based on certain conditions: the availability of reliable equipment and infrastructure, existence of clear and supportive policy, ease of use, and whether there are economic incentives.

> If we can provide comprehensive technical and infrastructure support, I estimate that more than 50 per cent of rural electric vehicles will be willing to participate in smart charging, because their charging starting time distribution is more discrete and flexible. Compared with the nine-to-five daily routine of urban electric car owners, the proportion of rural electric vehicle owners participating in smart charging should be significantly higher than that in urban areas – especially if subsidies or benefits are sufficient to allow participants to save money and earn money [such as through bidirectional charging].

In addition, most interviewees believe that if the above conditions are met and the price for smart charging or bidirectional is appropriate, or if there are subsidies or other market-based or income-based incentives for peak regulation, the uptake of smart charging or bidirectional charging will be greater in rural areas than that in cities. This relates to the availability of private charging facilities in rural areas, and to greater sensitivity to economic incentives in rural areas.

> I would guess 70 to 80 per cent of rural users would like to participate in smart charging if there are good smart charging policies in place. For those EV owners with private charging, the proportion of participation should be larger than in cities. Although participating in V2G entails more investment costs, two-way charging and discharging can provide flexible regulation resources for the power system, and bidirectional charging has greater benefits than smart charging alone. For rural EV owners with private charging… if the grid companies or the government bear the investment cost, a higher proportion of EV owners – probably 80 to 90 per cent – would participate in the interaction.

Barriers: The main barriers mentioned by interviewees include grid capacity constraints for EV charging generally (though bidirectional charging or smart charging could also ameliorate such constraints), a lack of business models for smart charging or bidirectional charging given China's current power retail pricing, and low awareness and knowledge of smart charging in rural areas.

Interviewees mentioned that provinces with the highest incomes and most well-developed charging infrastructure are most likely to adopt smart charging or bidirectional charging in ways that would help integrate renewable energy or reduce grid capacity constraints. Rural areas of Beijing and Shanghai municipalities, as well as rural areas in Guangdong, Zhejiang and Jiangsu would fit this profile.

For residents in these regions, the key issue lies in present driving needs – which tend to encourage EV owners to minimize cost and battery size – as opposed to the economics of smart charging or bidirectional charging. If adopting a larger vehicle or a larger battery becomes more economical because of the availability of V2G, this would will be fewer obstacles for rural buyers to use electric vehicles. Obtaining a lower charging price by charging from distributed solar PV could also encourage greater EV uptake in general. Hence, the present structure of rural EV ownership or driving and charging patterns should not be taken as a given, but rather as a dynamic situation that will likely evolve as distributed energy and economic incentives for smart charging or bidirectional charging become more widespread.

> But because the driving patterns are so varied and heterogeneous, it is a question as to what the future will be, and whether it will be the same as in the past. Because the driving habits and needs

of different groups may be different, analysis based on generalization and reasoning from the present is often problematic.

In summary, Chinese EV experts contacted for this study believe that because rural EV owners are price sensitive, they are very likely to participate in smart charging or bidirectional charging even if the revenue from participation in it is not very high, but the upfront equipment cost and present design of electricity prices in rural areas represent the most important barriers.

1.7 Summary: Smart charging and V2G are at an early phase, but progress accelerating

Smart charging is far from widespread worldwide and in China, mainly reliant on static time-of-use (TOE) pricing, with a few countries experimenting with dynamic pricing. China smart charging often focuses on industry demand response and, in some examples, has included power cuts during shortages that could risk damaging consumer acceptance of EVs. In a few cases, China has also piloted VPPs, albeit at a small scale.

V2G remains an area of heated debate, with many touting the benefits and other experts remaining sceptical of its potential. Barriers remain in multiple aspects, including consumer acceptance, electricity pricing, market design, taxation, technology standards, and uncertainty about battery degradation. On the flip side, the rapid introduction of new car models and bidirectional-capable charging equipment could accelerate adoption of bidirectional charging in different applications, even if commercial adoption is limited to a small number of vehicles or user types, such as for large EV fleets.

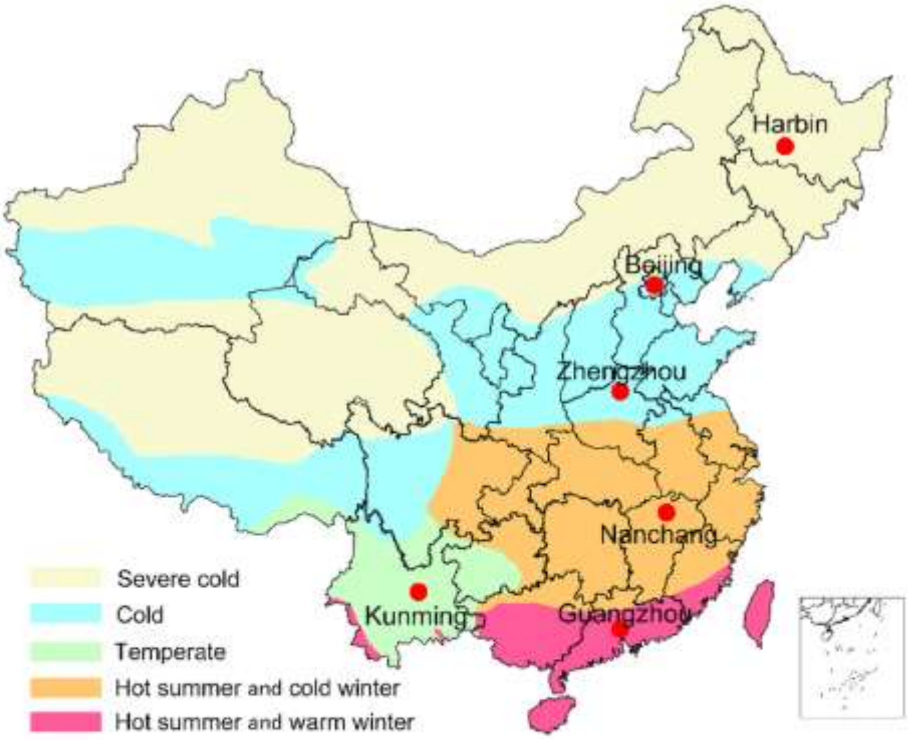
Regarding rural integration of EV charging with distributed PV, there are few concrete policies, though in 2023 several policies have mentioned or alluded to the possibility of using smart charging or V2G in rural areas or to balance renewables in rural areas. The rapid expansion of rural rooftop PV underway since 2021 under the Whole County PV programme, combined with increasing EV penetration in rural areas, is likely to result in significant developments, in terms of both policy and practice, that **could ultimately translate to policy momentum around promoting V2G specifically for integrating distributed rooftop PV** at the village or household levels.

2. Modelling and Analysis of Combining V2H with PV and heat pumps

- This chapter uses a model of hourly solar and climate data for the county level to evaluate the economic benefits of combining PV with EV charging in vehicle-to-home (V2H) mode. The purpose of bidirectional charging in this case is to both increase self-consumption of PV electricity, thereby reducing the need to upgrade local distribution grids, and to produce electricity cost savings for the household.
- The analysis finds that under the base case a household would receive modest electricity cost savings of around RMB 300 per year (Euro 39 per year) from adopting V2H bidirectional charging. V2G would have limited or no impact on the ability to complete daily trips while charging mainly at home.
- V2H produces more benefits in regions with reasonable winter solar output and higher winter heating load, and produces fewer benefits in regions with high cooling loads and lower heating loads.

This study builds on prior quantitative analysis that found a strong synergy between China's Whole County PV Programme and the use of electric air-source heat pumps for heating and cooling in the provinces of East China where the Whole County PV Programme is most active. Generally, the provinces of East China fall into either the Hot Summer Cold Winter climate zone or the Cold climate zone. That analysis found that heat pumps offered attractive payback periods for homes built to Chinese building standards with PV already installed.

Figure 2: Map of China climate zones



Source: Fan Xinying et al., *Energies*, 2020 (CC)

Note: This map is for illustrative purposes and does not represent the expression of any opinion concerning the legal status or sovereignty of any country or territory, the delimitation of frontiers or boundaries or the names of any territory, city or region.

The addition of an electric heat pump to a home with rooftop PV already installed can help absorb more of the electricity produced by the PV panel than would otherwise be the case. Because most of China has more balanced winter and summer PV output than in other countries – such as the US or Europe – PV can be used for relatively more winter heating load than elsewhere. However, although the combination of an electric air source heat pump (ASHP) can help improve the integration of electricity produced by distributed rooftop PV systems under the Whole County PV Programme, the analysis also showed that self-consumption rates only improved modestly. For all climate zones, home energy storage was required to improve PV self consumption beyond 30 per cent of the electricity produced by PV. Further, since energy storage systems would roughly double the cost of the installation of a heat pump, the payback periods appeared unattractive.

This study attempts to resolve this problem by modelling the addition of an electric vehicle battery with or without the ability to operate in vehicle-to-home (V2H) mode – in other words, with or without bidirectional charging capability. If an EV charges at home without V2H, it will still help absorb output from the home PV system, potentially increasing the PV self-consumption rate. This will reduce the share of electricity the PV system can provide, but potentially improve its economics, depending on when the vehicle charges and the time-of-use electricity prices for both consuming electricity and, for solar, injecting electricity from PV into the grid at times of surplus production.

If the EV and home charging system have the ability to charge bidirectionally, the EV can also serve as a battery to store surplus PV output, in place of a home energy storage system. Electric vehicles are already commonplace in rural China, although most are two- and three-wheeled vehicles with batteries too small to be readily used for bidirectional charging. However, based on interviews, most areas of rural China would have at least some households with four-wheeled electric vehicles. Further, interviewees suggested that households with four-wheeled EVs may use them more sporadically than urban residents with a regular commute. On the other hand, during agricultural season (mid-May and also October), larger EVs may be away from home charging for extended periods, especially during the daytime when surplus PV is available. On balance, however, the vehicle usage pattern in rural areas is relatively favourable for combining PV with

V2H compared to an urban or suburban commuter who is rarely parked at home at midday – even assuming that the urban resident has dedicated parking and rooftop solar, which is likely limited to wealthier residents of villa homes on the outskirts of cities.

The practicality of pairing V2H with a heat pump and PV depends on multiple factors. These include residential electricity prices, the structure of time-of-use prices and prices for injecting surplus PV electricity into the grid at midday, the cost premium of a bidirectional home charger, the battery capacity of the EV available for V2H at different times, and the travel patterns and driving distances of the EV.

The following represent some of the major assumptions used in this analysis:

- **PV and heat pumps:** As with the prior analysis of combining PV and ASHPs, the analysis assumes a fixed-tilt 5 kW rooftop PV system with no home energy storage, combined with a 5 kW home heat pump. The home is assumed to have 100 m^2 of climate controlled area and to be insulated to China's present standards for the Hot Summer Cold Winter climate zone.
- **Electricity prices:** Residential electricity prices are based on a time-of-use tariff with five price periods.[44] For PV electricity injected into the grid, the net price paid to is RMB 0.35/kWh for most periods, similar to the present level of compensation,[45] but assumed to be cut to RMB 0.175/kWh for midday hours from 10 am to 2 pm.
- **EV base case:** The modelled household has one EV with a 30 kWh battery back. The daily driving distance averages 50 km, with a maximum of 100 km. The vehicle efficiency is 0.2 kWh/km, leading to a total electricity consumption for EV charging of 3100 kWh per year (8 kWh per day, on average). All vehicle charging takes place at home from off-peak electricity, unless a trip cannot be completed with the battery capacity available, in which case the vehicle is assumed to charge away from home – but only to a level sufficient to complete the trip and return home.
- **Driving patterns:** Daily travel distance varies randomly throughout the year, with a uniform daily distribution from zero to the maximum daily distance (100 km, in the base case). The household is assumed to make between zero and two trips per day, depending on distance travelled.
- **V2H base case:** For the base case of a 30 kWh EV battery capacity, 10 kWh are assumed as available for bidirectional charging for those engaged in V2H – in other words, users will not discharge electricity from the EV battery for home use below a 20 kWh (66 per cent) state-of-charge. The home is equipped with a 7-kW bidirectional home charging system. The vehicle will recharge only from off-peak electricity, and overnight will leave a buffer of 20 per cent to enable some midday charging from surplus midday PV output. The battery will discharge into the home only at peak times, and will not discharge at off-peak times to restore the buffer. (In other words, if the EV charges from solar at midday and charges full to 30 kWh, this will not discharge back to the home during off-peak times.)[46]

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[44] Although residential electricity prices are currently insulated from time-of-use pricing in most of China, the adoption of time-of-use for reducing peak loads is a long-term trend, and national officials have encouraged provinces to shift to more granular time-of-use structures with at least five price periods. See "国家发展改革委有关负责同志就 《关于进一步完善分时电价机制的通知》答记者问 [NDRC officials reply to journalist questions regarding notice on further improving time-of-use electricity pricing]," National Development and Reform Commission, August 2021, at https://www.ndrc.gov.cn/xxgk/jd/jd/202108/t20210802_1292769.html; "全国各地最新销售电价表一览 [National listing of latest retail electricity prices]," Beijixing, 31 May 2021, at https://news.bjx.com.cn/html/20210531/1155249.shtml.

[45] See '户用光伏建设运行百问百答,' National Energy Administration and China Solar PV Industry Association, 31 August 2022, at https://www.nea.gov.cn/2022-08/31/c_1310657941.htm. However, some provinces are reportedly cutting the price paid for distributed solar to correspond with periods of peak solar output. See '11 省市的分时电价"狙击"分布式光伏 Time-of-use electricity prices in 11 provinces and cities "snipe" distributed photovoltaics],' PV Energy Circles, 23 November 2023, at https://mp.weixin.qq.com/s/ZoAhRsDl7-e_0jnpYfNwLQ.

[46] Other research has studied minimum state-of-charge for users engaged in V2G. See R. Somya and V. Sankaranarayanan, 'Optimal vehicle-to-grid and grid-to-vehicle scheduling strategy with uncertainty management using improved marine predator algorithm,' Computers and Electrical Engineering, 100, May 2022, at https://doi.org/10.1016/j.compeleceng.2022.107949. Optimal maximum charging levels are discussed in Emmanouil D. Kostopoulos et al., 'Real-world study for the optimal charging of electric vehicles,' Energy Reports, 6, November 2020, at https://doi.org/10.1016/j.egyr.2019.12.008.

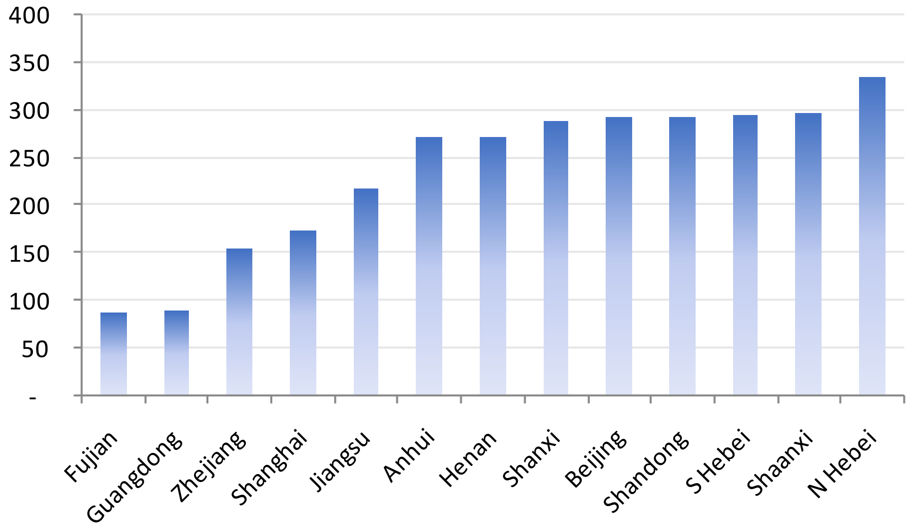
2.1 Results: savings from V2H

The results of the analysis show that V2H offers those with existing PV and ASHP modest electricity savings compared with owning an EV without V2H capability. Savings from V2H averaged RMB 236 per year across the 13 provinces considered. Further, EV ownership can substantially increase the percentage of self-consumption of electricity from rooftop PV, with or without V2H.

The sensitivity analysis shows that the benefit of V2H for either electricity savings or improving the ratio of PV self-consumption varies by region, and depends on daily driving patterns, battery size, amount of battery used for V2H, and the amount of buffer left overnight for storing midday surplus PV.

For the base case, the average annual electricity saved by adopting V2H versus EV charging with no V2H was RMB 236 per year. Of the 13 provinces considered, savings ranged from just RMB 87 to as high as RMB 335 per year for the base case; however, over half the regions experienced savings between RMB 250 and 300 per year. Even if the cost of purchasing a bidirectional charger falls significantly over the coming years, this cost savings is quite modest and inadequate to recover the upfront costs of the charging equipment.

Figure 3: Base case electricity cost savings (RMB per year) from V2H versus off-peak charging



Source: OIES, 2023

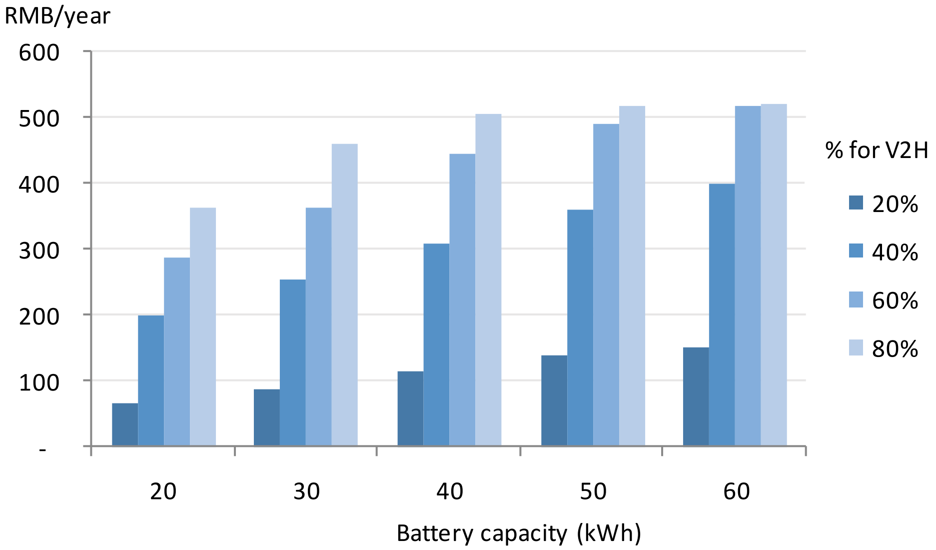
As can be seen at a glance, the regions with the greatest cost savings are clustered towards the regions with greater heating load. Higher heating load translates to greater ability to utilize surplus midday solar by adopting V2H. The correlation between heating load and annual electricity cost savings was 0.81, and the correlation between average winter temperature and annual savings was negative 0.93. In contrast, there was a small negative correlation with cooling load and annual savings. Cooling load is not only far smaller than heating load for most of China – including even the warmer provinces shown above – but cooling also has a closer match to daily PV output. Both of these considerations reduce the value of V2H.

Adding V2H capability substantially boosts self-consumption of PV output. In contrast to the topic of electricity cost savings, where northern regions are more favoured, self-consumption percentages tend to show better results in provinces with lower winter heating load. In warmer regions, adding V2H capability also results in a major improvement in the proportion of load met by PV. In Guangdong, this proportion reaches almost 60 per cent in the V2H case.

2.2 Sensitivity analysis of battery and V2H characteristics

V2H involves multiple trade-offs. A larger battery not only gives more driving range, but potentially more battery capacity that could be used to store surplus PV electricity. However, a larger battery costs more, and if the extra capacity is rarely used for driving or V2H, it may not be worth the extra expenditure. Since interviewees emphasized low purchase price as a central consideration for rural EV buyers, not necessarily driving range. For the base case household with a 5 kW rooftop PV system and a maximum daily driving distance of 100 km, the economic savings from V2H are only moderately sensitive to battery size. For the base case, in which a household uses between 20 and 30 per cent of the battery capacity for V2H, electricity cost savings approximately double between 20 kW versus a 40 kW battery size. However, if a larger proportion of the battery is used for storing midday PV output, more savings are possible, but a larger battery doesn't greatly improve the savings potential. This is because the surplus electricity from the 5 kW rooftop system is already fully stored with 30 kW of useable battery capacity. Of course, using more battery capacity to consume more surplus PV at peak electricity price periods implies greater likelihood of not being able to complete trips without an outside charge, which could negate the economic benefit – even aside from the inconvenience.

Figure 4: Annual electricity savings (RMB) for given battery capacity (kW) versus percentage of battery used for V2H



Source: OIES, 2023

A second major consideration for maximizing the electricity cost savings is the home charging buffer. In the absence of V2H, many EV owners prefer to charge full on a daily basis, or to the manufacturer's recommended charging amount, such as 80 per cent state-of-charge. If the battery is charged full every night using off peak power, this leaves no battery capacity available the following day for storing midday PV, unless the timing of trips happens to open up some spare capacity. However, leaving too large a buffer opens up the possibility of needing to charge the vehicle at peak electricity time periods, depending on trip length.

Another factor determining the value of saving a buffer to absorb daytime PV output is the relative price of nighttime charging compared to the price paid for excess solar PV output. The base case uses an assumption that PV is paid a value similar to the on-grid tariff for coal, or RMB 0.35/kWh, except for midday hours when this price is discounted by 50 per cent.[47] Only midday However, the overnight charging tariff under the time-of-use pricing scenario is around RMB 0.20/kWh, so that for most days excess PV output sent to the grid will earn more money for the household than would be saved by reducing overnight charging to arbitrage peak prices with midday solar output. Hence, in the base case, maintaining an overnight buffer to maximize self-consumption of PV does not produce any savings. The savings to using V2H in the base case are inversely proportional to the price paid for PV electricity sent back to the grid – in other words, as the price paid for surplus PV falls, the savings for adopting V2H rise. The sensitivity of annual electricity cost savings is more sensitive to this one factor – price paid for surplus PV sent to the grid – than any other variable.

[47] This assumption was also used in the analysis pairing heat pumps with PV, and was used for the base case here for consistency.

Completing most or all trips with home charging is likely a major priority for the majority of rural EV users, even in China. For the base case of an EV in Shandong province, with a maximum trip length of 100 km, a 5 kW home PV system, an electric ASHP, and 20 per cent overnight charging buffer, almost all trips can be completed with home charging using a 30 kW EV battery, with only a single day needing a charge away from home if the V2H capacity percentage was 40 per cent or 60 per cent. For a 20 kW battery, however, between 6 to 10 days would necessitate an outside charge to complete travel.

For a household with a 200 km maximum daily travel distance, a 40 kW battery is sufficient to complete most trips from home charging. However, for this case, a 20 kW battery would imply over 100 days requiring a charge away from home to complete travel, and use over 300 kWh from public chargers during trips, negating or significantly reducing the incentive to adopt V2H. A 30 kW battery would also require external charging on over 40 days.

2.3 Conclusions: V2H offers solar and EV households modest savings at little cost in convenience

The main result of the modelling analysis from this study show that bidirectional charging offers modest electricity cost savings for solar PV households in those regions where the Whole County PV Programme is most active – namely, North-central China. This is because these provinces combine relatively good solar resources, fairly balanced solar PV output in winter compared to summer, and high heating load compared to midday cooling load. With these characteristics, V2H can offer annual electricity cost savings of RMB 250 to RMB 300 in most of this region. These savings would be insufficient to enable recovery of the current upfront cost of adopting V2H for most users,[48] at least in the absence of equipment cost subsidies or additional subsidies for participating in V2H, such as might be offered by the grid companies. Savings are smaller in warmer provinces that can use midday solar for cooling in the summertime and have less need for heating in the winter.

Two changes would be necessary to make V2H more economically attractive: the upfront cost of charging equipment would need to fall, and the time-of-use price structure would need to provide greater savings opportunities for absorbing surplus solar output. In particular, this analysis shows that adjusting or removing the payment for sending power back to the grid at midday would more than double the annual savings. Further adjustment to time-of-use power prices to increase the peak-trough price differential would likely provide further incentive. However, any of these changes on their own would be insufficient to make V2H attractive on its own.

The second finding relates to trip lengths and durations. Although the analysis necessitates several simplifying assumptions, it nevertheless demonstrates that for a hypothetical household with approximately two EV trips per day and several hours of activity time per trip, the amount of time spent parked at home is sufficient to make V2H worthwhile as a method to boost self-consumption of surplus midday solar electricity. For an urban household with a uniform daily commute on weekdays and some daytime travel on weekends as well, there would be comparatively little opportunity to use V2H for absorbing midday solar output.

The third major finding relates to self-consumption of PV and household self-sufficiency. Although V2H could offer an economic way to increase self-consumption of surplus PV, it would not suffice to make a household entirely self-sufficient. Nor would V2H entirely eliminate the problem of midday overproduction at the local level. Self-consumption of PV rises to around 60 per cent, while self-sufficiency rises to 50 to 60 per cent. This implies that households and villages participating in the Whole County PV Programme may be able to moderate their need for distribution grid upgrades, but some upgrades and potentially central utility-scale storage will still be needed to absorb surplus solar PV production.

[48] As noted in Chapter 1, a bidirectional home charger in China could cost up to RMB 20,000.

3. Conclusions and lessons

Electrification of personal transportation is a critical aspect of the global low-carbon energy transition. China's rural areas, especially in eastern China, have begun to rapidly scale-up rooftop solar, offering potential synergies with other strategies to electrify household energy consumption, such as for heating and transportation. For many years, V2G and bidirectional charging have appeared to offer an eventual solution to the problem of variable output of local solar PV, and this is especially relevant in China, given weaknesses in local distribution grids.

As the modelling in this study shows, however, bidirectional home charging faces major challenges, both in terms of upfront cost and in the economics of charging. These barriers are present even for a hypothetical rural household with existing rooftop solar, an electric heat pump, and a variable driving and charging profile that would provide time for the vehicle to help absorb midday solar. Adjustments to rural household electricity prices, as well as lower cost bidirectional charging equipment, are necessary to make bidirectional charging a viable strategy. Possible solutions include sharing of charging equipment, and encouraging grid companies to subsidize and coordinate bidirectional charging, possibly through optimizing charging for the wider grid, instead of for a single household as studied here.

While this study emphasizes the barriers to bidirectional charging in rural China, there are reasons for optimism. First, costs are expected to fall rapidly. Second, electricity tariffs are also subject to efforts at increasing variable pricing to encourage better matching of loads with generation. Third, as more vehicles with bidirectional charging capability come to the market, new products and services are likely to follow. Lastly, both policy makers and consumers worldwide have high interest in bidirectional charging as a solution to various issues, including but not limited to renewable or low-carbon energy, making this field ripe for new commercial innovations and services.